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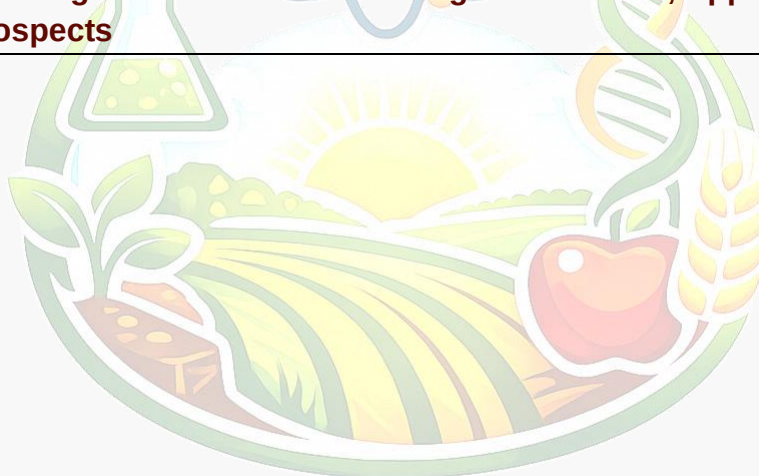
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Water Apple - A Promising Emerging Fruit Crop in South India

Article ID: 73700

Dr. M. Manikandan¹, Dr. S.P. Mirunalini¹, Dr. C. Jayalakshmi¹, Dr. A. Shanthi¹
¹Department of Horticulture, Pandit Jawaharlal Nehru College of Agriculture and Research Institute, Karaikal, U.T. of Puducherry.

Abstract

The myrtle family, Myrtaceae, constitutes over 5500 species, and *Syzygium* is considered the largest genus of the flowering plants within the family. The water apple, *Syzygium aqueum*, is a traditional fruit cum medicinal plant with various bioactive compounds distributed in all plant parts. These include phenolic compounds, flavonoids, tannins, terpenoids, and essential oils. *S. aqueum* extracts and their isolated compounds showed multiple beneficial biological effects such as antibacterial, antifungal, antidiabetic, analgesic, antimalarial, antioxidant, anti-inflammatory, and anticancer activities. This article is aimed at discussing all the available information about the production technology, nutritional value, traditional uses, and therapeutic properties of the fruits. This fruit is gaining importance in recent days around parts of Tamil Nadu and other south India.

Introduction

Water apple (*Syzygium aqueum*/samarangense), known locally as Jambu, is a high-yield tropical fruit cultivated in India (especially Kerala, Tamil Nadu, and AP) for its sweet, juicy fruit, which is rich in water content. It is a low-maintenance, fast-growing tree that thrives in sunny, well-drained tropical climates, often flowering 3-4 times a year, with significant harvest seasons usually in May-July and again in Nov-Dec.

Water apples are not only refreshing but also pack a nutritional punch. With around 90% water content, they are naturally hydrating and low in calories, making them an excellent choice for weight-conscious individuals (Triyono).

Key Vitamins and Minerals

Water apples are a good source of vitamin C, providing around 22% of the recommended daily intake per 100 grams. Vitamin C is a powerful antioxidant that supports immune function, skin health, and collagen production. These fruits also contain smaller amounts of vitamin A, vitamin E, potassium, calcium, magnesium, and manganese, all of which contribute to overall health and well-being.

A 100-gram serving of water apple nutrition value contains:

Nutrient	Amount
Calories	25 kcal
Carbohydrates	5.7 grams
Protein	0.6 grams
Fat	0.3 grams
Dietary Fiber	1.8 grams

Tips for Cultivation of Water Apple

Water apple (*Syzygium samarangense* or *S. aqueum*) cultivation requires a tropical climate, full sun, and well-draining, nutrient-rich soil with a pH of 5.5-7.5. Propagated mainly through air-layering or grafting, trees are planted 5-6m apart and start bearing in 2-4 years, with pruning, consistent irrigation, and pest management for high-yield fruits.

Production Technologies

Climate & Soil: Thrives in hot, humid tropical climates. Prefers loam to sandy loam soils that are well-draining but maintain moisture.

Propagation: Air layering is the preferred method for quick bearing (1.5-2 years) and retaining parent tree quality, although grafting and budding are also used.

Planting: Optimal spacing is 5 m x 5 m

Management:

a. Irrigation: Consistent, consistent, moisture is crucial for fruit quality. Drip irrigation is efficient, especially during the dry season and fruit development.

b. Fertilizer: A balanced fertilizer (NPK) should be applied every 6-8 weeks during the growing season. Organic manure/compost helps maintain soil organic matter.

c. **Pruning:** Annual pruning is essential to remove deadwood, open the canopy for sunlight, and maintain a reachable height for harvesting.

Pest & Disease Management:

a. **Fruit Fly/Borers:** The main concern is fruit fly; bagging fruits on the tree is a standard organic method to prevent damage.

b. **Aphids & Diseases:** Regular monitoring and application of appropriate insecticides/fungicides, or natural remedies (neem oil) to treat whiteflies or fungal spots.

Harvesting: Fruits should be harvested when they are fully colored (red/pink/white depending on variety) and firm, usually 3-4 months after flowering. They are highly perishable, requiring gentle handling

Pharmaceutical Properties of Water Apple

Rich Source of Antioxidants: Water apple is packed with antioxidants such as flavonoids, phenolic compounds, and vitamin C. These antioxidants help neutralize free radicals in the body, reducing oxidative stress and preventing cellular damage. By combating oxidative stress, water apple may lower the risk of chronic diseases like heart disease, cancer, and neurodegenerative disorders.

Hydration and Electrolyte Balance: Water apple has a high water content, making it an excellent fruit for hydration. Consuming water apple helps replenish fluids lost through sweating and daily activities, supporting optimal bodily functions. Additionally, it contains essential electrolytes like potassium and magnesium, which are vital for maintaining fluid balance, nerve function, and muscle contractions.

Supports Digestive Health: Water apple is rich in dietary fiber, which promotes healthy digestion by adding bulk to stool and facilitating regular bowel movements. This helps prevent constipation and supports overall gut health. The fruits natural compounds also possess mild laxative properties, aiding in the elimination of waste and toxins from the digestive tract. Additionally, water apple contains water and enzymes that soothe the stomach lining, reducing acidity and discomfort.

Boosts Immune Function: The presence of vitamin C and other immune-enhancing nutrients in water apple strengthens the bodys defense mechanisms against infections. Vitamin C stimulates the production of white blood cells, which are crucial for fighting pathogens. It also enhances antibody production and supports skin integrity, the bodys first line of defense. The antioxidants in water apple further reduce inflammation and oxidative damage, which can weaken immune responses.

Promotes Heart Health: Water apple contains potassium, a mineral essential for maintaining healthy blood pressure levels by counteracting the effects of sodium. Potassium helps relax blood vessel walls, improving circulation and reducing strain on the heart. The antioxidants in water apple prevent the oxidation of LDL cholesterol, a major factor in the development of atherosclerosis. Its fiber content also helps lower cholesterol levels by binding to bile acids and promoting their excretion.

Helps Manage Weight: Low in calories and high in water content, water apple is an ideal fruit for weight management. It provides a feeling of fullness and hydration without adding excess calories, which can help reduce overall food intake. The dietary fiber in water apple slows digestion and stabilizes blood sugar levels, preventing spikes and crashes that often lead to overeating.

Enhances Bone Strength: Water apple contains minerals like calcium, phosphorus, and magnesium, which are crucial for maintaining strong and healthy bones. Calcium and phosphorus are primary components of bone tissue, while magnesium aids in the absorption and metabolism of these minerals. Together, they help prevent bone density loss and reduce the risk of osteoporosis and fractures. The vitamin C in water apple also supports bone health by promoting collagen production, which is vital for bone matrix formation.

Regulates Blood Sugar Levels: Water apple has a low glycemic index and contains fiber that slows down the absorption of sugars in the bloodstream. This helps regulate blood sugar levels and prevents sudden spikes that can be harmful, especially for individuals with diabetes or insulin resistance. The fruits natural compounds may also improve insulin sensitivity, aiding in better glucose metabolism.

Supports Respiratory Health: Traditional uses of water apple include treating respiratory conditions such as asthma, bronchitis, and coughs. The fruit contains anti-inflammatory and antimicrobial properties that help soothe the respiratory tract and reduce irritation. Its hydrating effect also helps thin mucus, making it easier to expel and relieving congestion. Regular consumption may aid in preventing infections and improving lung function.

Importance of Water Apple

1. **Rich Source of Nutrients:** Water apples provide essential vitamins and minerals vital for overall health.

2. **Hydration Benefits:** High water content helps maintain proper hydration levels in the body.

3. **Antioxidant Properties:** Contains antioxidants that combat free radicals and reduce oxidative stress.

4. **Supports Digestive Health:** Dietary fiber aids in digestion and promotes regular bowel movements.
5. **Boosts Immune System:** Vitamins and antioxidants enhance the body's natural defense mechanisms.
6. **Low-Calorie Snack Option:** Ideal for weight management due to its low calorie and fat content.
7. **Anti-Inflammatory Effects:** Compounds in water apple may reduce inflammation and related health issues.
8. **Supports Heart Health:** Nutrients help regulate blood pressure and improve cardiovascular function.
9. **Promotes Oral Health:** Chewing water apples stimulates saliva production, reducing bacteria and tooth decay.



From Conflict to Crisis: How Wars Disrupt Energy Systems and Drive Global Food Insecurity

Article ID: 73701

Avinash C¹, Shevakula Manasa¹

¹Ph.D. Scholar, Division of Environmental Sciences, ICAR - Indian Agricultural.

Abstract

War-induced disruptions to global energy systems have far-reaching consequences beyond fuel shortages, particularly for agriculture and food security. The Russia-Ukraine war (2022) and the Iran-Israel-USA war (2026) triggered severe energy crises by damaging infrastructure, restricting trade, and destabilizing markets. These shocks led to sharp increases in fuel and fertilizer prices, directly impacting agricultural productivity and food supply chains. Developing countries, especially import-dependent nations like India, faced rising production costs and increased food insecurity. The article highlights how modern agriculture's dependence on energy amplifies vulnerability during geopolitical conflicts. It is necessary to adopt renewable energy, diversify supply, and improve efficiency to safeguard global food security against future crises.

Keywords: Energy crisis; War; Food insecurity; Agriculture; Fertilizer; Fuel prices; Supply chains; Energy resilience.

What is an Energy Crisis?

An energy crisis occurs when the supply of energy (oil, natural gas, coal, and electricity) falls sharply or becomes prohibitively expensive, disrupting the functioning of economies. Energy supports virtually every sector of modern life. Agriculture depends on fuel to operate machinery and produce fertilizers. Manufacturing requires electricity, transportation relies on oil, and hospitals and commercial buildings all depend on stable power supplies. When the energy supply is disrupted, the consequences cascade rapidly. Prices rise for goods and services. Inflation increases, and in severe cases, economic recession occurs.

How Does War Cause an Energy Crisis?

Wars disrupt energy systems through several interconnected mechanisms. Understanding these mechanisms is essential (Hossen, 2025).

Destruction of infrastructure: Oil fields, refineries, pipelines, power stations, and ports are frequent military targets. Their destruction reduces production capacity and halts exports.

Sanctions and trade restrictions: Nations at war, or their enemies, impose economic sanctions that cut off energy trade.

Market speculation and fear: Even before actual shortages occur, the fear of conflict causes oil and gas prices to rise on global commodity markets, creating future supply disruptions.

Forced redirection of supply chains: Nations that try to replace a banned supplier must compete for limited alternatives, further inflating prices worldwide.

Refugee and displacement crisis: Mass displacement caused by war reduces agricultural and industrial output in affected regions, compounding energy and food shortages.

Contemporary Case Studies: Russia-Ukraine (2022) and Iran-Israel-USA (2026) War

The two most significant recent examples of war-induced energy crises are the Russia-Ukraine conflict of 2022 and the 2026 Iran-Israel-United States war. Together, they caused the most severe consecutive energy shocks the world has experienced since the 1973 Arab Oil Embargo, and their impacts on agriculture and food security.

1. Russia-Ukraine War (2022): Russia's full-scale invasion of Ukraine, which began in February 2022, triggered the first major energy crisis of this decade. Russia is among the world's largest producers and exporters of oil and natural gas. Before the conflict, it supplied approximately 40% of the European Union's natural gas. Natural gas prices in Europe rose by over 300% within months of the invasion, reaching record highs not seen in decades (IEA, 2022). The consequences were severe and wide-ranging. Several European governments introduced emergency subsidies to shield consumers from price spikes. Industrial production in energy-intensive sectors, including steel, glass, and fertilizer, was curtailed across the continent.

2. Iran-Israel-United States War (2026): On 28 February 2026, Israel-USA launched military strikes against Iran, targeting Iran's nuclear facilities, missile infrastructure, and energy installations. Iran retaliated with strikes against US- Israeli targets and Gulf states hosting US forces, and closed the Strait of Hormuz, which is the narrow waterway through which 20% of the world's oil and the LNG trade passes every day. Before the conflict, around 3,000 vessels used the strait

monthly; within days of the closure, this fell to 5% of normal levels (HCL, 2026). The International Energy Agency (IEA) described the situation as the 'greatest global energy security challenge in history.' Iran retaliated by attacking Qatar's Ras Laffan facility, the world's largest LNG production complex, triggering an unprecedented shutdown of global LNG supply. Experts warned of a five-year setback for the world's energy system (CGEP, 2026).

Historical Examples: Wars and Energy Shocks

The link between armed conflict and energy crises is not new. History shows several important examples:

Table: Major War-Related Energy Crises and Their Global Impact:

Conflict	Year	Energy Impact
Arab Oil Embargo	1973	Oil prices quadrupled, and a global recession
Gulf War (Iraq-Kuwait)	1990	Oil prices doubled; Global supply cut by 4.3 million barrels/day
Iraq War	2003	Prolonged price inflation
Russia-Ukraine War	2022	Gas prices +300%; European energy emergency
Iran-Israel-US War	2026	Strait of Hormuz closed; IEA calls it 'greatest energy crisis in history'; LNG supply 5-year setback

Impact on Vulnerable Populations

Energy crises do not affect all people equally. The poorest households and least-developed nations bear the greatest burden, for several reasons:

1. Household energy poverty forces households to choose between heating, food, and medicine.
2. Import-dependent developing nations' import bills rise sharply.
3. Fertilizer production, tractors, pumps, and food processing plants all require fuel. The 2022 energy crisis pushed over 258 million people toward food insecurity (FAO, 2023).
4. Healthcare systems in energy-poor nations may face power outages.

Impact of Energy Crisis on Agriculture

Agriculture is one of the sectors directly affected by war-induced energy crises. Modern farming is a highly energy-dependent system. Natural gas is the primary raw material for producing nitrogen fertilizers such as urea and ammonium nitrate. When the Russia-Ukraine war disrupted global gas supplies, fertilizer prices skyrocketed by over 200% in 2022. Russia and Belarus together supply nearly 40% of the world's potash and nitrogen fertilizers (IFPRI, 2023). The crisis deepened in 2026 when the Iran-Israel-US war.

Diesel-powered tractors, harvesters, threshers, and irrigation pumps all depend on oil. In India, where smallholder farmers operate on thin margins, even a 20-30% rise in diesel prices can make cultivation economically not viable. Transportation of seeds, inputs, and harvested produce depends on fuel. Higher fuel costs translate directly into higher food prices at every step. The FAO Food Price Index reached its all-time high in March 2022, immediately following the Russia-Ukraine war. In 2026, the closure of the Strait of Hormuz showed a second severe blow to global food supply chains (FAO, 2026).

Impact on India and Global Agriculture

India imports approximately 85% of its crude oil needs. The 2022 energy crisis caused diesel prices to breach in many states, directly inflating the cost of agricultural operations at a time when the Rabi crop season was underway. Urea prices, though subsidised by the government, placed enormous pressure on the national fertilizer subsidy bill, which crossed 2.5 lakh crore in 2022-23 (MoCF, 2023). Smallholder farmers, who constitute over 85% of India's farming community, bear the greatest suffering. In Iran itself, food inflation surged to 105% by March 2026, with bread and edible oils rising year-on-year. Pakistan announced emergency measures, including a four-day government work week. With these combined supply disruptions, farmers across India, Africa, and South Asia faced severe fertilizer shortages. Global energy and food markets continued to face severe uncertainty. Investing in solar-powered irrigation, bio-fertilizers, and energy-efficient farm machinery is necessary for food security in India.

Pathways to Energy Resilience

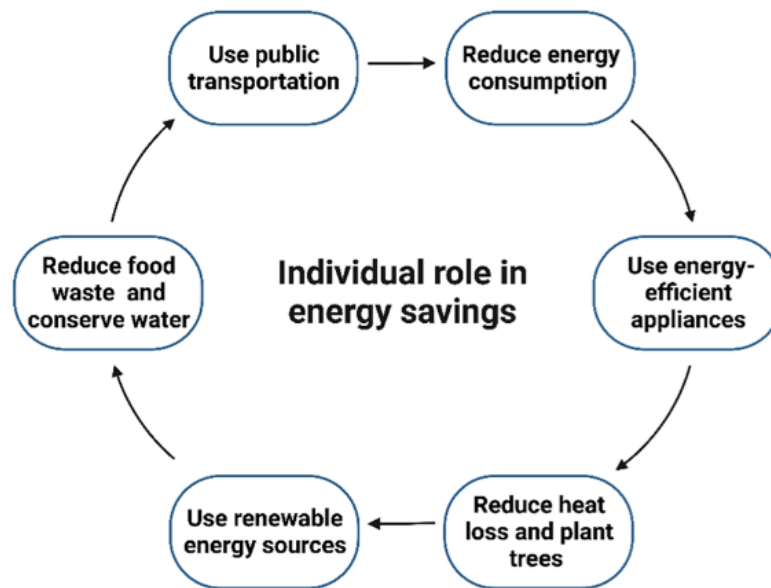
The energy crisis accelerated global interest in building more resilient, diversified, and sustainable energy systems. Key strategies include:

1. **Accelerating renewable energy deployment:** Solar, wind, and hydropower cannot be blockaded, sanctioned, or cut off by a hostile government.
2. **Diversification of supply:** Developing multiple import relationships, building strategic reserves, and investing in energy storage infrastructure.

3. Energy efficiency: Reducing energy consumption through better building insulation, efficient appliances, and sustainable urban planning reduces energy costs and import dependence.

4. International energy cooperation: Multilateral frameworks for energy security

5. Role of the individual in energy savings: use of public transport, environmental education, reducing consumption, and shifting towards renewable energy (Farghali et al., 2023).



Conclusion

The consequences of war reach into homes, farms, and industries across the globe. The energy crisis is one of the consequences. As the Russia-Ukraine conflict of 2022, the 2026 Iran-Israel-US war, the Arab Oil Embargo, and the Gulf War have all demonstrated, the disruption of energy supply from a single major producer can trigger global price spikes, recessions, food shortages, and humanitarian crises that fall hardest on the world's most vulnerable people. The solution lies not only in diplomatic efforts to prevent war but in building energy systems that are decentralised, diversified, and rooted in renewable sources that no nation can weaponize.

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Maggot Therapy: Nature's Tiny Surgeons in Wound Healing

Article ID: 73702

Kota Sahithi Chowdary¹, Repaka Harika¹, Gopu Sushma²

¹Ph. D Scholar, Indira Gandhi Krishi Vishwavidyalaya, Raipur.

²Ph. D Scholar, Professor Jayashankar Telangana Agricultural University.

Abstract

Maggot therapy, also known as larval therapy, is an ancient yet scientifically validated technique used in modern medicine for wound healing. It involves the controlled application of sterile fly larvae to remove necrotic tissue, control infection, and promote tissue regeneration. With the growing challenge of antibiotic resistance and chronic wounds, maggot therapy has re-emerged as an effective and economical alternative. This article highlights the mechanisms, applications, advantages, and future prospects of maggot therapy in wound management.

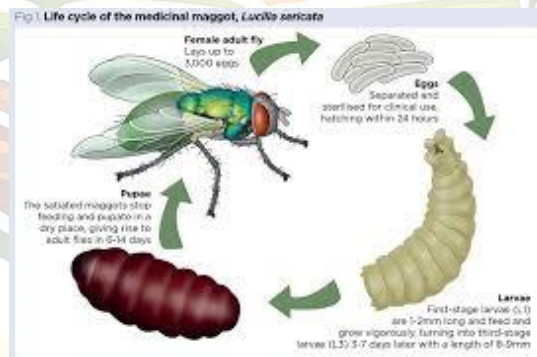
Keywords: Maggot therapy, larval therapy, wound healing, biodebridement, chronic wounds, medical entomology.

Introduction

The use of maggots in wound healing may appear unconventional, yet it is one of the oldest recorded medical practices. Historical observations indicated that wounds colonized by maggots often healed faster and showed fewer signs of infection. In modern medicine, this practice has been refined into a controlled therapeutic technique known as maggot therapy or larval therapy (Sherman, 2020). With increasing incidences of chronic wounds such as diabetic ulcers and the rise of antibiotic-resistant pathogens, maggot therapy is gaining renewed attention as a reliable and sustainable treatment option (Zubir *et al.*, 2020).

What is Maggot Therapy?

Maggot therapy involves the application of sterile larvae, typically of the green bottle fly *Lucilia sericata*, to non-healing wounds. These larvae are produced under sterile laboratory conditions to ensure safety and prevent contamination (Sherman, 2020). The therapy primarily aims at biodebridement, which is the removal of dead or infected tissue to facilitate wound healing.



Mechanism of Action

Maggot therapy promotes wound healing through multiple biological processes:

- 1. Debridement:** Maggots selectively consume necrotic tissue while leaving healthy tissue intact. This selective feeding makes them highly efficient biological debriding agents compared to mechanical or surgical methods (Zubir *et al.*, 2020).
- 2. Antimicrobial Activity:** Larvae secrete antimicrobial compounds that inhibit the growth of pathogenic microorganisms, including antibiotic-resistant bacteria. These secretions help reduce bacterial load and prevent infection (Nigam *et al.*, 2021).
- 3. Promotion of Tissue Regeneration:** Maggot secretions stimulate wound healing by enhancing cell proliferation, promoting angiogenesis, and increasing the formation of granulation tissue (Sherman, 2020).

Applications in Modern Medicine

Maggot therapy is widely used for the treatment of:

1. Diabetic foot ulcers
2. Pressure ulcers
3. Venous leg ulcers

4. Burn wounds
5. Post-surgical infections

It is particularly effective in chronic wounds where conventional treatments have failed (Zubir *et al.*, 2020).

Advantages of Maggot Therapy

1. Selective removal of necrotic tissue without damaging healthy cells
2. Effective against antibiotic-resistant bacteria
3. Accelerates wound healing and tissue regeneration
4. Cost-effective and minimally invasive
5. Reduces need for surgical debridement

Studies have shown that maggot therapy can significantly improve wound healing rates and reduce infection levels (Nigam *et al.*, 2021).

Limitations and Challenges

1. Psychological discomfort or aversion among patients
2. Mild pain or irritation during treatment
3. Limited acceptance in some clinical settings
4. Requires proper medical supervision.

Despite these limitations, the therapy remains safe and effective when applied under controlled conditions (Sherman, 2020).

Environmental and Medical Significance

Maggot therapy highlights the beneficial role of insects in medicine and demonstrates how natural biological processes can be harnessed for healthcare. It also reduces dependence on chemical treatments and antibiotics, contributing to sustainable medical practices (Zubir *et al.*, 2020).

Future Prospects

Ongoing research is focused on isolating bioactive compounds from maggot secretions for pharmaceutical applications. With advancements in biotechnology, these compounds may be developed into novel drugs for wound healing and infection control (Nigam *et al.*, 2021). The integration of maggot therapy with modern wound care techniques is expected to enhance its acceptance and effectiveness in the future.

Conclusion

Maggot therapy is a remarkable example of how nature can provide innovative solutions to medical challenges. By utilizing the biological capabilities of larvae, this therapy offers an effective, eco-friendly, and sustainable approach to wound management. With increasing challenges such as antibiotic resistance, maggot therapy is likely to play a significant role in future healthcare systems.

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Impact of Climate Change on Agricultural Prices and Trade

Article ID: 73703

Dr. V. Karthick¹, Dr. S. Vennila²

¹Assistant Professor, Department of Agricultural Economics, AC & RI,

²Assistant Professor, Department of Agronomy, AC & RI,

Tamil Nadu Agricultural University, Vazhavachavanur - 606 753, Tamil Nadu, India.

Abstract

Climate change is increasingly affecting agricultural systems, influencing production, prices, and trade. Rising temperatures, erratic rainfall, and extreme weather events such as droughts and floods reduce crop yields and increase pest and disease incidence. These disruptions create supply shortages, leading to higher food prices and increased price volatility, affecting both farmers and consumers. Climate change also alters global trade patterns by shifting comparative advantage and increasing dependence on imports. Government interventions, such as export restrictions, may stabilize domestic markets but can disrupt global trade. Overall, climate-resilient practices and effective policies are essential to ensure food security and market stability.

Introduction

Climate change is no longer a distant environmental concern, it is a present day reality reshaping agriculture across the globe. Rising temperatures, unpredictable rainfall, and an increase in extreme weather events such as droughts, floods, and cyclones are significantly affecting agricultural production systems (IPCC, 2021). Agriculture remains the backbone of food security and rural livelihoods, especially in developing countries like India. Any disruption in agricultural production has direct consequences on food availability, prices, and trade. Over the past decade, climate variability has contributed to fluctuating crop yields, leading to instability in agricultural markets (FAO, 2022). The relationship between climate change, agricultural prices, and trade is deeply interconnected. Reduced crop yields tighten supply, pushing prices upward, while surplus production in favorable years may cause price crashes. At the same time, countries increasingly rely on global markets to balance domestic shortages, thereby altering traditional trade patterns (World Bank, 2020). This article explores how climate change influences agricultural production, affects price behavior, and reshapes international trade, supported by real-world case studies.

Climate Change and Agricultural Production

Climate change impacts agricultural production through multiple pathways. One of the most critical factors is rising temperature. Higher temperatures accelerate crop maturity, reducing the grain-filling period and ultimately lowering yields, particularly for staple crops such as rice, wheat, and maize (Lobell et al., 2011). Rainfall variability is another major concern. Irregular monsoons lead to either droughts or floods, both of which severely damage crops and degrade soil quality. In India, monsoon irregularities have been closely linked to fluctuations in agricultural output (Birthal et al., 2014). Additionally, warmer and more humid conditions increase the incidence of pests and diseases, leading to higher crop losses and increased use of chemical inputs. This not only raises production costs but also affects environmental sustainability (FAO, 2022). Extreme weather events such as cyclones, heatwaves, and floods cause widespread destruction of crops, storage systems, and rural infrastructure. For example, cyclones in eastern India have repeatedly damaged paddy fields, affecting both production and local food supply. Overall, climate change introduces uncertainty into agricultural production, making it more vulnerable and less predictable.

Impact on Agricultural Prices

Rising Food Prices: One of the most immediate effects of climate change is the increase in food prices. When crop production declines due to droughts or floods, supply falls while demand remains relatively stable. This imbalance leads to higher prices for essential commodities such as cereals, pulses, fruits, and vegetables (Headey & Fan, 2008). For instance, during drought years in India, prices of rice and wheat often rise sharply. Similarly, livestock feed becomes more expensive, leading to higher prices for milk, meat, and eggs.

Price Volatility: Climate change also increases price volatility. Frequent production shocks cause sudden spikes in prices during poor harvests and price crashes during years of surplus production (Tadesse et al., 2014). This instability affects both producers and consumers. Farmers face uncertain incomes, while consumers struggle with fluctuating food costs, leading to food insecurity, especially among low-income households.

Rising Cost of Production: To cope with climate stress, farmers adopt adaptation measures such as irrigation, fertilizers, pesticides, and climate-resilient seeds. While these strategies help maintain yields, they significantly increase the cost of cultivation (Nelson et al., 2014). These higher costs are often passed on to consumers, contributing to sustained increases in food prices over time.

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Impact on Agricultural Trade

Changing Trade Patterns: Climate change alters the comparative advantage of countries in agricultural production. Countries experiencing frequent climate shocks may reduce exports, while food-deficit countries increase imports to meet domestic demand (World Bank, 2020). For example, India, traditionally a major producer of pulses, had to import large quantities during drought years, demonstrating how climate events can shift trade dynamics.

Policy Responses and Trade Restrictions: Governments often intervene in markets during climate-induced shortages. Common measures include export bans, import subsidies, and tariff adjustments. While these policies aim to stabilize domestic markets, they can disrupt global trade and contribute to price volatility (Anderson & Nelgen, 2012). For instance, export restrictions on wheat or rice can reduce global supply, pushing international prices higher.

Increased Dependence on Global Markets: Climate variability forces many countries to rely more heavily on international trade. While this helps bridge supply gaps, it also exposes countries to global price fluctuations. Low-income countries are particularly vulnerable, as they spend a larger share of income on food (FAO, 2022).

Selected Case Studies

Pulse Price Inflation (2015-16): Two weak monsoons caused a sharp rise in pulse prices in India, with inflation reaching over 30%. Imports from countries like Myanmar and Canada increased significantly (Government of India, 2016). **Wheat Export Restrictions (2022):** A severe heat wave reduced wheat yields, leading India to restrict exports to control domestic prices (USDA, 2022). **Onion Price Surge (2019):** Unseasonal rainfall damaged onion crops, causing prices to spike and prompting export bans. **Cyclone Amphan (2020):** Damaged paddy crops in eastern India, leading to localized price increases and reliance on public stocks. **Erratic Monsoon (2023):** Uneven rainfall led to reduced rice production and export restrictions to ensure food security.

Conclusion

Climate change is fundamentally transforming agricultural systems, influencing not only how food is produced but also how it is priced and traded globally. Its effects on production lead to supply shocks, which in turn drive price increases and volatility. At the same time, countries are becoming increasingly dependent on international trade to ensure food security. Addressing these challenges requires coordinated efforts at local, national, and global levels. Sustainable agricultural practices, supportive policies, and international collaboration will be crucial in building a resilient food system capable of withstanding the impacts of climate change.

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Multi - Layer Natural Farming System: An Ideal Approach for Better Livelihood of Small and Marginal Farmers

Article ID: 73704

R. F. Thakor¹, L. T. Kapur¹

¹Sr. Scientist & Head* and SMS (Soil Science), Gujarat Vidyapith Krishi Vigyan Kendra, Valsad - Gujarat 396195.

Introduction

Natural farming is a chemical-free, low-intervention agricultural system that works with nature's processes, integrating crops, cattle, and biodiversity to build eco-friendly self-sustaining ecosystems, minimizing labour and outside inputs by using farmers own properties like farm bio mass, cow dung and urine for bio-inputs, stimulating soil health, and avoiding chemical fertilizers and pesticides. It lay emphasis on minimal disturbance and maximizing natural cycles to create resilience, improve soil, and reduce costs.

The five layer or multilayer natural farming model developed by Padma Shri Subhash Palekarji and widely disseminated by Shri Acharya Devvratji incorporate multiple crop layers allows farmers to diversify their crop production to reduce risk elements associated with crop failure and price fluctuations. It enhances vertical stratification and Photosynthetic Path Efficiency (PPE), providing a biological protection against biotic and abiotic stressors. By replacing outside farm inputs with on-farm bio-inoculants (such as cow dung, urine, biomass), the system enhances microbial biodiversity and soil organic carbon sequestration.

The five fundamental pillars as imagined by Shri Acharya Devvratji (Jivamrut, Bijamrut, Mulching, Vapsa condition, crop diversity) play crucial role in maintaining soil fertility and productivity. (Yadav et.al.2022).

What is Multi-Layer Farming?

A Multi-layer farming is an extensive, broad based sustainable agricultural method in which different crops (root, herb, shrub, and vine) are grown together simultaneously, in vertical layers at different vertical heights (layers) in the same area. It generally includes growing plants at different heights. It is a form of polyculture that involves growing multiple crops in a given plot. This farming system utilizes vertical and horizontal dimensions to create a multi-layered ecosystem that boosts resource efficiency and biodiversity. It is found effective in providing year-round income, promoting environmental sustainability, and offering a viable solution for small and marginal farmers in resource-inhibited areas. The method allows for higher yields, reduced pest infestation, improved biodiversity, and better financial returns per unit area. This model integrates plant species with different sunlight requirements, ensuring thorough soil coverage while enhancing soil biodiversity, increasing carbon sequestration and improving water retention. This model was demonstrated in select villages of Valsad district of Gujarat state by Gujarat Vidyapith Krishi Vigyan Kendra as well as ATMA project to support sustainable agriculture for tribal farmers.

Key Advantages of a Multilayer Farming System

- 1. Higher Yield and Returns:** Farmers can achieve 2 to 3 times the earning from the identical area compared to traditional methods by harvesting multiple crops simultaneously. This is because each plant has its different root system and nutrients uptake from the soil are shared among the group.
- 2. Optimum Land and Resource Utilization:** It take full advantage of vertical space and uses resources like water and sunlight efficiently. It is estimated that adoption of this model save up to 70% water .It also helps to avoid soil depletion by interchanging different crops each year, thus no need to add amendments (such as compost or manure) every year.
- 3. Sustainable and Organic Approach:** The system enhance biodiversity, improves soil health, and encourages a natural, self-sustainable ecosystem that requires no outside chemical inputs like fertilizer, pesticides etc.
- 4. Reduced Weed and Pest Problems:** Because the soil is completely covered by different layers of plants, sunlight cannot reach the soil surface, significantly reducing weed growth. The diverse ecosystem also helps to naturally prevents pests and diseases. High biodiversity disturbs pest cycles, as different crops can act as "trap crops" or natural barriers to infestation.
- 5. Perennial Income and Employment:** The staggered, multi-crop production system guarantees a continuous, year-round harvest, which stabilizes income and offers consistent employment for agricultural labour. Diverse harvesting cycles provides regular supply of food ensuring household nutritional security.
- 6. Climate Resilience:** Multi-layered structure acts as a shield against climate-related destruction, such as high-intensity rain, extreme heat, reducing water evaporation, and decreases soil erosion.

7. Erosion and Landslide Mitigation: The widespread root systems of varied crops help to stabilize soil and reduce the risk of erosion, contributing to sustainable land management.

Multi-Layer Farming Demonstration Unit (KVK-Valsad)



In general multilayer model consists of five (5) layers. Also known as Panch-stariya model. So far Layer I is concerned the plants belongs to this layer require direct sunlight with high intensity of light ranging from 8K to 12K foot candles for maximum photosynthesis and ultimately for better growth of canopy. As the mango tree matures (peak bearing around year 10), its canopy can spread up to 8-8.5 meters, creating a shaded environment under it that dictates the selection of lower-layer crops while Layer II requires medium sunlight intensity between 5K to 7K foot candles. These are planted often at 5m intervals between the rows of mango trees. They grow faster than mango, providing additional secondary income in the early years (within 1 to five years) as the mango canopy matures. Level III and Level IV occupy the space between the medium-sized trees and the surface usually short duration vegetable crops and climbers crops. They are usually grown as annual or seasonal crops, providing regular income at short interval. This category plants have ability to tolerate reduced sun light. Layer V. Plants of this level are photosensitive plants they are flourish in partial shade and need less intensity sunlight between 3.7K to 5K foot candles. These are the most shade-tolerant and are ideal for planting once the mango canopy has closed (after year 8) or if one has already established orchard. They utilize the deep soil nutrients and provide high-value harvests in the partial shade of the upper layers.

Layer	Type of crop	Spacing	Example of crops	Purpose
Layer 1 Top (Overstory)	Tall trees that needs direct sunlight	10-12 meters	Mango	Long term income Wind protection
Layer 2 Middle secondary)	Medium trees	6-8 meters	Banana, Guava Moringa, Lemon	Steady income thought the year
Layer 3 Low (Secondary)	Bushy plants	2.5 to 4 meters	Brinjal ,Tomato Chilly etc.	Seasonal income
Layer 4 Vertical (Climbers)	Vine crops	Up to 1.5 to 2- meters heights	Bottle gourd Bitter gourd Ridge gourd etc.	Utilisation of vertical space and additional income
Layer 5 Root (Subsurface)	Tuber crops / short duration like Fenugreek, Coriander etc.	Under ground or ground level	Turmeric, Ginger, Sweet potato, Potato etc.	High value spices/tubers in partial shade with same soil nutrients

Multilayer Farming Demonstration Unit on Farmer Field



Conclusion

Multilayer farming represents a transition from extractive monocultures to regenerative polyculture, forest-inspired multi crop production models. It integrates tradition and agricultural innovation, not only addresses challenges in modern agriculture but also offers solutions to resource constraints and environmental sustainability. Therefore, this so called Zero budget natural farming multilayer cropping system is boon for the small and marginal farmers. This model offers a viable pathway towards sustainable agriculture that compliments ecological boundaries, enhances biodiversity, and empowers farming communities to flourish with nature.

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Spawn Production in Mushroom Cultivation - A Comprehensive Technical Review

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Kanak Goyal¹, Ankit Kumar¹, Anshuman Prajapati¹, Arvind Kumar¹, Garcia Doley¹, Shrvan Kumar¹

¹Rajiv Gandhi South Campus, Banaras Hindu University, Mizapur (UP)-231307.

Abstract

Mushroom spawn is a vegetative inoculum consisting of actively growing mycelium colonized on a sterilized carrier (e.g., cereal grains, sawdust). It functions analogously to seeds but is metabolically active, enabling rapid substrate colonization. Spawn is produced by inoculating sterilized substrate with a pure fungal culture under aseptic conditions; optimal incubation typically occurs at 20-25 °C until full colonization (7-21 days, species-dependent). High-quality spawn exhibits >95% colonization, low contamination (<1%), and vigorous hyphal growth, which can increase yield (biological efficiency) by 20-40% compared to poor-quality spawn. Mushroom spawn types include grain spawn (colonization 5-10 days; ~200-400 inoculation points/kg), widely used for Button= *Agaricus bisporus* and *Pleurotus ostreatus* due to rapid growth and high nutrients. Sawdust spawn (10-20 days) suits wood-decaying species like *Ganoderma lucidum*. Plug spawn (wooden dowels) requires 1-3 months for log colonization like Shitake=*Lentinula edodes*. Liquid spawn enables rapid mycelial distribution with 2-5 days recovery like *Cordyceps militaris*. Optimal conditions: 50-60% moisture and 20-25 °C for most cultivated species, ensuring efficient colonization and yield. Spawn quality directly influences colonization rate, contamination resistance, and final yield, making it a critical factor in commercial mushroom production systems.

Keywords: Mushroom spawn, fungiculture, *Cordyceps militaris*, *Agaricus bisporus* and *Pleurotus ostreatus*.

Introduction

Mushroom spawn is the vegetative mycelium of a mushroom fungus grown on a substrate, serving as the functional equivalent of seeds in conventional plant agriculture. It represents the inoculum used to initiate and sustain mushroom cultivation on a desired growing medium. Unlike plant seeds, which are reproductive structures, spawn consists of actively growing mycelial networks colonized on a carrier material, ready to expand and eventually produce fruiting bodies under appropriate environmental conditions.

The term 'spawn' is derived from the Old French word 'esprendre,' meaning to spread or expand – a fitting description for the vigorous, spreading mycelial growth observed during colonization. Technically, spawn is prepared by inoculating a sterilized substrate with a pure culture of a specific mushroom strain and allowing mycelial colonization to proceed until the entire substrate is fully colonized. This colonized material is then used to inoculate bulk growing substrates for commercial or small-scale mushroom production.

The concept of intentional mushroom spawn production dates to early 20th-century France, where mushroom growers first developed 'virgin spawn' for *Agaricus bisporus* (the common button mushroom). Since then, spawn production technology has evolved dramatically, incorporating advances in microbiology, sterilization technology, and strain improvement programs. Today, spawn production is a specialized discipline at the intersection of applied mycology, food science, and agricultural biotechnology.

The quality and viability of spawn are arguably the single most critical determinants of successful mushroom cultivation. Superior spawn ensures rapid and uniform substrate colonization, reduces contamination risk, and ultimately determines the biological efficiency and yield of the crop. Thus, understanding spawn production – from the selection of appropriate substrates to sterilization protocols and storage conditions – is fundamental to both small-scale growers and large commercial operations.

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Types of Mushroom Spawn/ Fungiculture

Mushroom spawn can be classified based on the nature of the carrier substrate used for mycelial growth. Each type has distinct characteristics, advantages, and limitations that make it suitable for specific applications and mushroom species.

1. Grain Spawn: Grain spawn is currently the most widely used type in commercial mushroom production globally. Cereal grains such as wheat, rye, sorghum, millet, and corn are sterilized and inoculated with mycelium. The high nutrient content of grains supports vigorous mycelial growth, and the rounded shape of grain kernels allows for even distribution throughout the bulk substrate during inoculation. Grain spawn offers high colonization rates, easy handling, and consistent results. It is widely used for Button= *Agaricus bisporus* and *Pleurotus ostreatus*.



2. Sawdust Spawn: Sawdust spawn is prepared from hardwood sawdust, often supplemented with wheat bran or rice bran to enhance nutritional content. This type is particularly favored for wood-degrading species such as Shiitake (*Lentinula edodes*), Oyster mushrooms (*Pleurotus* spp.), Lion's Mane (*Hericium erinaceus*), and Reishi (*Ganoderma lucidum*). Sawdust spawn integrates well with wood-based bulk substrates and supports the enzymatic colonization processes characteristic of ligninolytic fungi.



3. Straw Spawn: Straw spawn is made using pasteurized or sterilized wheat straw as the carrier. It is an economical option commonly used for Oyster, Rice straw mushroom production, particularly in developing countries and smallholder farming systems. While straw spawn is less dense in mycelial content compared to grain spawn, it offers cost-effectiveness and easy availability of raw materials.



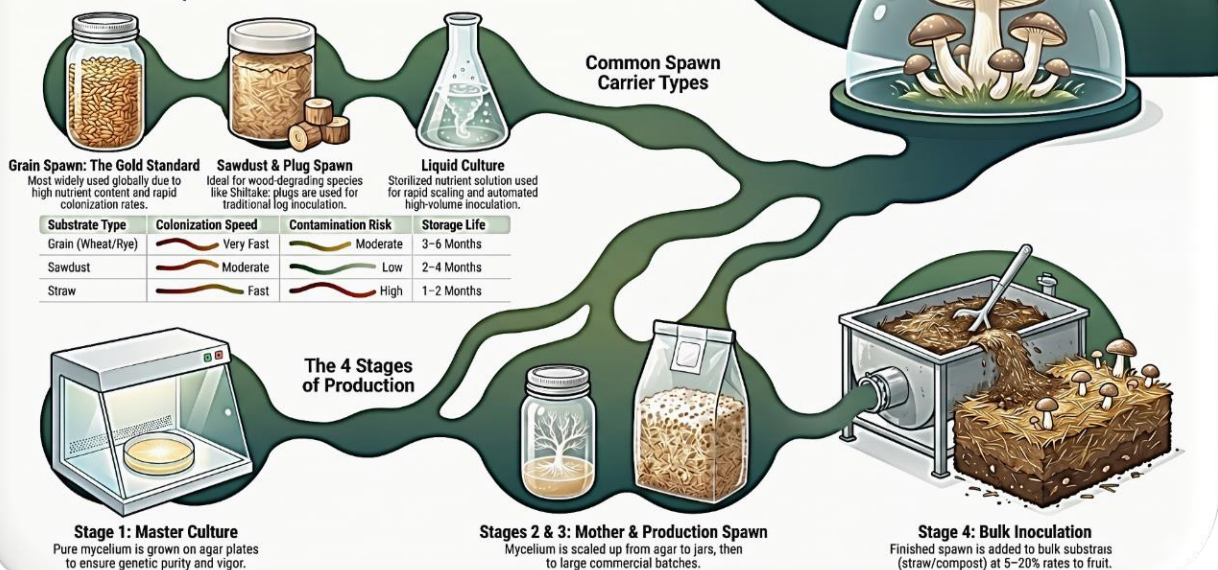
4. Plug Spawn (Dowel Spawn): Plug spawn consists of small wooden dowels or plugs fully colonized with mycelium. These are primarily used for log inoculation of species such as Shiitake and Oyster mushrooms in outdoor or semi-outdoor cultivation. Plugs are hammered into pre-drilled holes in hardwood logs, providing a long-term inoculation method suitable for traditional and artisanal mushroom growing.



5. Liquid Culture Spawn: Liquid culture spawn involves growing mycelium in a sterilized liquid nutrient solution. This approach allows for rapid mycelial propagation, easy scaling, and use as a direct inoculum for both spawn production and substrate colonization. Liquid cultures are particularly valuable for research, laboratory-scale production, and rapid inoculation of large volumes of substrate in automated systems. It is widely used for *Cordyceps militaris* and *C. sinensis*.



Mushroom Spawn Production: The Blueprint for Cultivation Success



6. Tissue Culture Spawn: Tissue culture spawn is derived from internal tissue fragments of fresh mushroom fruiting bodies, providing a reliable method to propagate known genetic strains. Tissue culturing is the primary technique used in strain preservation and the development of new spawn cultures from wild or cultivated mushrooms. Tissue culture is essential for propagating specific, high-yielding strains for commercial mushroom cultivation, such as Oyster, Milky, or White Button mushrooms.



Materials Required for Spawn Production

The successful production of high-quality spawn requires precise management of raw materials, equipment, and environmental conditions. Each material plays a specific functional role in the spawn production process.

2. Substrates and Amendments:

- Wheat, rye, millet, sorghum, or corn grains for grain spawn
- Hardwood sawdust (oak, beech, poplar) for sawdust spawn
- Wheat straw or rice straw for straw spawn
- Hardwood dowels or wooden plugs for plug spawn
- Wheat bran, rice bran, or gypsum as nutritional supplements (10-20%)
- Distilled or deionized water for liquid cultures and substrate hydration.

3. Sterilization and Pasteurization Equipment:

- Autoclave or pressure cooker (121°C, 15 psi) for sterilization of grain and sawdust substrates
- Hot water bath or steam pasteurization units for straw substrates
- Polypropylene bags, glass jars, or spawn bottles as substrate containers
- Filter discs or injection ports for gas exchange while maintaining contamination barriers
- Laminar flow hood or still air box for aseptic inoculation
- 70% isopropyl alcohol and ethanol for surface sterilization
- Bunsen burner or alcohol lamp for flame sterilization of tools
- Inoculation loops, scalpels, and forceps
- UV light sterilization units for work surfaces.



4. Culture Media:

- Potato Dextrose Agar (PDA) for master culture maintenance
- Malt Extract Agar (MEA) for mycelial growth and purity testing
- Liquid nutrient broth for liquid culture production
- Petri dishes, culture flasks, and test tubes for culture management

5. Incubation Facilities:

- Temperature-controlled incubation rooms or chambers (22-28°C depending on species)
- Humidity monitoring equipment
- Shelving systems for organized spawn storage and colonization.

The Multi-Stage Process of Spawn Production

Spawn production follows a hierarchical, multi-generation process designed to progressively scale up mycelial biomass while maintaining genetic purity and biological vigor. The process typically involves three to four distinct stages.

Stage 1 – Master Culture (Agar Culture): The process begins with the preparation of a pure master culture on agar media. A mushroom strain of known genetic identity is obtained either from a reputable culture library or through tissue culture of a selected fruiting body. The mycelium is grown on PDA or MEA plates under sterile conditions at the appropriate temperature for the target species. Master cultures are checked for purity, growth rate, and morphological characteristics before use.

Master cultures serve as the permanent genetic repository and are typically stored at 4°C for short-term preservation or in glycerol stocks at -80°C for long-term preservation. Transfer intervals on agar should be minimized to prevent genetic drift and sector formation.

Stage 2 – Mother Spawn (Grain or Sawdust Culture): A small amount of agar culture is used to inoculate sterilized grain or sawdust in spawn bottles or bags. This generates mother spawn – the first generation of substrate-based spawn. Substrate jars are inoculated under laminar flow conditions using aseptic technique. Following inoculation, containers are incubated at the appropriate temperature until complete mycelial colonization is observed (typically 14-28 days depending on species and substrate).

Mother spawn is the highest-quality, highest-purity spawn and is used exclusively for further spawn production rather than direct substrate inoculation. Careful inspection for contamination (visible discoloration, off-odors, or abnormal mycelial growth) is conducted before mother spawn is advanced to the next stage.

Stage 3 – Spawn Run (Production Spawn): Mother spawn is used to inoculate larger volumes of sterilized substrate to produce production spawn, also called spawn run or commercial spawn. Inoculation rates are typically 1-3% (v/v) for grain-to-grain transfers. The production spawn is incubated until full colonization, inspected for quality, and then used for bulk substrate inoculation or sold to mushroom farmers. Production spawn represents the final stage before crop production.

Stage 4 – Bulk Substrate Inoculation: Production spawn is used at 5-20% inoculation rates to colonize bulk growing substrates such as straw, supplemented sawdust blocks, compost, or coco coir. Once fully colonized, the substrate is moved to fruiting chambers where environmental triggers (fresh air exchange, temperature drop, light) initiate primordia formation and fruiting body development.

Sterilization Protocols: The sterilization of grain substrates requires autoclaving at 121°C and 15 psi for 60-90 minutes. Sawdust substrates typically require 2-4 hours of autoclaving due to their denser packing. Polypropylene bags and glass jars used for spawn must withstand repeated sterilization cycles. All sterilization equipment must be validated regularly using biological indicators (*Geobacillus stearothermophilus* spores).

Comparative Analysis of Spawn Substrates

The selection of an appropriate spawn substrate is a critical decision that influences colonization speed, contamination resistance, suitability for different mushroom species, and overall production economics. The following table provides a comparative analysis of the most common spawn substrate types. Among all substrate types, grain spawn (particularly rye and wheat) is considered the gold standard for most edible mushroom species due to its high nutritional content, rapid colonization, and ease of uniform mixing into bulk substrates. However, sawdust spawn remains preferred for wood-decomposing species where enzymatic compatibility between spawn and bulk substrate is critical for optimal colonization.

Different Spawn Substrates					
Substrate Type	Colonization Speed	Contamination Risk	Best Species	Cost	Storage Life
Grain (Wheat/Rye)	Very Fast	Moderate	<i>Agaricus</i> , <i>Pleurotus</i>	Moderate	3-6 months

Sawdust	Moderate	Low	Shiitake, Reishi, Lion's Mane	Low	2-4 months
Straw	Fast	High	<i>Pleurotus</i> spp.	Very Low	1-2 months
Plug (Dowel)	Slow	Very Low	Shiitake (logs)	Low	6-12 months
Liquid Culture	Very Fast	High	All species	Moderate	1-3 months

Factors Affecting Spawn Quality

Spawn quality is a multidimensional attribute determined by genetic, microbiological, physiological, and physical parameters. Understanding and controlling these factors is essential for consistent, high-performance spawn production.

1. Genetic Factors: The genetic quality of the parent strain fundamentally determines the biological potential of the spawn. Strains should be selected for high yield, fast colonization, resistance to common pathogens, and appropriate fruiting characteristics. Genetic degradation through repeated subculturing (senescence) leads to reduced vigor, irregular mycelial morphology, and poor fruiting. Regular strain rejuvenation through fruiting body tissue culture and cryogenic preservation protocols are essential to maintain genetic integrity.

2. Substrate Quality and Preparation: The nutritional composition, particle size, and moisture content of the substrate profoundly affect spawn quality. Grain substrates should be pre-soaked to achieve 40-50% moisture content before sterilization, ensuring adequate hydration without creating anaerobic pockets that favor bacterial contamination. Over-supplementation of substrates with nitrogen-rich amendments increases contamination risk from thermophilic bacteria and *Trichoderma* species.

3. Sterilization Efficiency: Incomplete sterilization is the most common cause of spawn failure. Factors affecting sterilization efficiency include autoclave load size, substrate density, container type, and cycle duration. Cold spots within autoclaved loads, particularly in densely packed grain bags, can allow survival of heat-resistant endospores of *Bacillus* and *Clostridium* species. Validation of sterilization cycles using biological indicators is a mandatory practice in commercial spawn laboratories.

4. Contamination Control: Contamination by molds, yeasts, and bacteria is the primary challenge in spawn production. The most common contaminants include *Trichoderma harzianum* (green mold), *Penicillium* spp. (blue-green mold), *Neurospora crassa* (red bread mold), and various bacterial species. Contamination control requires a multi-barrier approach: positive pressure clean rooms, HEPA-filtered laminar flow hoods, regular surface disinfection, and rigorous personal hygiene protocols for laboratory staff.

5. Incubation Conditions: Temperature during incubation must be precisely controlled and maintained within the optimal range for the target species. Most edible mushroom species colonize spawn optimally at 22-28°C. Excessive heat (above 30°C) accelerates aging and reduces viability, while temperatures below the optimum slow colonization and increase contamination vulnerability. Humidity management is equally critical – excessively dry conditions desiccate spawn, while high humidity promotes mold development on external surfaces of spawn containers.

6. Storage and Shelf Life: Following full colonization, spawn viability decreases over time due to metabolic activity, respiratory CO₂ accumulation, and gradual substrate depletion. Grain spawn stored at 4°C typically retains good viability for 3-6 months, while sawdust spawn has a somewhat shorter shelf life of 2-4 months. For long-term storage, liquid nitrogen cryopreservation at -196°C effectively halts metabolic activity and preserves viability indefinitely.

Strategic Importance in Cultivation

The quality and availability of spawn directly determine the productivity and economic viability of any mushroom cultivation enterprise. Spawn represents the biological foundation upon which the entire cultivation system is built, making its production and management a central strategic concern for mushroom farmers, agribusinesses, and policymakers.

From an economic perspective, spawn accounts for 10-30% of total production costs in commercial mushroom farming, depending on scale and species. However, its influence on final yield, colonization speed, and disease resistance makes it a disproportionately important input. Investments in superior spawn quality typically yield returns many times over through improved biological efficiency and reduced crop losses.

The development of locally produced, high-quality spawn has been identified as a key strategy for expanding mushroom production in developing countries. In regions where mushroom cultivation is an important livelihood strategy for smallholder farmers, access to reliable, affordable spawn is often the primary bottleneck limiting sector growth. Establishment of regional spawn production laboratories and farmer-managed spawn production units has therefore been a focus of many agricultural development programs across Sub-Saharan Africa, South and Southeast Asia, and Latin America.

From a food security perspective, mushrooms produced using well-designed spawn systems offer a highly efficient protein source, requiring significantly less land, water, and energy per unit of protein than conventional livestock or most plant crops. The ability to grow mushrooms on agricultural by-products (straw, sawdust, cotton waste) using carefully prepared spawn makes mushroom cultivation a model of circular economy agriculture.

Spawn quality also has implications for food safety. Poorly prepared spawn can introduce pathogenic or toxigenic fungi into the growing environment, posing risks not only to crop yield but also to consumer health. Regulatory frameworks in many countries now require commercial spawn to meet defined microbiological standards before sale.

Quality Standards for Commercial Spawn

Commercial mushroom spawn is subject to quality standards designed to ensure consistent performance, safety, and reliability. These standards address microbiological purity, mycelial vigor, moisture content, and packaging integrity.

1. Microbiological Purity: Commercial spawn must be free from bacterial contamination and competing molds. International standards typically specify zero tolerance for *Trichoderma* species, *Penicillium* species, and bacterial contaminants detectable by visual or microbiological assay. Spawn laboratories routinely perform plating assays on nutrient agar to verify purity before batch release.

2. Mycelial Vigor and Colonization Rate: High-quality spawn should exhibit vigorous, uniform mycelial growth when inoculated onto fresh substrate. Colonization rates are measured as the linear extension of mycelial front per day under standardized temperature conditions. Minimum acceptable colonization rates are typically defined by species and substrate type in commercial quality specifications.

3. Moisture Content: The moisture content of spawn substrates is a critical quality parameter. Grain spawn should contain 40-50% moisture at the time of sale. Excessively dry spawn indicates storage degradation and reduced viability, while overly wet spawn is prone to bacterial contamination. Moisture content is routinely measured using gravimetric drying methods.

4. Packaging and Labeling: Commercial spawn must be packaged in food-grade, gas-permeable polypropylene bags equipped with filter patches to allow CO₂ exchange while preventing microbial ingress. Proper labeling must include strain identification, production date, expiry date, storage conditions, inoculation rate recommendations, and target mushroom species. Traceability systems linking each batch to its production records are increasingly required for commercial spawn certification.

5. Performance Testing: Before large-scale distribution, commercial spawn batches undergo performance testing using standardized cultivation trials under controlled conditions. Key performance indicators include time to full substrate colonization, fruiting body initiation time, biological efficiency (yield/substrate weight), and mushroom quality attributes such as cap size, firmness, and color. Only batches meeting minimum performance thresholds are approved for commercial sale.

Conclusion

Mushroom spawn production represents a sophisticated and scientifically demanding discipline that underpins the entire mushroom cultivation industry. From the careful selection and maintenance of genetically superior strains, through the multi-stage sterilization and inoculation process, to the rigorous quality testing of finished spawn batches, every step requires technical precision and microbiological expertise.

The strategic importance of high-quality spawn cannot be overstated. It determines colonization success, crop yield, resistance to disease, and ultimately the economic viability of mushroom farming enterprises. As global demand for mushrooms continues to grow – driven by increasing recognition of their nutritional, medicinal, and environmental value – the role of advanced spawn production technology will only become more critical.

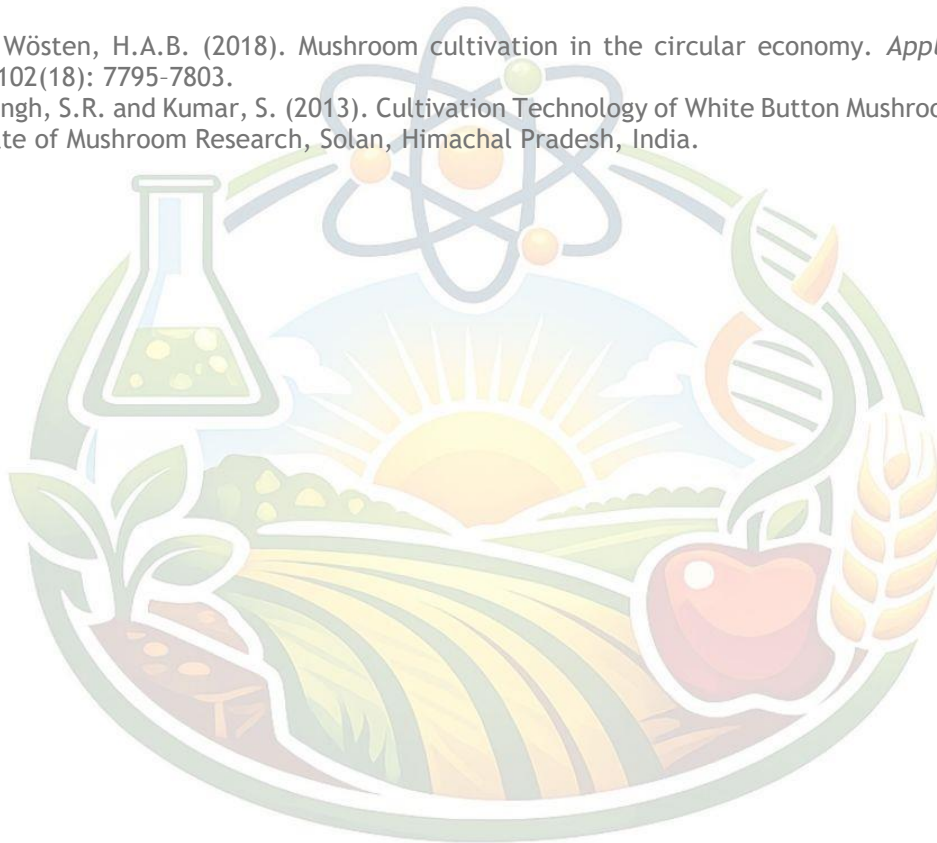
Future developments in spawn production are likely to focus on the integration of genomic tools for strain improvement, development of longer-lasting preservation technologies, automation of spawn production processes for greater consistency and scale, and the expansion of spawn production capacity in developing regions. These advances will be essential to meeting the challenges of global food security, sustainable agriculture, and the growing demand for functional food ingredients derived from edible and medicinal mushrooms.

For students, researchers, and practitioners in mycology and agricultural sciences, a thorough understanding of spawn production principles provides a fundamental platform for innovation and excellence in mushroom cultivation. The science of spawn production continues to evolve, and ongoing research into strain improvement, novel substrates, and contamination management promises to further elevate the productivity and reliability of mushroom farming systems worldwide.

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Chilli Crop Protection: An Integrated Approach

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J. Greeshma Sai¹, Dr. Ch. Shanmukhi², M. Neelima³, M. Sukumari⁴, Y. Sreyas Yagnik⁵

^{1,3,4,5}M.Sc. scholar, Department of Horticulture (Vegetable Science), School of Agriculture Sciences, Malla Reddy University, Hyderabad, Telangana 500043.

²Assistant Professor, Department of Horticulture (Vegetable Science), School of Agriculture sciences, Malla Reddy University, Hyderabad, Telangana 500043.

Abstract

Chilli (*Capsicum annuum* L.) is an important spice and vegetable crop widely cultivated in tropical and subtropical regions, especially in India. Its production is significantly affected by major insect pests such as thrips, pod borers, aphids, and mites, as well as diseases like damping-off, fruit rot and die-back, bacterial leaf spot, and fusarium wilt. These pests and diseases cause serious yield and quality losses by damaging plant tissues and reducing plant vigour. Effective management requires an integrated approach rather than reliance on a single method. Integrated Pest and Disease Management (IPDM), which includes cultural, mechanical, biological, and chemical practices, plays a crucial role in controlling pests and diseases. Adoption of IPDM strategies helps in reducing crop losses, minimizing pesticide use, and ensuring sustainable chilli production.

Introduction

Chilli (*Capsicum annuum* L.) is an important commercial spice and vegetable crop grown widely in tropical and subtropical regions. It is valued for its pungency, colour, and nutritional importance, contributing significantly to domestic use and export. However, its production is affected by several insect pests and diseases, leading to yield and quality losses. Major insect pests include thrips, aphids, mites, and pod borers, which cause direct damage and transmit viral diseases. Important diseases such as damping-off, fruit rot and die-back, bacterial leaf spot, and fusarium wilt reduce plant growth and productivity. Integrated Pest and Disease Management (IPDM), combining cultural, biological, mechanical, and chemical methods, is essential for effective and sustainable management while minimizing environmental impact.

Major Pest of Chilli

1. Chilli Thrips:

Symptoms and Nature of Damage: Thrips are minute, slender insects that mainly attack tender leaves, buds, and growing shoots. Both nymphs and adults lacerate plant tissues and suck the sap. Infested leaves show upward curling, crumpling, and drying, eventually leading to leaf shedding. Buds become brittle and fall off, while fruits develop light brown scars. Severe infestation occurs during dry weather and can cause 30-50% yield loss.

IPM Strategies:

Cultural: Maintain proper irrigation to reduce dry conditions favourable for thrips. Remove weeds and alternate host plants to break the pest cycle.

Mechanical: Install blue or yellow sticky traps to monitor and reduce thrips population. Regularly remove and destroy heavily infested plant parts.

Biological/Botanical: Apply neem-based formulations such as neem oil (3-5%) to reduce pest population in an eco-friendly manner.

Chemical: Treat seeds with imidacloprid (3-5 g/kg) to protect seedlings. Apply need-based foliar sprays of spinosad, fipronil, acephate, or diafenthuiuron, ensuring thorough coverage of the underside of leaves.

2. Chilli Pod Borers:

Symptoms and Nature of Damage: Larvae feed on leaves and fruits, causing irregular holes. Infested fruits may turn whitish and dry, with seeds consumed internally. *Helicoverpa* causes round holes, while *Utetheisa* produces ladder-like feeding marks on pods. Severe infestation leads to significant yield loss.

IPM Strategies:

Cultural: Deep summer ploughing helps destroy pupae in the soil. Growing trap crops like castor and marigold attracts pests away from chilli.

Mechanical: Use pheromone traps (4 per acre) for monitoring and mass trapping. Hand-pick larvae and destroy damaged fruits.

Biological: Spray NPV (SNPV/HaNPV @ 250 LE/acre) in the evening to target larval stages effectively.

Chemical: Apply novaluron or diflubenzuron to control early instar larvae. For severe infestation, spray spinosad, chlorpyrifos, thiodicarb, acephate, or quinalphos. Use poison baiting (rice bran + jaggery + insecticide) during evening hours.

3. Chilli Aphids:

Symptoms and Nature of Damage: Aphids colonize the underside of leaves and tender shoots, sucking plant sap. This results in leaf curling, stunted growth, and reduced fruiting. They secrete honeydew, which promotes sooty mould growth, reducing photosynthesis and overall plant vigour.

IPM Strategies:

Cultural: Remove weeds and avoid excess nitrogen fertilization, which encourages aphid multiplication.

Mechanical: Install yellow sticky traps and, in mild cases, wash plants with water to reduce aphid population.

Biological/Botanical: Apply neem-based products to deter aphids and reduce their reproduction.

Chemical: Spray methyl demeton (1 ml/l) or acephate (1.5 g/l) as need-based control measures.

4. Chilli Mites:

Symptoms and Nature of Damage: Mites are microscopic pests found on the underside of leaves. Their feeding causes downward curling, boat-shaped leaves, and rolling of leaf margins. Leaves may turn dark green, and terminal shoots show clustering. Severe infestation leads to the “murda” condition, significantly affecting plant growth and yield.

IPM Strategies:

Cultural: Use healthy seedlings and maintain proper plant spacing to reduce infestation.

Mechanical: Remove and destroy affected plant parts to prevent spread.

Biological/Botanical: Spray neem oil to suppress mite population.

Chemical: Apply dicofol (5 ml/l) or wettable sulphur (3 g/l). Avoid synthetic pyrethroids as they may aggravate mite problems. For combined infestation with thrips, spray phosalone, diafenthiuron, or chlorfenapyr.

Major Diseases of Chilli

1. Damping-off:

Symptoms: Seedlings die before or soon after emergence due to water-soaked lesions at the collar region, leading to stem shrivelling and collapse.

Favourable Conditions: High soil moisture and poor drainage, Relative humidity 90-100% and Temperature around 20 °C

IDM:

Cultural: Use well-drained nursery beds and Avoid overwatering

Mechanical: Remove infected seedlings

Biological: Seed treatment with *Trichoderma viride*

Chemical: Soil drenching with copper oxychloride (0.25%)

2. Fruit Rot and Die-back:

Symptoms: The disease causes drying of twigs from the tip (die-back), flower drop and shrivelling, resulting in few, small, poor-quality fruits with necrotic lesions having dark margins.

Spread: Seed-borne and airborne conidia and spread through rain splash and insects

IDM:

Cultural: Use disease-free seeds and remove infected twigs

Mechanical: Field sanitation

Chemical: Seed treatment with Thiram/Captan (4 g/kg), Spray Ziram (0.25%), Captan (0.2%), or copper oxychloride (0.25%) and Spray at flowering and fruiting stages

3. Bacterial Leaf Spot:

Symptoms: Small dark, greasy spots appear on leaves, which enlarge and coalesce, while fruits develop raised spots with a yellow halo, leading to severe leaf drop and fruit damage.

Spread: Seed-borne and spread by rain splash

IDM:

Cultural: Use disease-free seeds and Maintain field sanitation

Mechanical: Remove infected plants

Chemical: Seed treatment with mercuric chloride (0.1%) and Spray Bordeaux mixture (1%) or copper oxychloride (0.25%)

4. Fusarium Wilt:

Symptoms: The disease causes yellowing and wilting of leaves with upward rolling, accompanied by vascular discoloration in the stem, leading to plant death in patches.

IDM:

Cultural: Use resistant varieties and Crop rotation

Biological: Apply *Trichoderma viride* with FYM

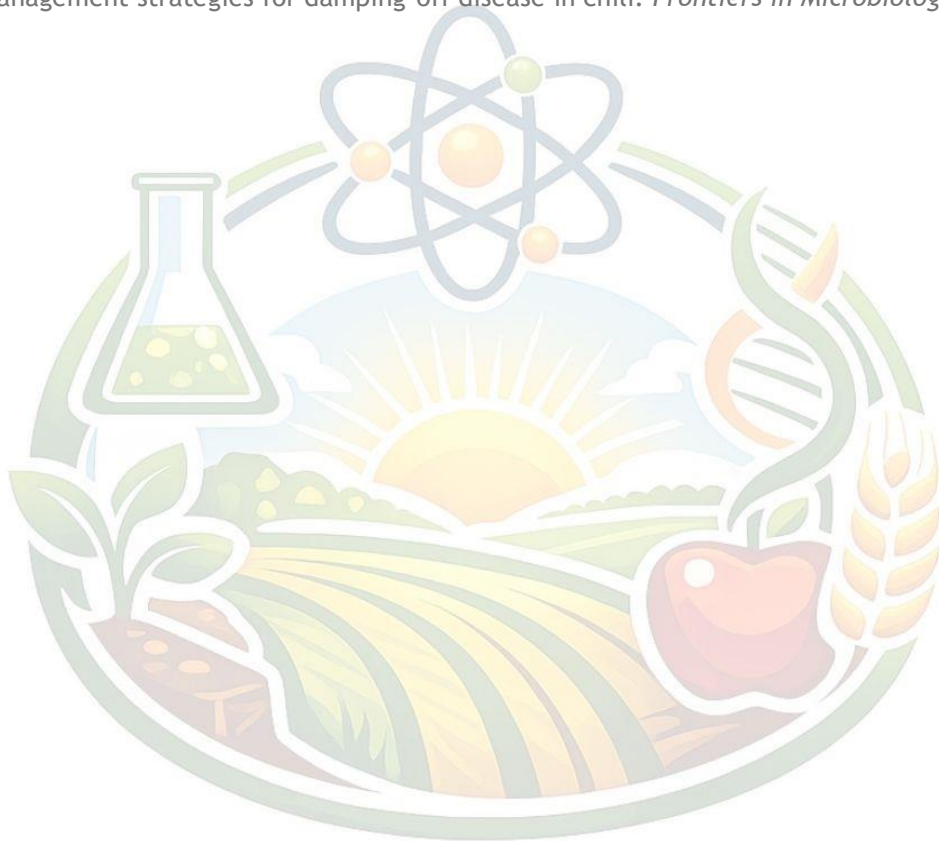
Chemical: Seed treatment with carbendazim (2 g/kg) and Soil drenching with Bordeaux mixture or copper fungicides.

Conclusion

Integrated Pest and Disease Management (IPDM) in chilli provides an effective and sustainable way to control pests and diseases while reducing dependence on chemicals. By combining cultural, biological, mechanical, and need-based chemical practices, farmers can protect crop health and improve yield and quality. Adoption of IPDM ensures eco-friendly chilli production, economic benefits, and long-term agricultural sustainability.

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Integrated Approaches for Managing Insect Pests and Diseases in Muskmelon

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I. Alekhya Reddy¹, Dr.Ch. Shanmukhi², S. Lakshmi Madhavi³, D. Geetha Priyanka⁴, J. Greeshma Sai⁵
^{1,3,4,5}M.Sc. scholar, Department of Horticulture (Vegetable Science) School of Agricultural Sciences, Malla Reddy University, Hyderabad, Telangana, 500043.

²Assistant Professor, Department of Horticulture (Vegetable Science) School of Agricultural Sciences, Malla Reddy University, Hyderabad, Telangana, 500043.

Abstract

Muskmelon (*Cucumis melo* L.) is an important cucurbit crop cultivated widely in tropical and subtropical regions of India. However, its productivity is significantly affected by various insect pests and diseases. Excessive reliance on chemical pesticides has led to environmental pollution, pest resistance, and health hazards. Therefore, Integrated Pest Management (IPM) and Integrated Disease Management (IDM), as recommended by the Indian Council of Agricultural Research, offer sustainable and eco-friendly approaches. These strategies combine cultural, biological, mechanical, and need-based chemical methods to manage pests and diseases effectively while minimizing environmental impact.

Introduction

Muskmelon is a high-value vegetable crop known for its sweet taste, nutritional richness, and market demand. It thrives well in warm climates and is widely grown across India, especially during summer. Despite its economic importance, muskmelon cultivation faces serious challenges due to insect pests such as red pumpkin beetle, aphids, and whiteflies, along with diseases like powdery mildew, downy mildew, and fusarium wilt. Unscientific pesticide use has resulted in pest resurgence, resistance development, and destruction of beneficial organisms. To overcome these issues, IPM and IDM approaches integrate multiple management practices based on ecological principles. These approaches aim to maintain pest populations below economic threshold levels while ensuring sustainability.

Pests and Diseases of Muskmelon (*Cucumis melo*)

Major Insect Pests:

Aphids (*Aphis gossypii*):

Nature of damage and Symptoms:

- Sap sucking from tender leaves and shoots
- Secretion of honeydew causes sooty mold development
- Stunted plant growth

Red Pumpkin Beetle (*Aulacophora foveicollis*):

Nature of damage and Symptoms:

- Adults feed on cotyledons, leaves, and flowers & Grubs damage roots and underground stems.
- Irregular holes on leaves.
- Severe damage at seedling stage leads to plant death.

Fruit Fly (*Bactrocera cucurbitae*)

Nature of damage and symptoms:

- Adult lays eggs inside fruits & Maggots feed on pulp
- Oozing from fruits
- Rotten and deformed fruits
- Mostly during fruiting stage

Leaf Miner (*Liriomyza trifolii*)

Nature of damage and Symptoms:

- Larvae feed within leaf tissue
- Serpentine (zig-zag) mines on leaves due to which photosynthesis is reduced.

Whiteflies (*Bemisia tabaci*)

Nature of damage and Symptoms:

- Sap sucking and virus transmission
- Yellowing and wilting of leaves
- Presence of honeydew and black sooty mold
- Transmits yellow vein mosaic virus

Major Diseases

Downy Mildew (*Pseudoperonospora cubensis*)

Symptoms:

Yellow angular spots on upper leaf surface

Grey/purple fungal growth on underside

Alternaria Leaf Spot (*Alternaria cucumerina*)

Symptoms:

Small brown spots with concentric rings

Spots enlarge and coalesce and severe defoliation also occurs

Anthraco (*Colletotrichum lagenarium*)

Symptoms: Water-soaked lesions on leaves and along with dark sunken spots on fruits

Powdery Mildew (*Erysiphe cichoracearum* / *Podosphaera xanthii*)

Symptoms:

White powdery fungal growth on leaves, stems, and vines

Leaves turn yellow and dry

Fusarium Wilt (*Fusarium oxysporum* f. sp. *Melonis*)

Symptoms:

Sudden wilting of vines

Yellowing of older leaves

Browning of vascular tissues

Viral Diseases (Mosaic)

Causal agents: Cucumber Mosaic Virus (CMV) & Watermelon Mosaic Virus (WMV)

Symptoms:

Mosaic mottling of leaves

Poor fruit development

Transmitted by aphids and whiteflies.

Integrated Pest and Disease Management in Muskmelon (*Cucumis melo* L.)

Integrated Pest and Disease Management (IPDM) is a holistic approach which combines cultural, mechanical, biological, botanical, and chemical methods to manage both pests and diseases sustainably.

Pre-Sowing Management:

Seed Selection

Use certified, disease-free seeds

Prefer resistant/tolerant varieties against wilt and mildews

Seed Treatment: *Trichoderma viride*, *Pseudomonas fluorescens*

Cultural Practices:

Follow crop rotation (2-3 years with non-cucurbits),

Ensure well-drained sandy loam soil & Maintain optimum spacing for aeration

Remove and destroy: Diseased plants, Pest-infested plant parts, Practice field sanitation Avoid water stagnation

Mechanical & Physical Methods

Install yellow sticky traps (10-15/acre), Use pheromone traps (cue-lure)

Handpick: Red pumpkin beetles, Damaged fruits

Biological Control

For Pests: Release/encourage natural enemies: Ladybird beetles (aphids) & Lacewings

Spray: *Beauveria bassiana* and *Verticillium lecanii*.

For Diseases:

Soil application of: *Trichoderma viride*, Suppresses soil pathogens like *Fusarium*.

Chemical Control

For Pests: Malathion imidacloprid & Spray Spinosad or bait sprays.

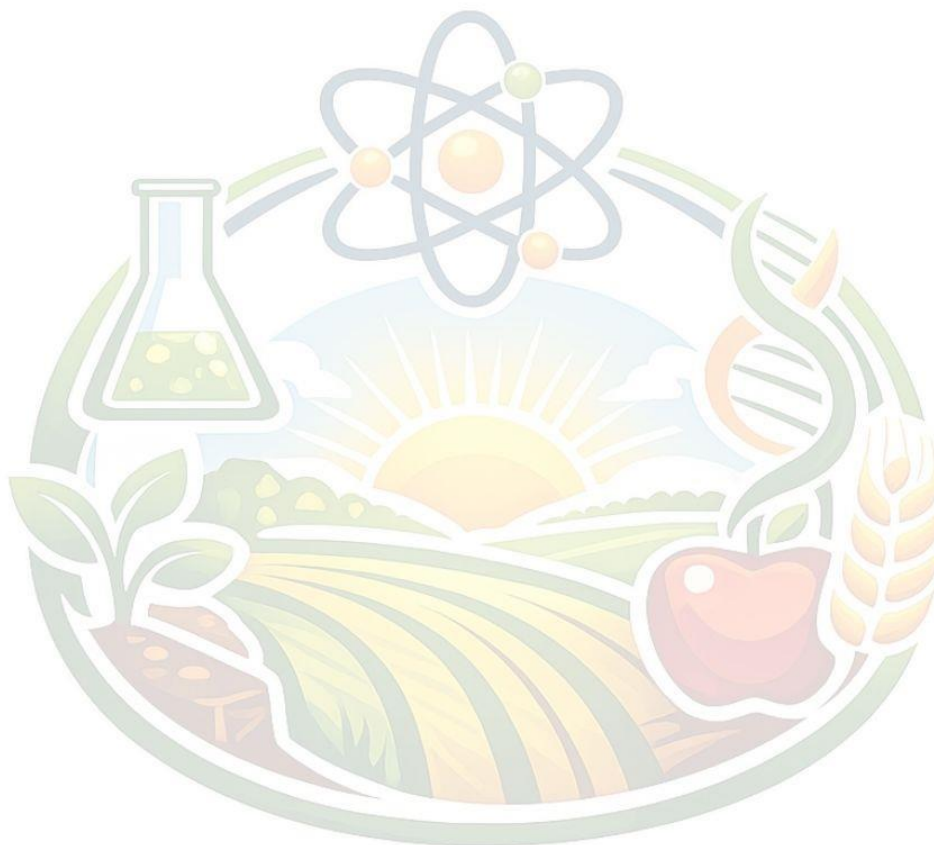
For Diseases: Wettable sulphur, Metalaxyl + Mancozeb Chlorothalonil / Mancozeb Carbendazim (soil drenching).

Conclusion

Integrated Pest and Disease Management (IPDM) in muskmelon is an effective and sustainable strategy that combines multiple control methods into a single system. By adopting IPDM practices, farmers can successfully manage major pests and diseases while ensuring environmental safety, economic profitability, and long-term soil health.

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NADEP COMPOST: A Sustainable Solution for Soil Health in Organic Farming

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 Patel Krutika Subodh¹, Ketan F. Satashiya¹, Alvira A. Rajwadi², Karuna M. Chaudhari³, Chudasam, S. D.³
²Assistant Professor, College of Agriculture, J.A.U., Mota Bhandariya.

¹Assistant Research Scientist, ARS, JAU, Amreli.

³Assistant Professor, ASPEE College of Agriculture, J.A.U., Khapat, Scientist, KVK, SDAU, Tharad.

Today the biggest problem in Indian Agriculture deterioration of soil due to overuse of chemical fertilizers. To overcome this problem organic manure application will play an important role by improving soil properties and maintaining its fertility. The problem of scarcity of decomposable materials like animal dung, prevailing within the country is because it is used as fuel in many rural areas. Thus, even if all available organic materials, including dung, were religiously and scrupulously collected, they would still not be sufficient to replace the organic constituents of the vast quantities of India's fast-degrading soils. This organic matter must be replaced and replenished if agricultural fertility is not to go on declining. So, the different methods of composting can be used to recycle the farm waste and provide organic matter to soil. The NADEP compost is one of the most commonly used and important method of preparation of compost. In the days where the cost of chemical fertilizer has become burden for the farmers as well as it is harmful to the environment, the preparation of compost could be an eco-friendly cost effective approach to provide the nutrients to the plants.

The NADEP method of making miracle compost was first developed by a Gandhian farmer named *Narayan Deorao Pandharipande* of Pusad, Maharashtra, India. He is popularly known as "*Nadepkaka*". The NADEP method of making compost is unique from other methods of composting as its real secret lies in the large quantities of compost the process can deliver with a minimum of human effort within a specific period of time. The method basically involves placing different layers of decomposable materials in a simple, mud-sealed structure designed with brick and mud water. It approximately converts 1 kg of animal dung into 40 kg of rich compost which can then be applied directly to the field. The multiplication factor is significant in view of the fact that in the tropics, there is rapid decomposition of organic materials in the soil. Compost can be prepared from a wide range of on farm organic materials viz., dead plant material such as crop residues, weeds, forest litter, kitchen waste, etc. Compost making is an efficient way of converting all kinds biomass into high value fertilizer that serves as a good alternative to farmyard manure, especially for crop-growing households without livestock.

Qualities of Compost

Although the quality of compost is best evaluated through the growth and productivity of the plants grown on soil treated with it, it is possible to evaluate compost quality through seeing, touching, and smelling:

1. Good quality compost is rich in plant nutrients and has a crumb-like structure, like broken-up bread.
2. It is either black or a dark brown colour, and it retains moisture efficiently; as a result, it does not dry out quickly. It smells lovely, like freshly ploughed, clean dirt.



Method of Preparation

Important Points to be Remembered:

1. The important technique in the manufacture of NADEP compost is that the entire tank should be filled in one go, within 24 hours and should not go beyond 48 hours, as this would affect the quality of the compost.
2. Thatched roof, Brick Wall Flooring, Air Vents, Green-farm technologies for small and marginal farms Resources Center for Sustainable Development.
3. Before filling: the tank is plastered by dilute cattle dung slurry to facilitate bacterial activity from all four sides. It is also filled in definite layers each layer consisting of the following sub layers.

Tank Preparation

1. A simple rectangular brick tank with enough spaces maintained between the bricks for proper ventilation is to be prepared.
2. The recommended size of the tank is 10 ft (length) x 5 ft (breadth) x 3 ft (height).
3. All the four walls of NADEP tank are provided with 6 vents by removing every alternate brick after the height of 1ft. from bottom for aeration.
4. Tank can be constructed in mud mortar or cement mortar.

Materials Required

1. Agricultural waste (Dry & green) - 1350-1400 kg.
2. Cattle dung or biogas slurry - 98 - 100 kg.
3. Fine sieved soil - 1675 kgs.
4. Water - 1350-1400 litres.

Filling of Tant

1. Sub-layer-1 - 4 to 6 ft thick layer of fine sticks, stems to facilitate aeration followed by 4 to 6 ft layer of dry and green biomass.
2. Sub-layer-2 - 4 kg of cow dung is mixed with 100 litres of water and sprinkled thoroughly on the agricultural waste to facilitate microbial activity.
3. Sub-layer-3 - 60 kg of fine dry soil is spread uniformly over the soaked biomass for moisture retention and acts as a buffer during biodegradation. Thus the proportion of organic materials for each layer is 100 kg. Organic biomass: 4 kg cowdung + 100 litres water + 60 kg soil. In this way, approximately 10 -12 layers are filled in each tank. After filling the tank, biomass is covered with 3 ft thick layer of soil and sealed with cow dung + mud plaster.

Maintenance

1. After 15-30 days of filling the organic biomass in the tank gets automatically pressed down to 2 ft.
2. The tank is refilled by giving 2-3 layers over it and is resealed.
3. After this filling the tank is not disturbed for 3 months except that it is moistened at intervals of every 6-15 days.
4. The entire tank is covered with a thatched roof to prevent excessive evaporation of moisture.
5. There should never be any space for cracks to appear. If they do, slurry should be added to them right away.
6. Under no circumstances should any cracks be allowed to develop. If they do, they should be promptly filled up with slurry.

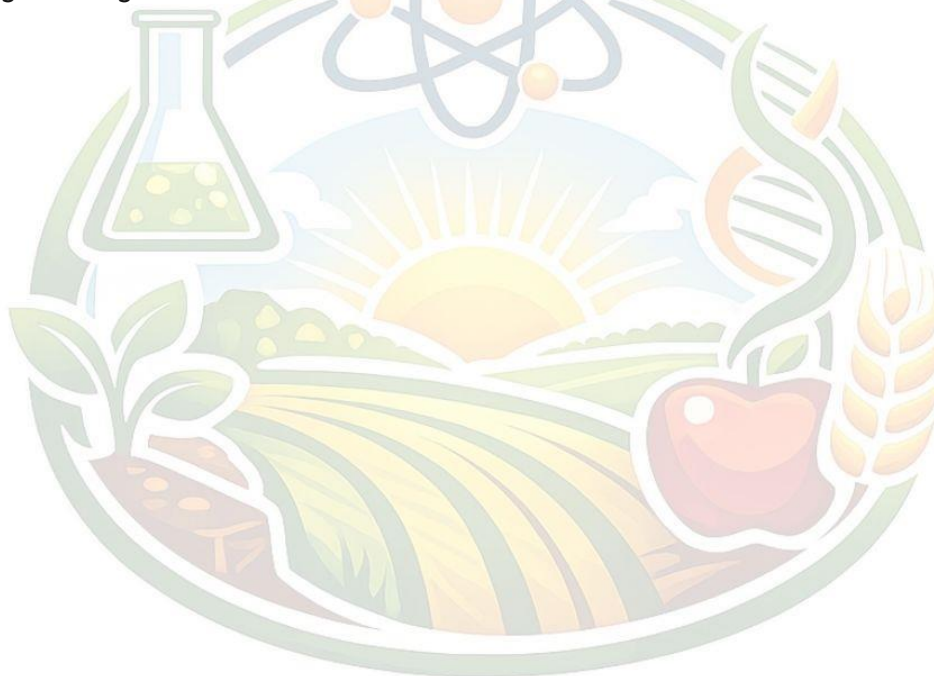


Advantages of Nadep Compost

1. Produces well-decomposed, uniform, and fine-textured compost with efficient nutrient conservation under aerobic conditions
2. Minimizes nutrient loss through reduced leaching and volatilization
3. No frequent turning required after filling, making it labour-efficient
4. Hygienic and eco-friendly, with no foul smell or fly nuisance
5. Reduces dependence on chemical fertilizers and external inputs
6. Lowers production costs while improving soil fertility and crop yield
7. Each NADEP tank yields about 2.5 tons of compost within 90-120 days
8. Suitable for all farmers, including small and marginal farmers, using locally available materials.

Conclusion

NADEP compost stands out as an efficient, eco-friendly and cost-effective method for improving soil fertility and promoting sustainable agriculture. In the phase of declining soil health due to excessive use of chemical fertilizers, this method provides a practical alternative by recycling farm waste into nutrient-rich organic manure. It not only maximizes compost production with minimal resources but also reduces nutrient losses through leaching and volatilization. The technique supports small and marginal farmers by lowering input costs while restoring soil structure and enhancing crop productivity. By adopting NADEP composting, farmers can also contribute to environmental conservation. Thus, it plays a vital role in moving Indian agriculture towards a more sustainable and self-reliant future.

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Adenium obesum: Nature's Living Sculpture in Bloom

Article ID: 73709

 Dr. S. P. Mirunalini¹, Dr. A. Shanthi¹, Dr. C. Jayalakshmi¹, Dr. M. Manikandan¹
¹Department of Horticulture, Pandit Jawaharlal Nehru College of Agriculture & Research Institute, Karaikal - 609 603.

If there's one plant that effortlessly blends beauty, resilience, and artistic charm, it is *Adenium obesum*, popularly known as the *Desert Rose*, belonging to Apocynaceae. With its striking swollen trunk, vibrant flowers, and bonsai-like appearance, this plant has become a favourite among gardeners and plant enthusiasts across the world.

A Plant That Looks Like Living Sculpture

Unlike most ornamental plants, the Desert Rose stands out for its **caudex**, a thick, swollen base that stores water. This unique feature gives it a sculptural, almost artistic look, making each plant one-of-a-kind. Its trumpet-shaped flowers bloom in shades of pink, red, white, and even multi-coloured varieties, creating a stunning visual contrast against its smooth grey-green stems. In fact, during peak flowering, the plant will be almost entirely covered with blooms, making it a true showstopper.



From African Deserts to Indian Homes

Native to the arid regions of Africa and the Arabian Peninsula, the Desert Rose has successfully adapted to tropical and subtropical climates. Today, it is widely cultivated in countries like India, Thailand, and the Philippines as a popular ornamental plant. Its ability to tolerate drought conditions makes it ideal for modern lifestyles, especially for people looking for low-maintenance yet eye-catching plants.



Why Gardeners Love It?

The growing popularity of Adenium is no surprise. Here's why it has become a must-have:

1. **Exotic appearance** - Looks like a natural bonsai without much effort
2. **Year-round interest** - Flowers and sculptural form add beauty even when not in bloom
3. **Low water requirement** - Perfect for dry climates and busy plant lovers
4. **Versatile use** - Suitable for pots, balconies, terraces, and landscaping

In recent years, the plant has gained commercial importance as a **potted ornamental**, though cultivation practices are still evolving due to limited standardized protocols.



Growing Your Own Desert Rose

1. **Sunlight:** Loves bright, direct sunlight
2. **Soil:** Needs well-drained soil to prevent root rot
3. **Watering:** Moderate—allow soil to dry between watering
4. **Propagation:** Commonly grown from seeds or cuttings

Interestingly, plants grown from seeds often develop a more attractive swollen base, which is highly valued by collectors.



More Than Just Beauty: Hidden Potential

Beyond its ornamental value, *Adenium obesum* is also gaining attention in scientific research. Studies reveal that it contains important phytochemicals with potential **antibacterial, antiviral, antioxidant, and even anticancer properties**. While these findings are promising, further research is needed before it can be widely used in medicine.



Natural Bonsai Character

Unlike traditional bonsai, *Adenium* doesn't need years of intensive training. Its swollen caudex (base) and thick stems naturally create a miniature tree-like appearance.



The Rising Star of Ornamental Horticulture

Once considered a collector's plant, *Adenium obesum* has now entered mainstream gardening. Its unique blend of elegance and toughness makes it a symbol of **beauty thriving under adversity**. Whether you're a seasoned gardener or just starting out, adding a Desert Rose to your collection is like bringing home a piece of living art.



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Mushrooms: The Superfood Powering Nutrition, Health, and Sustainable Food Security

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Bharat Chandra Biswal¹, Gayatri Moharana¹

¹ICAR- Central Institute for Women in Agriculture, Bhubaneswar-751003.

Abstract

Mushrooms have always been treasured and appreciated due to their immense role in curing various degenerative diseases. Also, their unique taste and flavour make them a demanding food for every man's plate. Mushrooms have a great nutritional value since they are quite rich in protein, with an important content of essential amino acids and fiber, and poor in fat. Mushrooms contain 50 to 65% total carbohydrate, 19 to 35% proteins (with various biological and medicinal activities such as lectins) and 2 to 6% fat content of their dry matter. In mushrooms unsaturated fatty acids are found to be predominant over saturated fatty acids especially palmitic acid, oleic acid and linoleic acid, while the proportion of linolenic fatty acids is very limited. Mushrooms rich in fat soluble vitamins along with ergosterol content are thought to be the only vegetarian source for vitamin D. It has been observed and established that mushrooms are wonderful food with their immense nutraceutical properties. the chemical composition and nutritional value of the most consumed species as fresh cultivated mushrooms: *Agaricus bisporus* (white and brown mushrooms), *Pleurotus ostreatus* (oyster mushroom), *Pleurotus eryngii* (King oyster mushroom), *Lentinula edodes* (Shiitake) and *Flammulina velutipes* (Golden needle mushroom).

Introduction

Meeting the food demand for the increasing population from the limited land resource is a big challenge for our Indian democracy in this vulnerable climate change era. In addition to this, widespread malnutrition and associated diseases are more common among the economically poor population. Indian diet is primarily based on cereals (wheat, rice and maize), which is deficient in protein. Supplementation of mushroom recipe in Indian diet will bridge protein gap and improve the general health of socio-economically backward communities. Earlier mushrooms were considered as an expensive vegetable and were preferred by affluent peoples for culinary purposes. Currently common populace also considers mushroom as a quality food due to its health benefits. A mushroom is a macro fungus with a distinctive fruiting body and large enough to be seen with the naked eye and to be picked by hand (Miles and Chang, 2004). Mushrooms belong to the family Agaricaceae. The types of mushrooms differ in colors, shapes, surfaces, and activities (Ogidi *et al.*, 2020). They are produced over the ground of soil or on their food sources, such as decaying wood in a moist and cold environment (Ogidi *et al.*, 2020). Mushroom is a general term used mainly for the fruiting body of macro-fungi (Ascomycota and Basidiomycota) and represents only a short reproductive stage in their life cycle (Das, 2010).

Mushroom Production Scenario in India

India's mushroom production has shown a consistent upward trajectory in recent years, reaching approximately 0.33 million tonnes (MT) in 2023-2024 and securing its position among the world's top five producers (Sharma, 2024). This growth reflects a steady rise from 0.24 MT in 2019-2020 to 0.31 MT in 2022-2023, indicating sustained expansion in the sector (Annual Report, 2022; Sharma, 2020, 2024). Button mushroom (*Agaricus bisporus*) dominates with a 70% share (235,200 tonnes), followed by oyster mushroom (*Pleurotus spp.*) at 17% (57,120 tonnes), paddy straw mushroom (*Volvariella volvacea*) at 9% (30,240 tonnes), milky mushroom (*Calocybe indica*) at 3% (10,080 tonnes), and other varieties, such as *Auricularia polytricha*, *Lentinus edodes*, and *Flammulina velutipes*, at 1% (3360 tonnes) (Sharma, 2024). Between 2010 and 2017, India's mushroom industry grew at an annual rate of 4.3%. However, in 2017, button mushroom's share peaked at 73%, while oyster, paddy straw, and milky mushrooms accounted for 16, 7, and 3%, respectively (Sharma *et al.*, 2017). The different mushroom species of production scenario in India are highlighted in Table 1.

Table 1: Different mushroom species of production scenario in India

Sl. No.	Mushroom species	Yield (t)	Percent share
1.	Button mushroom	235,200	70
2.	Oyster mushroom	57,120	17
3.	Paddy straw mushroom	30,240	9
4.	Milky mushroom	10,080	3

Growing Your Own Desert Rose

The Indian diet is largely cereal-based-relying on staples like wheat, rice, and maize-which often leads to a gap in protein intake; incorporating mushroom-based dishes can help bridge this gap and improve the nutritional status, especially

among socio-economically disadvantaged communities. Once considered a luxury food enjoyed mainly by affluent groups, mushrooms are now widely accepted as a nutritious and accessible food due to their well-recognized health benefits. They are often described as a “complete health food,” suitable for all age groups from children to the elderly, although their nutritional value can vary depending on species, growth stage, and environmental conditions. Mushrooms are rich in high-quality protein, dietary fiber, vitamins, and essential minerals, while also containing a diverse range of digestible carbohydrates such as starches, pentoses, hexoses, disaccharides, amino sugars, sugar alcohols, and sugar acids, with total carbohydrate content ranging from 26-82% on a dry weight basis. Their crude fiber mainly consists of partially digestible polysaccharides and chitin, which support digestive health. Notably, mushrooms contain very low levels of fat, with a higher proportion of beneficial polyunsaturated fatty acids, resulting in low calorie content. They are completely free from cholesterol and instead contain ergosterol, a compound that acts as a precursor for vitamin D synthesis in the human body. The protein content in edible mushrooms typically ranges from 12-35%, varying across species, and although their amino acid profile differs, they are generally rich in threonine and valine but relatively low in sulphur-containing amino acids like methionine and cysteine, making them a valuable addition to a balanced diet. The nutritive value of different mushroom species on dry weight basis is highlighted in Table 2.

Table 2: Nutritive values of different mushrooms (dry weight basis g/100g):

Mushroom	Carbohydrate	Fibre	Protein	Fat	Ash	Energy k cal	Source
<i>Agaricus bisporous</i>	46.17	20.90	33.48	3.10	5.70	499	Stamets, 2005
<i>Pleurotus sajor-caju</i>	63.40	48.60	19.23	2.70	6.32	412	Stamets, 2005
<i>Lentinula edodes</i>	47.60	28.80	32.93	3.73	5.20	387	Stamets, 2005
<i>Pleurotus ostreatus</i>	57.60	8.70	30.40	2.20	9.80	265	FAO, 1972
<i>Vovarella volvaceae</i>	54.80	5.50	37.50	2.60	1.10	305	FAO, 1972
<i>Calocybe indica</i>	64.26	3.40	17.69	4.10	7.43	391	Doshi and Sharma, 1995
<i>Flammulina velutipes</i>	73.10	3.70	17.60	1.90	7.40	378	Crison and Sand, 1978
<i>Auricularia auricula</i>	82.80	19.80	4.20	8.30	4.70	351	Crison and Sand, 1978

For thousands of years, edible fungi have held a special place in traditional diets and healing practices across cultures. Today, science is beginning to explain why mushrooms have long been valued as natural health boosters. They are packed with unique bioactive compounds such as polysaccharides, triterpenoids, low-molecular-weight proteins, glycoproteins, and other immune-supporting substances that contribute to overall well-being. Regular consumption of mushrooms has been linked to a wide range of health benefits. They help strengthen the immune system, support general health, and may reduce the risk of chronic diseases like cancer by slowing tumour growth. Mushrooms are also known to assist in regulating blood sugar levels, combating harmful microbes including viruses, bacteria, and fungi, and reducing inflammation. In addition, they play a role in supporting the body's natural detoxification processes. With growing awareness, mushrooms are increasingly being recognized as valuable supplements to modern medicine, offering supportive care in the prevention and management of various diseases. The medicinal properties of some important mushroom species are highlighted in Table 3.

Table 3: Medicinal values of some important mushrooms

Mushroom	Compounds	Medicinal properties	Courtesy
<i>Ganoderma lucidum</i>	Ganoderic acid	Augments immune system Liver protection	Lin and Zhang, 2004 Wang <i>et al.</i> , 2007
	Beta-glucan	Antibiotic properties Inhibits cholesterol synthesis	Moradali <i>et al.</i> , 2006 Komoda <i>et al.</i> , 1989
<i>Lentinula edodes</i>	Eritadenine Lentinan	Lower cholesterol Anti-cancer agent	Enman <i>et al.</i> , 2007
<i>A. bisporous</i>	Lectins	Enhance insulin secretion	Ahmad, 1984
<i>P. sajor-caju</i>	Lovastatin	Lower cholesterol	Gunde and Cimerman, 1995
<i>G. frondosa</i>	Polysaccharide Lectins	Increases insulin secretion Decrease blood glucose	Horio and Ohtsuru, 2001
<i>Auricularia auricula</i>	Acidic polysaccharides	Decrease blood glucose	Yuan <i>et al.</i> , 1998
<i>Flammulina velutipes</i>	Ergothioneine Proflamin	Antioxidant Anti-cancer activity	Bao (2008) Ikekawa <i>et al.</i> , 1985

<i>Trametes versicolor</i>	Polysaccharide-K (Kresin)	Decrease immune system depression	Coles and Toth, 2005
<i>Cordyceps sinensis</i>	Cordycepin	Cure lung infections Hypoglycemic activity Cellular health properties Anti-depressant activity	Li <i>et al.</i> , 2006 Ko <i>et al.</i> , 2009 Nishizawa <i>et al.</i> , 2007

Future Thrust

The future of mushrooms lies in their growing role as a high-value crop and functional food within modern agriculture and health sectors. Professionally, there is immense scope for expanding mushroom cultivation through advanced technologies such as climate-controlled production systems, vertical farming, and precision agriculture to ensure year-round supply and higher productivity. Emphasis should also be placed on developing improved strains with enhanced yield, nutritional quality, and disease resistance. Value addition through processing into products like mushroom powder, nutraceuticals, ready-to-eat foods, and supplements can significantly boost income and market demand. Furthermore, strengthening supply chains, cold storage, and marketing infrastructure will help reduce post-harvest losses and improve profitability for growers. Research and innovation in medicinal properties, bioactive compounds, and pharmaceutical applications of mushrooms offer promising opportunities for interdisciplinary collaboration. Capacity building, skill development, and entrepreneurship promotion-especially among rural youth and women-can transform mushroom cultivation into a sustainable livelihood option. Overall, integrating mushrooms into food, health, and agri-business systems will be a key thrust area for future professional growth and development.

Conclusion

Mushrooms are emerging as a powerful solution to some of India's most pressing nutritional and health challenges. Rich in high-quality protein, essential nutrients, and unique bioactive compounds, they not only help bridge dietary gaps-especially in cereal-based diets-but also offer significant medicinal benefits, from boosting immunity to managing chronic diseases. With increasing production, wider acceptance, and growing scientific validation, mushrooms are no longer a luxury but a practical, affordable, and sustainable food choice. Promoting their cultivation and consumption can play a vital role in improving public health, supporting livelihoods, and ensuring nutritional security for future generations.

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Camouflage Masters: Survival Tricks of Insects

Article ID: 73711

Kota Sahithi Chowdary¹, Repaka Harika¹, Gopu Sushma²

¹Ph. D Scholar, Indira Gandhi Krishi Vishwavidyalaya, Raipur.

²Ph. D Scholar, Professor Jayashankar Telangana Agricultural University.

Abstract

Insects are among the most successful organisms on Earth, and one of their greatest survival tools is camouflage. Through millions of years of evolution, insects have developed remarkable strategies to blend into their surroundings, deceive predators, and even imitate other organisms. From leaf-like wings to twig-like bodies and striking mimicry, these adaptations allow insects to avoid detection and enhance survival. This article explores the fascinating world of insect camouflage, focusing on mechanisms such as crypsis, mimicry, masquerade, and behavioural adaptations.

Keywords: camouflage, mimicry, insect defense, adaptation, crypsis, survival strategies.

Introduction

In natural ecosystems, survival often depends on avoiding predation. Insects, being small and vulnerable, are prime targets for a wide range of predators. Instead of relying solely on physical defenses, many insects depend on camouflage, an evolutionary adaptation that allows them to remain unnoticed in their environment (Ruxton *et al.*, 2004). These strategies are shaped by natural selection, where individuals with better concealment are more likely to survive and reproduce.

Types of Camouflage in Insects

1. Crypsis (Blending with the Environment): Crypsis is the most widespread form of camouflage, where insects match the colour, texture, and pattern of their surroundings. This makes them nearly invisible to predators. For instance, the stick insect resembles a dry twig, effectively avoiding detection. Similarly, leaf insects mimic green foliage with remarkable precision. Such adaptations reduce predator recognition and increase survival chances (Cott, 1940).



2. Mimicry (Imitating Other Organisms): Mimicry involves insects resembling other organisms to deceive predators. In Batesian mimicry, harmless species imitate harmful ones, such as hoverflies resembling bees or wasps, thereby deterring predators (Bates, 1862). Another form, Müllerian mimicry, occurs when multiple harmful species share similar warning signals, reinforcing predator learning and avoidance (Müller, 1879).



3. Masquerade (Disguising as Inanimate Objects): In masquerade, insects resemble objects that predators typically ignore, such as leaves, twigs, or bird droppings. Certain caterpillars adopt this strategy to avoid detection. Unlike crypsis, masquerade relies on misidentification rather than invisibility (Skelhorn *et al.*, 2010).

4. Disruptive Coloration: Disruptive coloration involves bold patterns that break up the outline of an insect's body, making it harder for predators to recognize its shape. Contrasting colours and irregular markings help insects blend into complex backgrounds, reducing the likelihood of attack (Stevens & Merilaita, 2009).

5. Behavioral Camouflage: Camouflage is often enhanced by behaviour. Many insects remain motionless or mimic environmental movement, such as swaying like leaves in the wind. Some species actively choose resting sites that complement their coloration, further improving concealment (Ruxton *et al.*, 2004).

Evolution of Camouflage

The diversity of camouflage strategies in insects is a direct outcome of natural selection. Over generations, individuals with traits that improve concealment are more likely to survive predation and pass these traits to offspring. This evolutionary process leads to highly specialized and efficient camouflage mechanisms (Cott, 1940; Ruxton *et al.*, 2004).

Ecological Significance

Camouflage plays a vital role in shaping predator-prey interactions and maintaining ecological balance. While prey insects use camouflage to avoid predators, some predatory insects also rely on it to ambush their prey. Thus, camouflage contributes to biodiversity and ecosystem stability (Stevens & Merilaita, 2009).

Conclusion

Insects demonstrate extraordinary adaptations in their ability to remain hidden from predators. Through crypsis, mimicry, masquerade, and behavioral strategies, they have evolved into masters of disguise. These survival mechanisms not only highlight the power of evolution but also inspire innovations in science and technology. Understanding insect camouflage provides valuable insights into ecology, evolution, and applied sciences.

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Diseases and Pests in Mushroom Cultivation and their Management

Article ID: 73712

Arushi Bharti¹, Surabhi Kumari¹, Sawli Saloni¹, Dnyaneshwari Pustode¹, Neha Suman¹, Shrvan Kumar¹
¹RGSC, Banaras Hindu University, Varanasi (U.P.), India.

Abstract

Mushroom cultivation has significant potential to enhance food and nutritional security while contributing to environmental sustainability by recycling agricultural waste materials. However, this industry faces constant threats from fungal contaminations that manifest as destructive diseases or rapidly spreading competitor molds. These contaminants can emerge at various stages of production, causing growth retardation, deformation, or decomposition, which leads to substantial losses in both the quality and quantity of the harvest. This review focuses on various prevalent fungal diseases—dry bubble, wet bubble, cobweb, and green mold—along with slippery scar and yellow rot. The taxonomic classification of major fungal pathogens is summarized using phylogenetic trees to illustrate their current placement. Additionally, the article reviews nine competitor molds and provides detailed information on their causative agents, signs and symptoms, disease cycles, epidemiology, and management strategies.

Keywords: Fungal pathogens, mushroom disease management, mycoparasites, phylogeny, signs and symptoms.

Introduction

Mushrooms are heterotrophic macrofungi with either hypogaeal or epigeal growth habits, renowned for their nutritional and medicinal properties and cultivated globally. Mushroom production is a vital microbial technology that offers significant commercial value by facilitating the large-scale recycling of agricultural waste and alleviating pressure on arable land through controlled environment cultivation. Over the past decade, the mushroom industry has emerged as a rapidly expanding and thriving sector worldwide. Current estimates indicate there are over 2,000 species of edible mushrooms, with total global production of mushrooms and truffles reaching over 50 million tons in 2023; Asia is the leading production region, with China as the primary producer.

Despite this growth, the proliferation of fungal contaminants—including both pathogenic species and competitor molds—remains a persistent obstacle. Contamination typically occurs due to poor hygiene practices and inadequate sterilization. Reports indicate that more than 130 fungal pathogens and competitor molds across 58 genera affect major cultivated mushroom species. Pathogens from the order Hypocreales are among the most impactful, including genera such as *Hypomyces*/*Cladobotryum*, *Zarea*, *Mycogone*, and *Trichoderma*. These organisms are responsible for economically significant diseases like cobweb, dry bubble, wet bubble, and green mold. Integrated disease management approaches, including the use of biological control agents and selective fungicides, are increasingly employed to maintain production quality worldwide.

Classification of Mushroom Diseases:

1. Fungal Diseases (& Competitor Molds)
2. Bacterial Diseases
3. Viral Diseases
4. Insect & pest
5. Abiotic & Physiological Disorders.

Table 1: List of mushroom infectious diseases and moulds with their causal organisms

Sl. No.	Diseases Name	Causal Agents
Fungal Diseases		
1	Olive Green Mould	<i>Chaetomium olivaceum</i> and other species
2	Green Moulds	<i>Trichoderma aggressivum</i>
3	Black Moulds	<i>Mucor</i> spp., <i>Rhizopus</i> spp., <i>Fusarium</i> spp., <i>Cephalosporium</i> spp., <i>Gliocladium</i> spp., <i>Papulospora</i> spp.
4	White Plaster mould	<i>Scopulariopsis fimicola</i>
5	Brown Plaster mould	<i>Papulospora byssina</i>
6	Lipstick mould	<i>Sporendonema purpurascens</i>
7	False truffle	<i>Diehliomyces microsporus</i>
8	Cinnamon mould	<i>Peziza ostracoderma</i>
9	Wet bubble	<i>Mycogone perniciosa</i>
10	Cobweb	<i>Cladobotryum dendroides</i>
11	Pink mould	<i>Trichothecium roseum</i>
12	Fusarium rot	<i>Fusarium</i> spp.

13	Soft mildew or Cobweb	<i>Cladobotryum dendroides</i>
14	Inky cap	<i>Coprinus lagopus</i> , <i>Coprinus comatus</i>
15	Truffle disease	<i>Pseudobalsamia microspora</i>
16	Dry bubble	<i>Lecanicillium fungicola</i>
17	Mat	<i>Chrysosporium luteum</i>
18	Confetti	<i>Chrysosporium merdarium</i> (teleomorph <i>Gymnoascus uncinatus</i>)
19	Sepedonium yellow mold	<i>Sepedonium niveum</i> (teleomorph <i>Hypomyces</i> sp.)
20	Nematode-trapping fungi	<i>Arthrobotrys</i> spp.
21	Aphanocladium cap spot	<i>Aphanocladium album</i>
22	Gill mildew	<i>Cephalosporium</i> spp.
23	Hormiactis cap spot	<i>Hormiactis alba</i>
24	Shaggy stipe	<i>Mortierella bainieri</i>
Bacterial diseases		
1	Bacterial blotch	<i>Pseudomonas tolaasii</i>
2	Wet Spot/Sour Rot	<i>Bacillus</i> spp.
3	Mummy	<i>Pseudomonas tolaasii</i>
4	Actinomycetes colony	<i>Thermoactinomyces</i> , <i>Micromonospora</i> , <i>Thermomonospora</i> spp., <i>Thermomonospora chromogena</i> and others
Viral diseases		
1	Mushroom virus X	Mushroom virus X (MVX)
2	La France	La France isometric virus (LIV)

Fungal Diseases

Fungal pathogens are the most significant threat, with species in the order **Hypocreales** (such as *Hypomyces*, *Mycogone*, and *Trichoderma*) being particularly impactful.

Major Pathogenic Fungal Diseases

1. Dry Bubble (*Verticillium* spp.):

a. Causal Agent: *Lecanicillium fungicola* (formerly *Verticillium fungicola*).



b. **Symptoms:** Early infection causes undifferentiated lumps of tissue (bubbles). Late infection leads to "stipe blow-out," curved stems, or sunken brown spots on the caps.



c. Management: Adopt strict hygiene and control insect vectors like phorid and sciarid flies. Chemical controls include **Dithane Z-78** (0.25-0.5%), **Sporgon**, or **Topsin M** applied at casing. Biocontrol options include plant extracts like neem, cinnamon, and thyme.



2. Wet Bubble (Mycogone Disease):

a. Causal Agent: *Mycogone perniciosa* (syn. *Hypomyces perniciosus*).



b. Symptoms: Mushrooms become a white, puffy, malformed mass. As the disease progresses, it exudes **amber-colored liquid droplets** with a foul odor and eventually decomposes.

c. Management: Use sterilized casing soil and maintain extreme hygiene. Spraying **Benomyl** (0.5g/m²) right after casing is highly effective. Surface treatment with 0.8% formalin also prevents outbreaks.



3. Cobweb (Soft Mildew):

a. Causal Agent: *Cladobotryum dendroides*.

b. Symptoms: A fluffy, white, cobweb-like mycelium spreads over the casing and mushrooms, eventually turning pink or red with age. It causes soft wet rot in fruiting bodies.

c. Management: Improve ventilation and keep relative humidity below 85%. Chemical control includes **Benomyl**, **Metrafenone**, or **Dithane Z-78**. Affected areas can be covered with damp paper towels to prevent spore dispersal.



4. Green Mold:

a. Causal Agent: *Trichoderma aggressivum* or *T. viride*.



b. **Symptoms:** Appears as dense white cushions on substrate that turn **dark blue-green** upon sporulation. It inhibits pinhead formation and can cause necrotic lesions on mushrooms.

c. **Management:** Ensure proper pasteurization of compost and avoid high humidity. Effective fungicides include Carbendazim (0.05%), Benlate, or Mancozeb. Immersing substrate in 60°C water for 30 minutes can reduce contamination.



Competitor Molds (Weed Fungi)

1. False Truffle:

a. Causal Agent: *Diehliomyces microsporus* or *Pseudobalsamia microspora*.



b. **Symptoms:** Forms cream-colored, wrinkled, **brain-like masses** in the compost or casing. At maturity, it turns reddish-brown and releases spores with a chlorine-like odor.

c. **Management:** Avoid high temperatures (above 26-27°C) during spawn run. Spent compost should be "cooked out" at 70°C for 12 hours.



2. Plaster Molds (White and Brown):

a. Causal Agents: *Scopulariopsis fimicola* (White) and *Papulaspora byssina* (Brown).



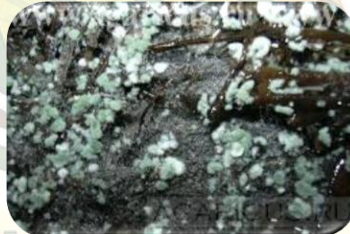
b. Symptoms: White plaster mold forms dense patches resembling plaster. Brown plaster mold starts white and turns cinnamon-brown or rust-colored. Both prevent mushroom mycelium growth.

c. Management: Ensure proper compost aeration to avoid anaerobic zones. Treat with 2% formalin or Carbendazim (0.05%).

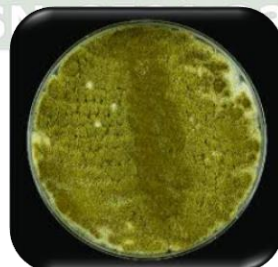


3. Olive Green Mold:

a. Causal Agent: *Chaetomium olivaceum* or *C. globosum*.



b. Symptoms: Appears as greyish-white fine mycelium in compost, later forming grey-green fruiting bodies. Its presence often indicates excess ammonia in the compost.



c. Management: Improve Phase II composting to eliminate ammonia and ensure adequate fresh air during pasteurization.

3. Inky Cap:

a. Causal Agent: *Coprinus* spp.

b. Symptoms: Long slender stalks with small caps that dissolve into a black inky liquid.

c. Management: Indicates improper composting; re-pasteurize spawn trays at 60°C for 2 hours to eliminate ammonia.



Other Fungal Contaminants

1. Mat and Confetti: Caused by *Chrysosporium* species; they form dense mycelial layers that interfere with primordia formation. Management requires high-temperature pasteurization (70°C for 12 hours).

2. Lipstick Mold: *Sporendonema purpurascens* causes white mycelium that turns **pink to cherry red**. It is managed through strict hygiene and proper compost conditioning.

3. Cinnamon Mold: *Chromelosporium fulvum* forms expansive circular patches that turn golden brown or cinnamon. Controlled by avoiding over-sterilization of casing and applying **Carbendazim**.

4. Slippery Scar and Yellow Rot: Specific to *Auricularia* and *Ganoderma*, these *Scytalidium* species cause glossy dark-brown scars on mycelia or greenish-yellow discoloration on stipes. Management involves hygiene and eliminating contaminated wood.



Lipstick mold (*Sporendonema purpurascens*)



Cinnamon mold (*Chromelosporium fulvum*)

General Management Strategy

To combat fungal diseases across the farm, experts recommend an integrated approach:

1. Strict Hygiene: Use foot-dips, door seals, and HEPA filters. Clean tools with formalin and lime-wash rooms between crops.

2. Pasteurization: Maintain Phase II compost at 60°C to eradicate most pathogens.

3. Environmental Control: Manipulate humidity and temperature to favor the mushroom crop over the pathogens (e.g., keeping cropping areas below 18°C for certain diseases).

4. Biological Control: Use eco-friendly alternatives like *Bacillus subtilis* or botanical extracts (Tulsi, Neem) to suppress growth without leaving chemical residues.

Table 2: Common chemicals used to control diseases in mushroom

Fungicide	Against Pathogen	Dose
Benomyl and Carbendazim	<i>Dactylium</i> , <i>Mycogone</i> , <i>Trichoderma</i> , <i>Verticillium</i>	Mix 240 g/100m ² with casing or in water @ 240g/200 L/100m ²
Chlorothalonil	<i>Mycogone</i> , <i>Verticillium</i>	200 ml/200 L/100m ² ; 1st spray 1 week after casing & 2nd after 2 weeks
Prochloraz manganese	<i>Dactylium</i> , <i>Mycogone</i> , <i>Verticillium</i>	300g/100 L/100m ² for single spray OR 113g/100 L/100m ² if 2 sprays

Thiabendazole	<i>Dactylium</i> , <i>Verticillium</i>	<i>Mycogone</i> ,	Mix 240 g/100m ² with casing or in water @ 240g/200 L/100m ²
Zineb	<i>Dactylium</i> , <i>Verticillium</i>	<i>Mycogone</i> ,	350 g/100m ² (dust) every week after casing; 1 kg/1000 L @ 5 L/10m ² after casing & between flushes

Source: TNAU Agritech Portal: Sustainable Agriculture, Mushroom: Major Diseases of Mushroom.

Bacterial Diseases

Bacterial diseases represent a significant threat to commercial mushroom cultivation, often leading to substantial economic losses through reduced yield and diminished market value. Most bacterial infections are caused by species within the genus *Pseudomonas*, and their spread is heavily encouraged by conditions such as warm temperatures, high humidity, and poor aeration.

The following are the major bacterial diseases affecting mushroom crops and their detailed management strategies:

1. Bacterial Blotch (Brown Blotch): Bacterial blotch is the most common and economically impactful bacterial disease worldwide.

a. **Causal Agent:** *Pseudomonas tolaasii*.

b. **Symptoms:** Pale yellow areas or blotches appear on the mushroom cap, eventually turning golden yellow, yellow-brown, or deep chocolate brown. In severe cases, the stipe (stem) is also affected with circular or irregular spots. These lesions can coalesce, leading to rapid deterioration and a repulsive odor.



c. **Transmission:** The infection is often introduced via contaminated soil and spread by water splashes, picker tools, flies, mites, and beetles.

Management:

a. **Environmental Control:** This is the primary defense. Maintain relative humidity at **80%** or lower and ensure caps dry within two to three hours after watering by using fans and increasing ventilation.

b. **Temperature Management:** Maintain a stable difference of **1°C to 1.5°C** between wet and dry bulb readings to prevent condensation on the mushrooms.

c. **Chemical Treatment:** Use **chlorinated water (100-150 ppm chlorine solution)** for watering to lower bacterial populations on the mushroom surface. Stabilized oxine at 200 ppm can also be added to pre-harvest wetting treatments.

d. **Watering Practices:** Avoid watering on consecutive days and do not water mushrooms within one to two days of harvest.

2. Mummy Disease: Mummy disease is frequently encountered and can affect specific sections of a production chamber.

a. **Causal Agent:** A fluorescent pseudomonad proximate to *Pseudomonas tolaasii* (sometimes cited as *Pseudomonas aeruginosa*).



b. Symptoms: Infected mushrooms exhibit **curved stems with tilted caps**. Rhizomorphs at the stem base are stringy and cling tightly to the casing. The base may be swollen and covered in fluffy mycelium. Internally, the stem tissue may show longitudinal brown streaks or spots. Affected mushrooms die and become tough, dry, and leathery.

Management:

a. Isolation: Once identified, isolate diseased areas by removing the compost **1.5 meters** on either side of the infection to a width of **20 cm** and covering the trench with plastic.

b. Sanitation: Thoroughly pasteurize compost at the end of the crop cycle. Disinfect netting, shelving, and trays with **formalin solution@5%** or hydrated lime before reuse.

c. Environment: Lower humidity and use 150 ppm chlorine solution in watering cycles.

3. Wet Spot (Sour Rot): This disease is characterized by its distinct, unpleasant smell.

a. Causal Agent: *Bacillus* spp., which produce heat-resistant endospores.

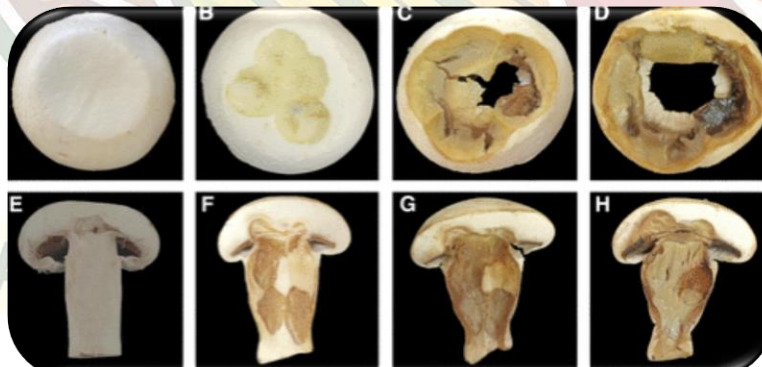
b. Symptoms: A dull gray to mucus-like brownish slime appears, emitting a foul odor described as smelling like rotting apples, dirty socks, or burnt bacon.

Management: To kill the heat-resistant endospores, **soak the grain at room temperature for 12 to 24 hours** prior to sterilization; this encourages spores to germinate, making them vulnerable to heat.

4. Cavity Disease: Cavity disease results in physical deformities in the fruiting bodies.

a. Causal Agent: *Burkholderia gladioli* pv. *agaricicola* (formerly *Pseudomonas cepacia*).

b. Symptoms: Symptoms range from minor blotching to severe pitting, with **large, extensive cavities** extending from the cap surface deep into the stipe. The tissue degradation is caused by toxins and enzymes like chitinase and glucanase.



Management: Biological control using competing microorganisms is a promising research area, though commercial products are still under development.

General Preventative Management for Bacterial Diseases

As chemical treatments are limited by residual risks, experts emphasize strict hygiene and environmental management:

1. Sterilization: Ensure proper pasteurization of compost and casing soil to eradicate initial bacterial populations.

2. Filtration: Use **HEPA filters** to exclude particles of 2 microns and above from fresh air entering the growing rooms.

3. Sanitation: Clean all tools and collector boxes regularly; lime-wash rooms between crop cycles and use **2% formalin** to disinfect spawning areas.

4. Worker Hygiene: Limit worker movement between old and new crops and ensure the use of foot-dips and disinfected clothing.

Viral Diseases

Viral diseases in mushroom cultivation, primarily affecting *Agaricus bisporus*, can lead to dramatic production losses and are often difficult to control because they frequently remain asymptomatic until harvest. The most significant viral threats include **La France disease** (also known as Dieback or X-disease) and **Mushroom Virus X (MVX)**.

Major Viral Diseases and Symptoms

1. La France Disease (Dieback/X-disease): This is the most prevalent viral illness and is caused by several different virus types, including the **La France isometric virus (LIV)**. The most typical symptom is the development of "**drumsticks**," characterized by a small, tilted cap on an elongated, unstable stalk. Affected mushrooms may also appear **shriveled, leathery, and brown-colored**. Under humid condition stripe become watery and grey.

2. Mushroom Virus X (MVX): This novel disease can cause **brown discoloration** in white button mushroom varieties. It is also linked to "open veil" symptoms, where the cap opens prematurely and gills develop early.

General Indicators: Reliable signs of viral infection include a **significant reduction in yield**, delayed first breaks, and slow, depressed growth of mycelium. Cream and off-colored mushroom varieties generally suffer less than pure white varieties.



Detailed Management Strategies

Because there are no effective chemical treatments for viruses once a crop is infected, management relies entirely on **strict exclusion and sanitation** to prevent the entry of viral particles via spores or contaminated mycelium.

1. Environmental and Physical Controls:

- Air Filtration:** Use **HEPA filters** in spawning and cropping areas to capture spores (sized approximately 5 by 7 µm), which are a major vector for transmitting viruses.
- Positive Pressure:** Maintain **increased air pressure** in spawning regions to prevent outside air from sucking spores into the facility.
- Ventilation:** Ensure ventilation systems are tight and do not create negative pressure that might bypass filters.

2. Hygiene and Sanitation Standards:

- Thermal Disinfection ("Cooking Out"):** At the end of a crop cycle, the growing room, trays, and spent compost must be **heated to 70 °C for 12 hours** to eradicate all viral inoculum.
- Equipment Sterilization:** All tools, machines, and reusable plastic containers must be cleaned and disinfected before use. Surfaces such as doors, floors, and walls should be treated with **4% formaldehyde** or a solution of Sodium Pentachlorophenate.
- Exclusion of Wood:** Growing units should **avoid using wooden parts**, as wood can harbor contaminated mycelium from previous harvests that is difficult to sterilize.

3. Operational Practices:

- Spore Management:** Diseased mushrooms must not be allowed to open and release spores. Workers should **collect immature carpophores** before spore release occurs.
- Worker Restrictions:** Limit worker movement, particularly in the spawning region, and ensure all clothing is cleaned and disinfected regularly.
- Storage Logistics:** Avoid storing or shipping **spawn and harvested mushrooms in the same cooler** to prevent cross-contamination.
- Casing Techniques:** The **ruffling technique** can be used to break up and relocate mycelium within the casing layer.

4. Varietal Selection:

- a. **Resistant Strains:** Utilizing tolerant or resistant mushroom strains is highly recommended. *Agaricus bitorquis* is specifically reported to be tolerant to viral diseases.
- b. **Strain Rotation:** Changing spawn strains or using alternate varieties that do not **anastomose** (fuse mycelia) can help minimize the build-up of virus inoculum levels.

Insect & Pests

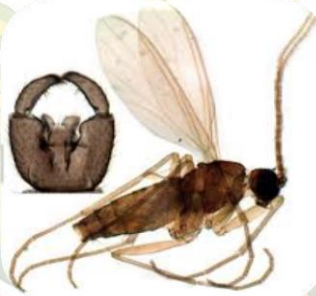
In mushroom cultivation, pests such as insects, mites, and nematodes pose a dual threat: they cause direct physical damage to the crop and act as major vectors for fungal and bacterial diseases. Effective management requires a combination of **strict hygiene, physical barriers, and targeted chemical or thermal treatments.**

1. Mushroom Flies (Sciarids, Phorids, and Cecids): Flies are the most common and destructive pests in commercial mushroom production.

- a. **Causal Agents:** Common species include *Megaselia halterata* (Phorid), *Lycoriella mali* (Sciarid), and various Cecid flies.



- b. **Damage and Symptoms:** Adult flies lay eggs on the substrate or mushrooms. The emerging larvae feed on the mushroom mycelium and penetrate the fruiting bodies, making them riddled with tunnels and unfit for consumption. Furthermore, these flies are confirmed vectors for pathogens like **dry bubble** (*Lecanicillium fungicola*) and **green mold** (*Trichoderma aggressivum*).



- c. **Management:**

- i. **Physical:** Screen all doors, windows, and ventilators with fine mesh (30 mesh nylon or wire net) to prevent entry.
- ii. **Trapping:** Use fly traps or repellents within the growing house.
- iii. **Chemical:** Application of insecticides such as **Dichlorvos 76 EC** (0.5ml per liter of water) every 3-4 days, or mixing **Diaflowbenzoran** into the compost.

2. Nematodes (Eelworms): Nematode infestations typically arise from improperly sanitized manure or contaminated water and tools.

- a. **Causal Agents:** *Ditylenchus mycelophagus* and *Aphelenchoides* species are the primary offenders.
- b. **Damage and Symptoms:** Nematodes feed directly on the mushroom mycelium. This destroys the mycelial network and stops the flow of nutrients to developing pinheads, causing them to die and eventually leading to a complete crop failure if left unchecked.
- c. **Management:**
 - i. **Thermal Control:** The most effective defense is proper **pasteurization**; nematodes in their active stage cannot survive temperatures above 50°C.
 - ii. **Sanitation:** Maintain rigorous hygiene in the composting area and ensure the use of clean water for irrigation.



3. Mites: Mites are often introduced via contaminated straw or by clinging to the bodies of flies.

a. Causal Agents: *Tarsonemus myceliophagus* and *T. floriculus* (Tarsonemid mites).



b. Damage and Symptoms: These tiny arthropods chew the surface of the mushroom. While they may not destroy the entire crop, their feeding sites often become infected with **secondary bacteria**, leading to pitting, discoloration, and a decline in quality.



c. Management:

i. **Chemical:** Periodic spraying of the walls and compost with acaricides like **Kelthane** or **Diacophal 50 EC** (1-2ml).

ii. **Hygiene:** Maintain extreme cleanliness in the production house and surrounding environment to prevent mite migration.

4. Springtails: Springtails are small, group-dwelling insects that thrive in the dark, humid environment of mushroom beds.

a. Causal Agents: *Lepidocyrtus* sp., *L. cyaneus*, and *Seirairicolor*.



b. Damage and Symptoms: They consume mycelium within the compost, causing it to "disappear" during the spawn-run. On fruiting bodies, they cause slight pitting and browning; in species like **Oyster** and **Shiitake**, they specifically destroy the gill linings.



c. Management:

i. **Disinfection:** Spray beds with **0.05% Malathion** for disinfection.

ii. **Preventative Treatment:** Mix **Diazinon (30 ppm)** into the compost during the filling stage to inhibit population growth.

5. Beetles: Beetles are less common but act as significant carriers of infection.

a. **Causal Agents:** *Sacphiso manigrofaceatum* and *Sacphiso mapictummotschulsky*.



b. **Damage and Symptoms:** Recognized by golden lines on their bodies, these insects scrap the tissues of young buds and mature mushrooms. Their primary danger is that they **transmit bacterial blotch disease** from one bed to another.

c. **Management:** Primarily managed through maintaining high sanitation standards and restricting the movement of tools between beds.

6. Other Pests (Slugs, Snails, and Mice):

a. **Slugs and Snails:** These pests chew large portions of the mushroom body, causing grotesque deformities. They should be physically removed and destroyed upon detection.

b. **Mice:** Small rodents are noted vectors for *Trichoderma spp.* (green mold) spores, carrying the pathogen on their fur as they move through the facility. Management involves sealing entry points and maintaining a clean perimeter around the farm.

General Integrated Pest Management (IPM)

1. **Peak Heating:** "Cooking out" the growing room and spent compost at **70 °C for 12 hours** at the end of the cycle to kill residual pests and their eggs.

2. **Environmental Manipulation:** Maintaining relative humidity around **80%** and ensuring rapid drying of mushroom caps after watering to discourage pest activity and secondary infections.

3. **Chemical Hygiene:** Regular use of **2% formalin** to disinfect spawning areas and tools.

Abiotic /Physiological Disorders

Abiotic or physiological disorders in mushroom cultivation are non-infectious abnormalities caused by deviations in environmental parameters from the optimum requirements. These factors create unfavorable growing conditions that can lead to significant qualitative and quantitative losses, sometimes reducing production to as little as 20% of a normal harvest.

Major Abiotic Disorders

1. Stroma:

a. **Cause:** Repeated use of old or multiplied spawn, excessive CO₂ levels, high water content in compost, or a prolonged spawn run.

b. **Symptoms:** Discrete white patches of mycelium aggregate on the compost or casing surface, eventually forming a dense layer that can be peeled off. This layer forms in advance of pinning and prevents normal fruiting.

2. Rose Comb:

a. Cause: Exposure to hydrocarbons, phenols, or fumes from diesel oil, kerosene, petrol, engine exhaust, or oil-based paints and pesticides.



b. Symptoms: The mushroom develops grotesque gill-like growths on the cap, giving it a comb-like appearance. Affected mushrooms may burst, split, or turn brown, making them completely unmarketable.

3. Hard Cap or Hard Gill (Flock):

a. Cause: Degeneration of spawn cultures or dramatic changes in the temperature of the compost or spawn.

b. Symptoms: The cap is hard, brittle, and opens prematurely. Gills are rudimentary, poorly developed, distorted, and lack normal brown pigmentation, appearing pink or white instead.

4. Open Veil:

a. Cause: A period of **water stress** (1-3 days) followed by generous watering. It can also be triggered by excessive CO₂ levels or temperature fluctuations.

b. Symptoms: The cap opens prematurely while the gills are fully developed. Sometimes the cap remains disproportionately smaller than the stem.

5. Cracked mushroom (Malformed mushroom):

a. Cause: This disorder is caused by sharp **fluctuations in humidity and temperature** within the growing environment.



b. Symptoms: The mushroom exhibits **physical deformities and cracks** on the cap surface, which results in both quantitative and qualitative production losses.

6. Scales or "Crocodile Skin":

a. Cause: Poor climate control, specifically **excessive drying** or high air velocities. It can also be caused by strong formaldehyde vapors or excess pesticides.

b. Symptoms: The surface tissue fails to grow while the cap continues to develop, causing the outer skin to tear and burst into scales resembling crocodile skin.

7. Weepers, Leakers, and Strinkers:

a. Cause: Low-moisture compost (less than 64%) coupled with a high-moisture casing layer.

b. Symptoms: Mushrooms exude water droplets from the cap or stem. If the droplets stay on the mushroom, they are "leakers"; if the water flows or falls from the cap, they are "weepers".

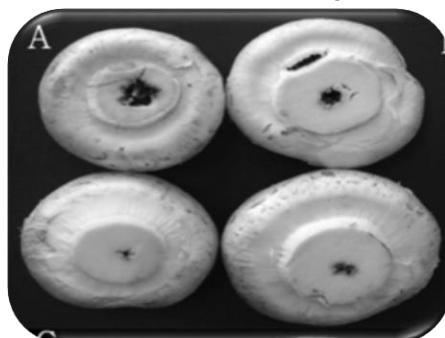
8. Mass Pinning:

a. **Cause:** A sudden fall in temperature, excessive aeration, or early lowering of CO₂ concentration below recommended levels.

b. **Symptoms:** An overwhelming number of pins form simultaneously, often below the casing layer.

9. Hollow Core and Brown Pith:

a. **Cause:** General watering issues and water stress, afflicting cream strains more than white strains.



b. **Symptoms:** A circular gap or hole is visible in the center of the stem when trimmed after harvest, which reduces the sale price, especially if the core is brown.

10. Long Stem:

a. **Cause:** Too high a CO₂ concentration in the growing room.

b. **Symptoms:** The stems extend excessively (often called "drumsticks") to reach better air quality.

Management Strategies

The management of abiotic disorders relies almost entirely on precise **environmental and cultural control**:

1. **Climate Regulation:** Maintain optimum levels of temperature, humidity, and CO₂ throughout different stages of growth. **Intermittent cross-ventilation** for 3-4 hours daily is recommended after pinhead appearance to prevent CO₂ accumulation.

2. **Chemical Safety:** Avoid exposing crops to harmful vapors. To test the safety of paints or caulking compounds, growers should apply them to a board and place it next to developing mushrooms to check for symptoms before general use.

3. **Watering Discipline:** Maintain stable humidity (60-70% or 70-80% depending on the stage) and avoid cycles of extreme drying followed by heavy irrigation.

4. **Spawn Management:** Use only **fresh, high-quality spawn** and avoid repeated multiplication, which leads to degeneration. Spawn should be handled and stored carefully to minimize the risk of stroma.

5. **Air Filtration:** Use **HEPA filters** to exclude particles of 2 microns and above from the fresh air entering the growing rooms to ensure a clean environment.

6. **Substrate Preparation:** Use fresh substrate for compost and ensure composting floors are tiled or cemented and covered with a roof to prevent contamination or unfavorable chemical reactions.

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Dryland Farming and the Search for the Perfect Plant Ideotype

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Abhinav Singh¹, Santosh Korav¹

¹Department of Vegetable science, School of Agriculture, Lovely Professional University (Phagwara)
Jalandhar- 144411.

Abstract

Dryland farming has a big problem: it needs to grow crops that make money in dry places with little rain and high evaporation. In these tough conditions, traditional high-yield crop varieties often don't work, so we need to use both strict soil moisture conservation methods and plants that are very well adapted to the conditions. This depends on ideotype breeding, which is a targeted method that creates a theoretical model of the perfect plant with the right mix of morphological and physiological traits to get the most out of a certain environment. The ideal "stress" or "climate" ideotype for dryland farming is one that maximizes water conservation. Important traits are a deep, productive root system that can get moisture from the subsoil, a short height with few, narrow leaves to keep water from getting lost through transpiration

Keywords: Dryland farming, Ideotype, High-yield crop, Evaporation, Transpiration.

Introduction

Dryland farming is the profitable way to grow crops without irrigation in places where there isn't much water. It depends on careful physical soil management, like stubble mulching, contour tillage, and summer fallowing, to get the most rainwater and keep evaporation to a minimum. However, even the best soil management can't make a plant that doesn't fit thrive in a dry, harsh climate. This biological constraint has compelled agricultural science to transcend traditional plant breeding and adopt the ideotype concept.

A crop ideotype is a theoretical, idealized biological model of a plant that was first suggested in the late 1960s. It is purposefully designed with a specific mix of structural and physiological traits that are meant to increase yield and resilience in a certain environment. Scientists want to breed "stress" or "climate" ideotypes for farming in dry areas. These tough plants are designed to have deep, extensive root systems that can reach water below the surface, short, narrow leaves that help them lose less water through transpiration, and faster life cycles that let them grow up before all the moisture in the season is gone. Plant breeders are laying the groundwork for the future of agriculture and global food systems by carefully designing these specialized crops. This is important because the world is becoming more and more dry.

The Concept of Ideotype Breeding

C.M. Donald changed the way people thought about crops in 1968 by introducing the "ideotype." A crop ideotype is a theoretical, idealized biological model of a plant that has a specific combination of morphological and physiological traits that are meant to maximize yield and quality in a certain environment.

Ideotype breeding, on the other hand, focuses on specific, heritable traits instead of breeding for unclear overall yield. Breeders are like architects who make plans based on the stressors in the environment. Ideotypes are put into groups based on what they do. A "competition ideotype" has tall, leafy plants that do better than their neighbors, while a "crop ideotype" has weak competitors that do better when planted closely together in commercial fields. For dryland farming, breeders work on "climate ideotypes," which are meant to adapt to changes in heat and rainfall, and "stress ideotypes," which are meant to be very resistant to both biotic and abiotic stressors.

Architecting the Perfect Ideotype for Different Crops

The ideal plant depends heavily on the specific crop species. Developing dryland or stress ideotypes requires selecting traits that drastically reduce water demands while maximizing resource scavenging.

1. Wheat: Donald suggested a short, strong stem to keep the wheat from lodging, a few small leaves to keep transpiration to a minimum, and an upright leaf canopy. Erect foliage lets more sunlight reach the plant canopy, which helps photosynthesis, and it also keeps the plant from getting too hot in the middle of the day. The best wheat has a big, upright ear and awns (bristles) that help with photosynthesis and using water efficiently in the ear.

2. Rice: It wants a short culm, a low but very productive tillering capacity, thick, dark green erect leaves, and a strong, deep root system. "Aerobic rice" ideotypes try to combine the yield of lowland varieties with the drought tolerance of highland varieties so that they can grow in different environments.

3. Maize: A modern maize ideotype puts a lot of emphasis on root architecture, which is often called "steep, cheap, and deep." This includes a big primary root with long lateral branches that quickly use moisture from deep subsoil and a single whorl of brace roots. Above ground, maize should have stiff leaves that grow vertically above the ear and horizontally below it. It should also have a long grain-filling period and slow leaf senescence (stay-green traits).

4. Cotton: Rainfed, dryland cotton requires extreme earliness, a compact stature, few small and thicker leaves, and synchronous bolling to survive water scarcity.

5. Oilseed Brassica: Ideotypes for these crops target an optimized flowering time, apetalous flowers, long upright pods, pod shattering resistance, and a high number of seeds per pod.

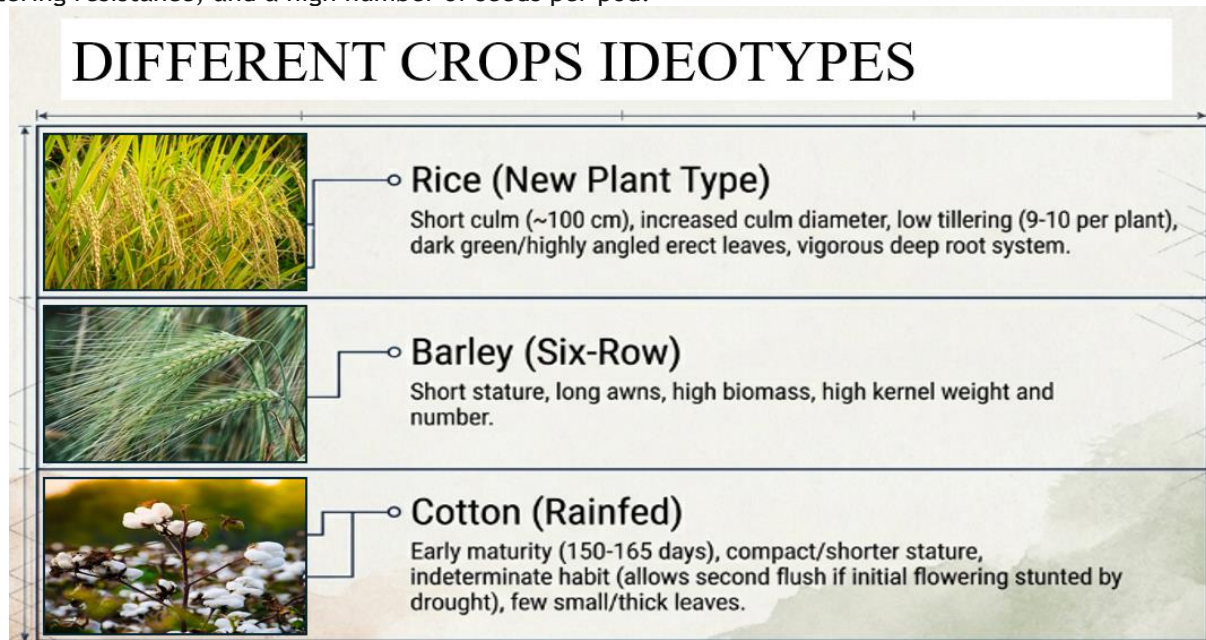


Fig. 1 Different crop ideotypes for major field crops

Across many dryland species, accelerated phenology (earliness) is paramount, allowing the plant to complete its life cycle before seasonal moisture is completely exhausted. In dicots (like certain legumes), an indeterminate growth habit is favoured so the plant can pause its development during mid-season droughts and produce a secondary flush of flowers once rains return.

Challenges and Conflicting Factors in Ideotype Expression

Despite the clear biological advantages of these theoretical blueprints, actual elite crop varieties frequently deviate from the theoretical ideal. Several interacting factors explain this complexity:

1. Trade-offs with Biotic Stress: Traits that conserve water can inadvertently invite disease. A plant bred for extreme density may conserve soil moisture but create a humid microclimate perfect for fungal pathogens.

2. The Domestication Syndrome: Thousands of years of human agriculture have created genetic bottlenecks, narrowing the genetic diversity of major crops. Early farmers inadvertently selected for traits like seed retention and reduced branching, meaning the specific genetic material required to build the perfect stress ideotype may no longer exist in modern cultivars.

3. Farmer Preference and Socio-Economics: An ideotype is only useful if farmers are willing to plant it. Cultural biases frequently override biological efficiency. Farmers often prefer a visually pleasing, deep dark green crop, assuming it indicates health. However, modern physiological studies reveal that reducing a canopy's chlorophyll content actually decreases light oversaturation, increases photosynthetic efficiency, and conserves nitrogen.

4. Cropping Systems and the Ideomix: A lot of ideotypes are made for monocultures. But intercropping is often used in sustainable farming. A plant that is best suited for a monoculture will not do well when it has to compete for light and roots with other plants in a mixed-species system. This needs a "ideomix," which is the process of creating traits that work well together.

The Future: Accelerating Design with Technology

Traditional ideotype breeding is undeniably slow and expensive, requiring years of trial and error. However, the integration of advanced technology is rapidly accelerating the timeline for developing the crops of the future.

1. Advanced Phenotyping: Unmanned Aerial Vehicles (UAVs) and gantry robotic systems with multi-spectral sensors are taking the place of manual field measurements. These tools quickly scan fields and make 3D models that are geometrically correct and measure leaf angles, canopy architecture, and photosynthetic efficiency in real time.

2. Process-Based Computer Simulation: Scientists can now design and test ideotypes *in silico*. Functional-Structural Plant Models (FSPMs) simulate plant growth in three dimensions over time, factoring in complex variables like root competition and light distribution. Software can integrate global climate projections to predict optimal traits decades into the future. For example, using the Sirius simulation model for a projected hotter climate in 2050, scientists determined that future wheat ideotypes will need heavily optimized phenology and a radically extended grain-filling period.

3. Genomic Selection: By combining these ecophysiological computer models with quantitative genetics, scientists can link specific physical traits directly to their underlying DNA markers. This combined approach bypasses years of field evaluation, allowing breeders to mathematically predict the probability of successfully recombining complex traits.

Conclusion

Dryland farming is a complicated process that involves carefully managing the physical landscape to catch and hold onto rainwater. However, even the best soil management can't make a plant that isn't suited for a harsh environment grow well. The crop ideotype is a very important biological map that lets scientists design plants with the right root structures, specialized canopies, and aggressive life cycles to deal with very dry conditions. The "perfect" plant is always changing because of cultural preferences, disease trade-offs, and the fact that the environment is always changing. The combination of traditional agronomy with advanced 3D modeling and genomics is a powerful sign of hope. We can make sure that the foundation of global food production lasts for generations by designing crops that can survive the climates of the future.

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Artificial Intelligence (AI) and Internet of Things (IoT) in Agricultural Machinery

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Shivesh Chandra Pandey¹, Vikki Prasad Sahu²

¹Research scholar Department of Farm Machinery and Power Engineering, College of Agricultural Engineering and Technology, AAU, Godhra, Gujarat, India-389001.

²Research Scholar, Swami Vivekanand College of Agricultural Engineering Technology and Research Station, IGKV, Raipur, Chhattisgarh 492012.

Introduction

Agriculture is one of the oldest and most important occupations in human civilization. Since ancient times, farming has been the primary source of food, raw materials, and livelihood for millions of people around the world. Traditional agriculture mainly depended on manual labor, animal power, and simple farming tools for operations such as ploughing, sowing, irrigation, and harvesting. Although these traditional methods supported agricultural production for centuries, they were slow, labor-intensive, and often unable to meet the growing demand for food created by rapid population growth. As the global population increased and agricultural land became limited, the need for more productive, efficient, and sustainable farming systems became increasingly important. In recent decades, agriculture has undergone major technological transformation through the development of farm mechanisation and digital farming systems. Modern agricultural machinery such as tractors, harvesters, seed drills, irrigation systems, and sprayers have significantly improved productivity and reduced dependence on manual labor. However, modern agriculture now faces new challenges including labor shortages, climate change, declining water resources, increasing production costs, soil degradation, and the need for sustainable resource management. To overcome these challenges, advanced technologies such as Artificial Intelligence (AI) and the Internet of Things (IoT) are being integrated into agricultural machinery and farming systems.

Artificial Intelligence refers to computer systems and software capable of performing tasks that normally require human intelligence. These tasks include learning, decision-making, image recognition, prediction, and problem-solving. AI systems can analyze large amounts of agricultural data, identify patterns, and provide intelligent recommendations for improving farming operations. The Internet of Things, commonly known as IoT, refers to a network of interconnected devices, sensors, machines, and communication systems that collect, exchange, and process real-time information through the internet. IoT enables machines and equipment to communicate with each other automatically without continuous human involvement.

The integration of AI and IoT into agricultural machinery has created a new concept known as smart farming or precision agriculture. In smart farming systems, sensors, GPS devices, drones, cameras, and intelligent software continuously monitor field conditions such as soil moisture, crop health, temperature, humidity, nutrient levels, and machine performance. The collected data is analyzed using AI algorithms, which then help farmers make accurate decisions regarding irrigation, fertilizer application, pest management, harvesting, and machinery operation. This improves efficiency, reduces input wastage, and increases crop productivity.

Modern agricultural machinery is becoming increasingly intelligent and automated. Tractors are now equipped with GPS guidance systems and autonomous driving technology. Smart irrigation systems use soil moisture sensors and automated controllers to supply water according to crop requirements. AI-powered drones monitor crop conditions and perform precision spraying operations. Robotic harvesting systems use image recognition and sensors to identify mature fruits and harvest them carefully without causing damage. These developments are transforming agriculture from a labour-intensive activity into a technology-driven production system. One of the major advantages of AI and IoT technologies in agriculture is their ability to improve precision and resource efficiency. Traditional farming methods often involve excessive use of water, fertilizers, pesticides, and fuel because decisions are based mainly on general observation rather than accurate data. AI and IoT systems enable farmers to apply inputs only where and when required. This not only reduces production costs but also minimizes environmental pollution and supports sustainable agriculture. Another important contribution of AI and IoT is automation. Labor shortages are becoming a serious problem in many agricultural regions because rural workers are shifting toward urban employment opportunities. Automated machinery and robotic systems help reduce dependence on manual labor and improve operational speed. Farmers can also monitor machinery and field conditions remotely through smartphones, computers, and cloud-based platforms, making farm management more convenient and efficient.

AI and IoT technologies are also improving decision-making in agriculture. Weather forecasting systems, crop monitoring sensors, and predictive analytics help farmers identify potential problems before serious damage occurs. Early detection of diseases, pest attacks, nutrient deficiencies, and irrigation stress allows timely corrective action and reduces crop losses. Predictive maintenance systems in machinery also help detect equipment problems before machine failure occurs, reducing repair costs and downtime. Despite their numerous advantages, the adoption of AI and IoT technologies in agriculture still faces several challenges. High installation costs, limited internet connectivity in rural areas, lack of

technical knowledge, and inadequate training facilities restrict the use of advanced systems among small farmers. Data privacy, cybersecurity, and infrastructure limitations are additional concerns associated with digital agriculture. However, continuous technological development, government support programs, and increasing awareness among farmers are gradually improving the adoption of smart agricultural technologies.

The future of agriculture will depend heavily on intelligent machinery and digital farming systems. AI and IoT technologies are expected to play a major role in improving agricultural productivity, conserving natural resources, reducing environmental impact, and ensuring food security for the growing global population. As agriculture continues to modernize, the integration of AI and IoT with agricultural machinery will become one of the most important foundations of sustainable and precision farming systems.

AI and IoT in Smart Tractors

Modern tractors are becoming intelligent machines equipped with GPS guidance systems, sensors, cameras, and artificial intelligence software. These smart tractors can perform operations with high accuracy and minimal human involvement.

GPS-guided tractors use satellite positioning systems to maintain precise movement across the field. This reduces overlap during ploughing, sowing, and spraying operations, saving fuel, seeds, fertilizers, and chemicals. AI systems further improve tractor performance by analyzing field conditions and adjusting machine operations automatically.

Autonomous tractors are one of the most advanced developments in agricultural mechanisation. These tractors can operate without drivers using AI, sensors, cameras, and navigation systems. Autonomous tractors follow programmed routes, avoid obstacles, and perform agricultural tasks independently.

AI and IoT in Precision Irrigation

Water management is becoming increasingly important because of declining groundwater resources and irregular rainfall patterns. AI and IoT technologies have significantly improved irrigation efficiency through smart irrigation systems.

IoT-based irrigation systems use soil moisture sensors, weather sensors, and water flow meters to collect real-time field data. AI algorithms analyze this information and determine the exact water requirement of crops. Irrigation systems then operate automatically according to crop needs.

Smart irrigation systems help reduce water wastage, prevent over-irrigation, and improve crop health. Farmers can monitor irrigation activities remotely through smartphones or computers. Automated irrigation also reduces labor requirements and electricity consumption.

AI and IoT in Crop Monitoring and Plant Protection

Crop monitoring and plant protection are among the most important activities in modern agriculture because crop productivity is highly affected by pests, diseases, nutrient deficiencies, and environmental stress conditions. In traditional farming systems, farmers mainly depended on manual field observation to identify crop problems. This method was time-consuming, labor-intensive, and often inaccurate because diseases or pest attacks were detected only after visible damage appeared in the field. Delayed identification frequently resulted in severe yield losses and excessive use of pesticides. The introduction of Artificial Intelligence (AI) and the Internet of Things (IoT) has significantly improved crop monitoring and plant protection by enabling real-time field observation, early problem detection, and precision application of chemicals.

AI and IoT technologies work together through the use of sensors, cameras, drones, wireless communication systems, and intelligent software. IoT devices installed in agricultural fields continuously collect information related to crop growth and environmental conditions. These devices monitor factors such as temperature, humidity, soil moisture, nutrient levels, leaf color, and pest activity. The collected data is transmitted through wireless networks to cloud-based platforms or computer systems where AI algorithms analyze the information and provide recommendations to farmers.

One of the most important applications of AI and IoT in agriculture is crop health monitoring. Healthy crops show specific patterns in leaf color, canopy structure, growth rate, and moisture condition. AI systems analyze field images and sensor data to identify abnormal crop conditions at an early stage. This allows farmers to take corrective action before problems spread throughout the field. Early detection is extremely important because diseases and pest attacks can spread rapidly and reduce crop productivity significantly if not controlled in time.

Drones equipped with high-resolution cameras and IoT sensors have become highly valuable tools for crop monitoring. These drones fly over agricultural fields and capture aerial images from different angles. Multispectral and thermal imaging technologies help detect crop stress that may not be visible to the human eye during normal field inspection. AI systems process these images and identify areas affected by water stress, nutrient deficiency, weed infestation, fungal infection, or insect attack.

For example, when crops experience nitrogen deficiency, leaf color gradually changes from dark green to pale yellow. AI image analysis systems can identify such color variations and notify farmers about nutrient deficiency before severe symptoms develop. Similarly, thermal imaging sensors detect temperature changes in plants caused by water stress or

disease infection. These technologies help farmers apply fertilizers and irrigation more accurately according to crop requirements.

AI and IoT technologies are also transforming weed management practices in agriculture. Traditional weed control methods often involve spraying herbicides uniformly across the entire field, even in areas where weeds are absent. This increases chemical wastage, production costs, and environmental pollution. Smart AI-based sprayers use cameras and sensors to identify weeds separately from crops. Once weeds are detected, the sprayer applies herbicides only to affected areas. This targeted spraying system reduces chemical usage while improving weed control efficiency.

Plant disease detection is another important application of AI in agriculture. Machine learning algorithms are trained using thousands of crop images showing different disease symptoms. When drones or cameras capture images of infected crops, AI systems compare them with stored data and identify specific diseases accurately. Farmers receive instant notifications regarding disease type, severity, and recommended control measures. Early disease identification helps reduce crop losses and prevents the spread of infection to healthy plants.

IoT-based weather monitoring systems further improve plant protection management. Weather conditions such as temperature, humidity, rainfall, and wind speed strongly influence pest and disease development. IoT weather stations continuously collect environmental data from the field. AI systems analyze these conditions and predict the possibility of pest outbreaks or disease spread. Farmers can then apply preventive measures before severe infestation occurs. Predictive plant protection systems reduce unnecessary pesticide application and improve crop safety.

Drone spraying technology is another major advancement in crop protection. Agricultural drones equipped with AI systems can spray pesticides and fertilizers rapidly and accurately over large areas. Drone sprayers maintain uniform chemical distribution and reduce human exposure to harmful pesticides. These systems are especially useful in difficult terrains, waterlogged fields, and tall crops where traditional spraying equipment faces operational difficulties.

AI and IoT technologies also improve sustainability in agriculture by reducing excessive chemical use. Precision spraying systems apply pesticides, fungicides, and fertilizers only where required, minimizing environmental contamination and preserving soil and water quality. Reduced chemical exposure also improves food safety and protects beneficial insects and microorganisms present in agricultural ecosystems.

Another important benefit of AI and IoT in crop monitoring is remote farm management. Farmers can monitor crop conditions through smartphones, tablets, and computers without physically visiting fields repeatedly. Real-time alerts regarding irrigation stress, disease symptoms, pest attacks, and machinery performance improve decision-making and save time. Remote monitoring is especially useful for large farms where continuous manual inspection is difficult.

Despite these advantages, several challenges still affect the adoption of AI and IoT technologies in crop monitoring and plant protection. High equipment cost, internet connectivity issues, lack of technical training, and data management problems limit adoption among small farmers. Advanced systems such as drones, sensors, and AI software require proper technical knowledge and maintenance for efficient operation. In many rural areas, inadequate digital infrastructure also affects system performance.

AI and IoT in Harvesting Machinery

Harvesting machinery has also become more intelligent with the integration of AI and IoT technologies. Modern combine harvesters use sensors and AI systems to monitor grain losses, crop yield, moisture content, and machine performance during harvesting.

Yield mapping systems collect data about crop productivity across different parts of the field. This information helps farmers identify low-yield and high-yield areas for better field management in future seasons.

AI-powered robotic harvesting systems are increasingly used for fruits and vegetables. Cameras and image-processing systems identify mature fruits, while robotic arms carefully pick crops without causing damage.

Advantages of AI and IoT in Agricultural Machinery

The integration of AI and IoT into agricultural machinery provides several important advantages. These technologies improve operational efficiency, precision, and sustainability in farming systems.

One major advantage is improved decision-making. AI systems analyze large amounts of agricultural data and provide accurate recommendations regarding irrigation, fertilizer application, pest control, and harvesting schedules.

AI and IoT also increase precision in agricultural operations. Smart machinery reduces overlap, minimizes input wastage, and improves resource utilization. Automated systems reduce labor requirements and improve operational speed.

Challenges of AI and IoT in Agricultural Machinery

Despite their advantages, AI and IoT technologies also face several challenges in agriculture. High installation and equipment costs limit adoption among small farmers. Advanced machinery and digital systems require significant investment and technical knowledge. Internet connectivity and electricity supply are also major concerns in rural areas.

IoT systems depend on reliable communication networks for data transfer and remote monitoring. In regions with poor infrastructure, system performance may be affected. Another challenge is the lack of technical training and support services. Farmers require education and training to use AI and IoT systems effectively.

Future Scope of AI and IoT in Agricultural Machinery

The future of agricultural mechanisation will be strongly influenced by AI and IoT technologies. Smart farming systems are expected to become more affordable, efficient, and widely available. Future machinery will increasingly operate autonomously with minimal human intervention.

Electric tractors, robotic weeders, AI-powered drones, and automated irrigation systems are expected to become more common in modern agriculture. Machine learning and big data analysis will further improve crop prediction, disease detection, and resource management.

Conclusion

Artificial Intelligence and the Internet of Things are transforming agricultural machinery and modern farming systems. These technologies improve precision, automation, efficiency, and decision-making in agriculture. Smart tractors, automated irrigation systems, AI-based sprayers, drones, and robotic harvesters are changing the way agricultural operations are performed.

The integration of AI and IoT with agricultural machinery represents one of the most important developments in modern agriculture. These technologies will play a major role in achieving sustainable food production, improving farm efficiency, and supporting the future growth of global agriculture.

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Tomato Surplus and Price instability in Bihar: A Sustainable Approach through Post-Harvest Management and Value Addition

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Rishika Kumari¹, Archana Kumari²

¹M.Sc. (Ag.) Agronomy, Department of Agriculture, Jharkhand Rai University, Ranchi.

²Faculty Associate, Department of Agriculture, Jharkhand Rai University, Ranchi.

Abstract

Tomato Cultivation plays a significant role in the agriculture economy of Bihar. Despite high production levels, farmers frequently face economic losses due to Surplus production, price price crashes, inadequate storage facilities, and limited processing infrastructure. The problem is not restricted to seasonal glut but also includes the persistent issue of non-remunerative prices. This paper examines the major challenges associated with tomato production and marketing and proposes sustainable solutions through post-harvest management, value addition, and institutional support. Establishing processing units, improving cold storage facilities, strengthening Farmer Producer Organizations (FPOs), and promoting branding strategies are identified as key interventions to stabilize farmer income and generate rural employment.

Keywords: Tomato cultivation, Price instability, post-harvest management, Value addition, Rural employment, Agribusiness development.

Introduction of Tomato

Tomato (*Solanum lycopersicum* L.) is one of the most important and widely cultivated vegetable crops in the world, valued for its nutritional richness, economic importance, and versatile culinary uses. It belongs to the family Solanaceae, which includes crops such as potato, brinjal, and chilly. Tomatoes are considered a protective food because they are rich in vitamins, minerals, antioxidants, and dietary fiber, making it an essential component of a healthy diet. It is widely consumed in fresh as well as processed forms and is used in salads, curries, soups, sauces, ketchup, puree, and juice.

Tomato originated in western South America and was later domesticated in Mexico before spreading to Europe and other parts of the world. In India, it was introduced during the British period and has become one of the most cultivated vegetable crops due to its adaptability to different climatic conditions and increasing market demand.

Tomatoes are a herbaceous annual plant that produces fleshy berry-type fruits, generally red in color when ripe due to the presence of lycopene, a natural antioxidant. It contains about 94-95 percent water and is a rich source of vitamin C, vitamin A, potassium, calcium, and phosphorus. Lycopene present in tomatoes is known for its health benefits, including reducing the risk of heart disease and certain cancers. Regular consumption of tomatoes also improves immunity, digestion, and skin health.

Economically, tomatoes are one of the most profitable vegetable crops because of its short duration, high yield potential, and continuous demand throughout the year. India is the second-largest producer of tomato in the world after China, and Bihar is one of the important tomato-producing states in eastern India. Districts such as Nalanda, Patna, Vaishali, and Samastipur are major tomato-growing regions in Bihar.

In conclusion, tomato is an essential vegetable crop with high nutritional, economic, and agricultural significance, contributing greatly to food security and farmer income.

Problem Statement

Tomato farming is widely practiced due to its high productivity and demand, yet farmers face serious economic challenges. The major problem arises during peak harvesting seasons when a large quantity of tomatoes enters the market at the same time. This creates a surplus situation where supply exceeds demand, leading to a sharp decline in market prices. In many cases, farmers are forced to sell their produce at prices lower than the cost of production, resulting in heavy financial losses.

Another key issue is the dominance of middlemen in the marketing system. Most farmers, especially smallholders, do not have direct access to organized markets and depend on local traders. Due to limited bargaining power, lack of market information, and urgent need for cash, farmers often accept low prices, while intermediaries earn higher profits. This imbalance reduces farmers' income and discourages sustainable production.

Poor post-harvest infrastructure further worsens the situation. Tomatoes are highly perishable and require proper handling, storage, and transportation. However, the absence of cold storage facilities, grading, and scientific packaging leads to significant losses.

Traditional methods of transport and poor road connectivity increase spoilage during transit. As a result, post-harvest losses can reach up to 20-30 percent.

Additionally, the lack of food processing industries limits the use of surplus tomatoes. Instead of converting excess produce into value-added products like puree or sauce, a large portion goes to waste. Farmers also lack awareness and training in post-harvest management and value addition.

Overall, the problem lies in surplus production, weak market systems, inadequate infrastructure, and limited processing facilities, which together reduce farmers' profitability and sustainability.

Strategies for Managing Tomato Surplus in Bihar

Tomato surplus and price instability have become major concerns for tomato farmers in Bihar, often leading to severe financial losses during peak harvesting seasons. Bihar is one of the major tomato-producing states in eastern India, with districts such as Nalanda, Patna, Vaishali, Samastipur, and Muzaffarpur contributing significantly to production.

However, due to overproduction, inadequate storage facilities, poor transportation, and weak market infrastructure, farmers frequently face market glut and sudden price crashes. Therefore, effective and sustainable solutions are necessary to manage tomato surplus and ensure stable prices for farmers.

One of the most important solutions is the development of cold storage facilities specifically designed for vegetables. Since tomatoes are a highly perishable crop, it deteriorates quickly after harvesting if not stored properly. In Bihar, the majority of available cold storage units are used for potato storage and are not suitable for tomatoes. As a result, farmers are forced to sell their produce immediately after harvesting, even when prices are low.

Establishing cold storage units in major tomato-producing areas would help farmers preserve tomatoes for a longer period and avoid distress selling during market glut. This would allow them to wait for better prices and reduce post-harvest losses.

In conclusion, tomato surplus and price instability in Bihar can be effectively managed through cold storage development, promotion of processing industries, better transportation, collective marketing through FPOs, and market diversification. These measures can reduce post-harvest losses, improve price stability, and enhance farmer income. A coordinated effort from government, farmers, private investors, and agricultural institutions is essential to build a sustainable and profitable tomato supply chain in Bihar.

Economic and Social Impact of Post-Harvest Management of Tomato

Post-harvest management is an essential aspect of tomato production that helps maintain fruit quality, reduce spoilage, and increase profitability for farmers. Tomatoes are a highly perishable vegetable crop due to their high moisture content, delicate skin, and soft texture, which make it prone to rapid deterioration after harvesting. In Bihar, where tomato is cultivated extensively in districts such as Nalanda, Patna, Vaishali, Samastipur, and Muzaffarpur, poor post-harvest handling often results in significant losses. Therefore, efficient post-harvest management is necessary to preserve tomato quality and ensure better market returns.

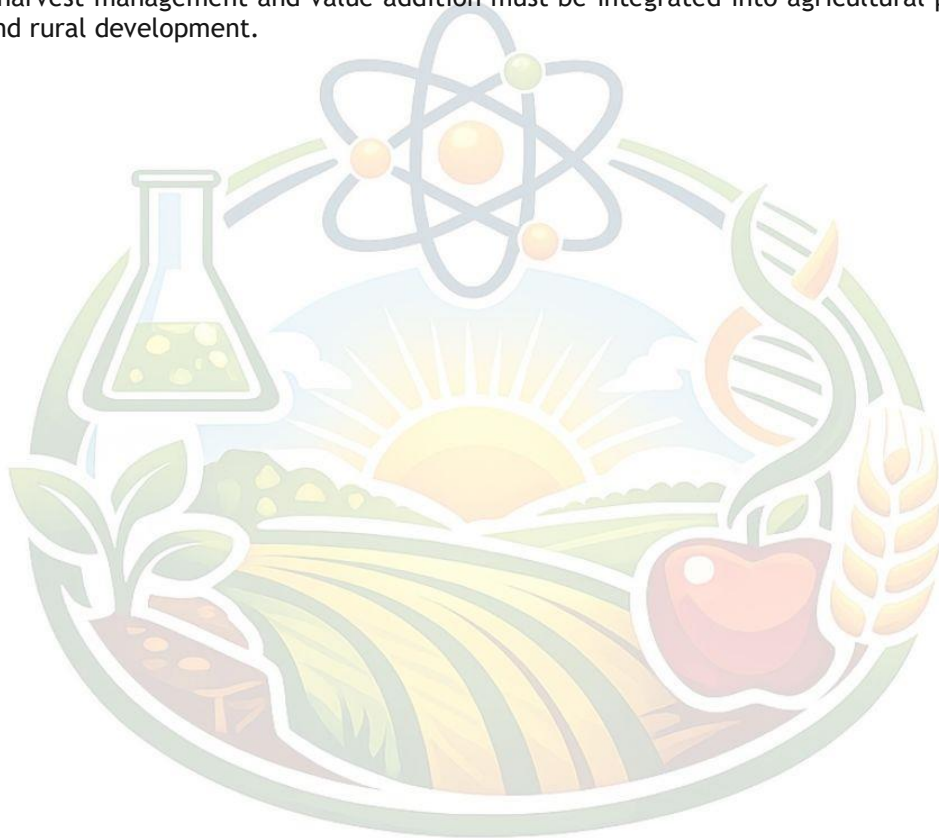
1. The first step in post-harvest management is harvesting at the proper stage of maturity. Tomatoes intended for distant markets should be harvested at the mature green or breaker stage, while those local markets may be harvested at the pink or fully ripe stage. Harvesting should preferably be done during the cooler hours of the day, such as early morning or late evening, to reduce field heat and slow down respiration. Careful handling during harvesting is important to prevent bruising, cracking, or cuts, as damaged fruits spoil more quickly.
2. After harvesting, tomatoes should be sorted and graded. Sorting involves removing damaged, diseased, and overripe fruits, while grading is done based on size, shape, color, and quality. Grading improves uniformity and market appeal, helping farmers obtain better prices. However, many farmers in Bihar sell mixed-quality tomatoes without grading, which lowers the overall market value of the produce.
3. Cleaning is another important step in post-harvest handling. Tomatoes should be washed with clean water to remove dirt, dust, and pesticide residues. Clean produce is more attractive to consumers and has better market demand. In advanced systems, chlorinated water may be used to reduce microbial contamination and improve shelf life.
4. Packaging plays a crucial role in protecting tomatoes during storage and transportation. Traditional packaging methods such as bamboo baskets, gunny bags, and plastic sacks are still widely used in Bihar, but these often lead to bruising and crushing. Scientific packaging using ventilated plastic crates or corrugated boxes is more effective in reducing physical damage and maintaining freshness. Proper packaging also improves ventilation and prevents overheating of the fruits.
5. Transportation is another critical factor affecting post-harvest quality. Tomatoes are often damaged during transport due to rough roads, overloading, and improper stacking in vehicles. To minimize losses, tomatoes should be transported in well-ventilated vehicles and handled carefully during loading and unloading. Better road connectivity and improved transportation facilities can help reduce transit damage and ensure timely delivery to markets.

6. Storage is important in extending the shelf life of tomatoes and reducing distress sales. Under normal room temperature, tomatoes remain fresh for only a few days. However, when stored at 12-15°C with 85-90 percent relative humidity, their shelf life can be extended up to two to three weeks. In Bihar, the lack of vegetable-specific cold storage facilities forces farmers to sell immediately after harvest, even when market prices are low. Expanding cold storage infrastructure can help reduce losses and stabilize tomato supply.

7. Value addition through processing is another important component of post-harvest management. Tomatoes can be processed into products such as ketchup, sauce, puree, paste, and dried tomato products. Processing helps utilize surplus production, reduces wastage, and provides farmers with additional market opportunities.

Conclusion

The crisis faced by tomato farmers is not solely due to surplus production but also due to structural weaknesses in marketing and post-harvest systems. Increasing production without strengthening storage and processing infrastructure leads to recurring economic distress. A farm-to-processing-to-market approach is essential for sustainable agricultural development. Post-harvest management and value addition must be integrated into agricultural policy to ensure long-term profitability and rural development.



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Technology- Driven Precision Cultivation of Vegetables

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Debiya Leitanthem¹, Osi Siram²

¹Ph.D. Research Scholar, Department of Horticulture (Vegetable Science), College of Agriculture, Central Agricultural University, Imphal-795004, Manipur.

²Ph.D. Research Scholar, Department of Agronomy, College of Agriculture, Central Agricultural University, Imphal-795004, Manipur.

Introduction

Production of vegetables is a uniquely high-risk and capital-intensive sector that demands more rigorous management than other agricultural enterprises. To thrive, growers must master both financial and marketing strategies while flawlessly executing a complex production system. This comprehensive process spans from the initial selection of crops and varieties to precise soil preparation, irrigation and integrated pest management, ultimately concluding with the specialized handling and sales of the final harvest. Precision farming, also popularly known as precision agriculture, focuses on enhancing crop productivity, reducing input costs and mitigating the environmental footprint of agricultural practices (Narayan and Narayan, 2014). Essentially, it represents an integrated approach that employs crop data, advanced technologies and efficient management strategies to optimize and manage agricultural production while minimizing associated risks. The fundamental idea behind precision agriculture is that different areas within the same field vary in terms of soil characteristics, nutrient composition, moisture content and microclimatic conditions. To assess and manage these spatial differences, advanced tools such as Global Positioning Systems (GPS), Geographic Information Systems (GIS), remote sensing and sensor networks are utilized for real-time mapping and monitoring of field variability (Grisso *et al.*, 2009). Site-specific crop management (SSCM) is also a branch of precision agriculture that optimizes decisions on resource application and agronomic practices by aligning them more precisely with the field-specific variations in soil and crop requirements. In recent years, precision farming centers around the later strategies that actively take notice of the spatial variability of the land in order to mitigate ecological damage while boosting agricultural productivity (Mahanta *et al.*, 2024).

Smart Technologies in Enhancing Vegetable Production

1. Global Positioning Systems (GPS)- It is a computer-based technique that relies heavily on satellites. GPS satellites broadcast signals enabling receivers to compute their position in real time providing ongoing location data during movement. This precise, on-demand location information facilitates mapping of crop, soil and water measurements (Shanwad *et al.*, 2002). It is widely utilized in yield mapping and variable rate fertilizer/pesticide application. Harvester travel speed and material flow rate are recorded during yield mapping. Using GPS, farmers can assure that every inch of their field is effectively utilized, avoiding waste and improving yield (Neményi *et al.*, 2003).

2. Geographic Information Systems (GIS)- Geographic Information Systems (GIS) provide a versatile toolkit for storing, retrieving and editing spatial data for numerous purposes. For farming professionals, its capacity to analyse, visualize agricultural landscapes and processes proves particularly valuable (Mani *et al.*, 2021). Its applications encompass crop yield estimation and forecasting, soil fertility assessment, analysis of cropping patterns and agricultural monitoring, evaluation of drought conditions and detection/control of pests and crop diseases (Saha, 2023).

3. Remote sensing- Remote sensing is the process of gathering information on crops and fields from a distance, usually using satellite pictures or sensor-equipped drones. Farmers may take the help of remote sensing to get crucial information about crop health, soil moisture levels and nutritional deficits. It assists farmers to enhance crop yields and save input costs by using this data to make well-informed decisions about irrigation, fertilization and pest management (Chaudhari *et al.*, 2024). This technology is mainly incorporated in soil and drainage maps, weed management, water and nutrient stress and forecasting of yields with NDVI data.

4. Variable Rate Technology (VRT): VRT is a method employed for the precise application of various agricultural inputs, including seeds, fertilizers, irrigation water and tillage, tailored to the specific requirements of different management zones within agricultural fields (Pawase *et al.*, 2023). It may adopted in two methods- the sensor-based and map-based approach. Through the use of VRT, specific field locations receive tailored nutrient doses, leading to better harvest and a smaller environmental footprint.

5. Yield monitors: These are harvesting equipment-mounted agricultural yield measurement devices. The monitor records and stores yield data at regular intervals, coupled with GPS data. GIS software uses yield data to create the yield maps (Nabi *et al.*, 2017).


Fig: Mapping of Crops with GIS

Fig: VRT Pesticide application

Precision Management of Soil, Water and Nutrient Resources

Farmers exploit specialized mapping techniques to overcome soil variability for management of field inputs efficiently. Soil Maps through Grid Sampling involves dividing a field into uniform squares to collect samples. However, a single grid may consist of multiple soil types, leading to inaccurate data. To increase precision, smaller grids must be used even if it significantly increases the labour and cost of sampling. Drainage Maps can be made with CIR Imagery. Color infrared (CIR) aerial photography identifies hidden underground drainage tiles by detecting moisture levels. In these images, dry soils reflect more light than wet soils.

By filtering out soil-type interference, experts can digitize and geo-reference these photos to point out the exact locations of tile lines and identify any blockages or malfunctions. Integration of soil moisture sensors along with real-time weather data in precision irrigation, allows farmers to apply water with assured accuracy targeting the exact location and timing a plant requires. This data-driven approach eliminates unnecessary waste and conserves water resources while simultaneously promoting healthier and more optimized crop development (Yan *et al.*, 2020). Similarly, precision fertilization is utilized by diagnosing the nutrient levels of crop and soil. Then, supplying the crops with fertilizer and nutrients in precise quantity according to the needs of the plant and area.

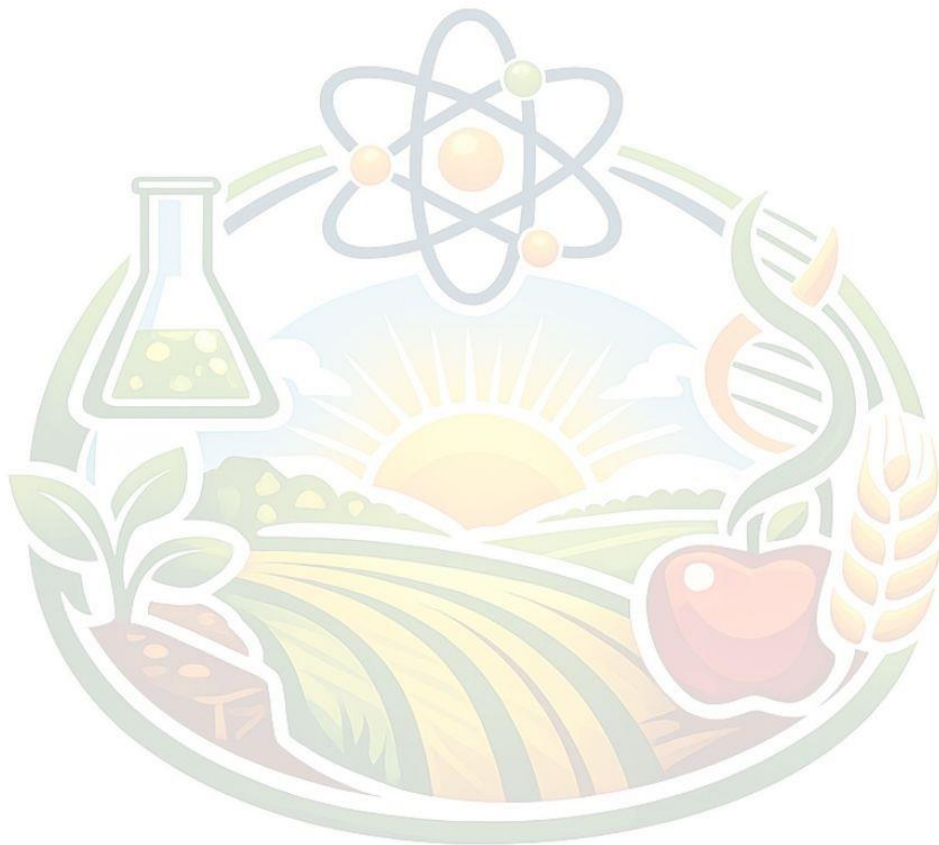
Constraints of Precision Vegetable Farming

Adoption of precision vegetable farming faces several main hurdles which primarily involve financial and structural barriers like high equipment costs, limited credit and small land sizes. Additionally, knowledge gaps including a lack of technical skills, package of practices and limited research support along with resource shortages like labour, water and pumping inefficiency which hinder its progress. These issues are further supplemented by market challenges, such as low prices of vegetables and the hesitation of many farmers regarding the effectiveness of reduced input levels.

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When the Pacific Warms, India Thirsts: Super El Niño 2026 and the Threat to India's Monsoon and Agriculture

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Avinash C¹, Shevakula Manasa¹

¹Ph.D. Scholar, Division of Environmental Sciences, ICAR - Indian Agricultural Research.

Abstract

The El Niño-Southern Oscillation (ENSO) is among the most consequential climate drivers affecting Indian agriculture and food security. In 2026, the World Meteorological Organization (WMO) and the India Meteorological Department (IMD) raised high-confidence alerts about the emergence of a Super El Niño. It is characterized by sea surface temperature (SST) anomalies exceeding +2.0°C in the central equatorial Pacific. IMD projects the 2026 Southwest Monsoon at 92% of the Long Period Average (LPA), with a 35% probability of a deficient season, more than double the historical baseline of 16%. This article discusses current forecast data, scientific studies, and historical analogues to assess the threat to Indian agriculture and monsoon, while identifying moderating factors and evidence-based adaptive strategies.

What is El Niño and Super El Niño?

“After a period of neutral conditions, climate models are now strongly aligned. There is high confidence in the onset of El Niño, followed by further intensification.”

- Wilfran Moufouma Okia, Chief of Climate Prediction, WMO (April 2026)

El Niño is a periodic climate phenomenon driven by abnormal warming of sea surface temperatures (SSTs) in the central and eastern equatorial Pacific Ocean, and it is a warm phase of the El Niño-Southern Oscillation (ENSO). Under normal conditions, easterly trade winds drive warm surface water toward Australia, sustaining moisture-laden monsoon winds over South Asia. During El Niño, these winds weaken, allowing the warm water mass to drift eastward, ultimately disrupting precipitation patterns across the Indo-Pacific region.

Super El Niño is defined by SST anomalies exceeding +2.0°C above the 1991-2020 climatological baseline in the Niño 3.4 region (5°N-5°S, 170°W-120°W; the primary area in the central Pacific used to monitor ENSO) – far beyond the +0.5°C threshold for a standard El Niño event. Cai et al. (2021) demonstrated that the frequency and intensity of extreme El Niño events are increasing under a changing climate and global warming, with the probability of such events projected to roughly double in a 2°C warmer world. Azad & Rajeevan. (2016) showed that the ENSO-monsoon inverse relationship may intensify in future warming scenarios, with the spectral signature shifting to shorter 3-5 year periodicities.

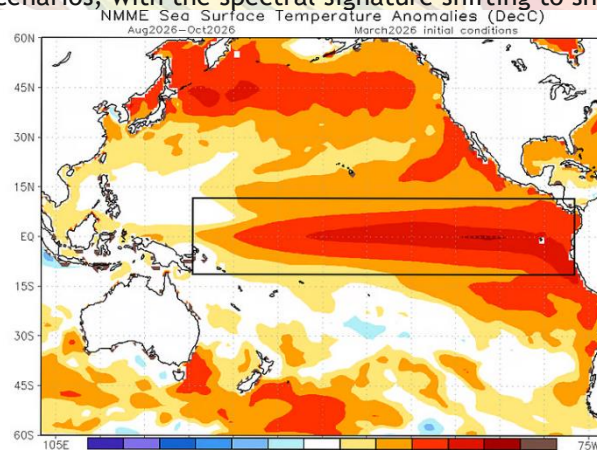


Figure 1. Sea Surface Temperatures Forecast for the El Niño phenomenon in the Equatorial Pacific Ocean from August to October 2026 (Source: Akshit, 2026)

The Super El Niño: Current Status

As of April 2026, ENSO remains in a neutral phase following the end of the 2025-26 La Niña. However, rapidly rising subsurface heat and near-average SSTs in the equatorial central Pacific are strong precursors to El Niño development. NOAA. (2026) predicts a 61-70% probability of El Niño occurring between June and August 2026, persisting through year-end.

NASA's GISTEMP data confirms March 2026 as one of the hottest months ever recorded, with global mean temperatures approximately 1.27°C above the 1951-1980 baseline (NOAA, 2026). India had already recorded 60% below-normal rainfall

in January-February 2026, and IMD issued heatwave alerts across Punjab, Haryana, Delhi, Rajasthan, Uttar Pradesh, Madhya Pradesh, Bihar, and Odisha.

Impact on the Southwest Monsoon in India

Southwest Monsoon (June-September) gives nearly 70% of the annual rainfall and supports 60% of the country's crop-growing area. Athira et al. (2023) studies confirmed significant spatial asymmetry, that the central and peninsular India face severe deficits during El Niño, while parts of the northwest show atypical responses modulated by the Indian Ocean Dipole (IOD) and Pacific Decadal Oscillation. The IOD is a climate pattern involving alternating SSTs between the western and eastern Indian Ocean that impacts regional weather.

According to IMD, the April 2026 forecast, India is expected to receive around 92% of the LPA rainfall during the monsoon season, which is about 800 mm compared to the normal average of 868 mm. This is considered one of the weakest initial monsoon forecasts in the last 26 years. IMD also estimated a 35% chance of a deficient monsoon season, much higher than the historical average of 16%. Similarly, Skymet Weather predicted monsoon rainfall at 94% of LPA and warned that El Niño conditions may become stronger during August-September 2026.

Table 1. Major El Niño Events' Impact on Indian Monsoon Rainfall and Agriculture:

Event	Rainfall (% LPA)	Key Agricultural Impact
1982-83	81%	Severe drought; widespread crop failures
2002-03	81%	Foodgrain output fell approximately 18 MT
2009-10	78%	Worst drought in 37 years; sugarcane & rice most affected
2015-16 (Super El Niño)	86%	Widespread drought; Agricultural GVA +0.7% (buffered by irrigation & MSP)
2026 (Forecast)	-92% (IMD)	35% probability of a deficient season; Kharif crops at risk

Sources: IMD, 2026; Parvati et al., 2024; Iizumi et al., 2014.

Cascading Effects on Indian Agriculture

Agriculture contributes 18% of GDP and supports 70% of its population. More than 50% of the farmed area is rainfed. Subash et al. (2023) confirmed that rice, soybean, maize, and groundnut yield in India were significantly reduced in drought-stress regions during El Niño episodes.

1. Crop yield losses: Parvati et al. (2024) reported that during the warm ENSO period, rice production in India decreased by an average of 3.4 million tonnes (7%). Iizumi et al. (2014) found that El Niño causes yield reductions across 22-24% of global harvested area, with India particularly in rice, wheat, and pulse crops.

2. Food inflation: According to ICRA, inflation measured by the Consumer Price Index (CPI) may rise to around 4.5-5.0% in FY27 if monsoon conditions remain weak. Food inflation alone could increase by up to 0.4% due to crop failures in rain-fed agricultural areas. The RBI has officially described El Niño as “upside inflation risk,” which could further increase prices.

3. Water and power stress: Reduced reservoir inflows will cut hydroelectric output and increase electricity demand for groundwater pumping. Chakraborty & Singhai. (2021) study showed that the asymmetric response of the Indian Summer Monsoon to ENSO positive phases is stronger during concurrent warm Indian Ocean conditions, a scenario likely in 2026.

Moderating Factors

Indian Ocean Dipole (IOD): A positive IOD tends to partially counteract El Niño's drying effect on India. IMD confirmed that a positive IOD is likely to develop in the second half of the monsoon, supporting August-September rainfall.

Weakening transmission channel: Elara Capital (2026) showed that during 1982-2002, six out of seven El Niño events negatively affected agricultural Gross Value Added (GVA), but since 2004, only two out of seven events have caused such damage. This reduced impact is mainly due to better irrigation facilities, Minimum Support Price (MSP) support, and crop insurance schemes. According to NABARD (2022), income from cultivation now contributes only about one-third of total rural household income, while the remaining income comes from wages, livestock activities, non-farm businesses, and government support programs.

Adaptive Strategies

1. Crop diversification: Skymet and IMD urge farmers to avoid water-intensive paddy in deficit-forecast regions and shift to drought-tolerant millets, short-duration pulses, and oilseeds. Patel et al. (2014) demonstrated in Gujarat that crop switching during El Niño phases significantly stabilised farm incomes.

2. Micro-irrigation expansion: Drip and sprinkler systems reduce water use by 30-50%. India's solar irrigation scheme (PM-KUSUM) can simultaneously address water stress and rising energy costs, a dual dividend during El Niño years.

3. Strengthening PMFBY coverage: Pradhan Mantri Fasal Bima Yojana must be extended to coarse cereals, pulses, and oilseeds (the crops with the highest El Niño vulnerability).

4. ICT-based advisory: IMD's Gramin Krishi Mausam Sewa and district-level agrometeorological advisory services can enable timely sowing decisions, protecting yields even in a challenging monsoon.

Conclusion

The developing Super El Niño of 2026 poses a serious threat to India's monsoon system, agricultural productivity, food security, and rural economy. Historical evidence and current climate forecasts indicate an increased probability of rainfall deficits, crop losses, food inflation, and water stress, particularly in rainfed regions. However, improved irrigation infrastructure, crop insurance, diversified rural livelihoods, and early-warning systems may reduce the severity of impacts compared to past El Niño events. Strengthening climate-resilient agriculture through crop diversification, micro-irrigation, and ICT-based advisories will be essential for safeguarding farmers' livelihoods and ensuring national food security under increasing climate variability.

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Dry Flowers - Forever in Bloom: India's Growing Dry Flower Sector: Techniques, Products, and Potential

Article ID: 73718

K. Priyanka¹, X. M Rofica xavier¹, J. Purushothamman², Senthilkumar A³

¹B.SC. (Hons.) Agriculture Students, The Indian Agriculture College, Radhapuram.

²Assistant Professor (Hort.), The Indian Agriculture College, Radhapuram.

³Assistant Professor (Soil Science), The Indian Agriculture College, Radhapuram.

“From cradles bloom to funerals wreath, flowers walk with human breath”. Flowers are delicate, colorful structures that perfectly capture the splendour of nature. Flowers have cultural, emotional, and ecological significance in addition to their aesthetic value. They have been used for millennia to express feelings that cannot be expressed verbally and in rituals and festivities.

“Flowers grace each step of life, from first hello to final goodbye”. Freshly cut flowers are stunning and striking, but even with the greatest chemicals, they are difficult to maintain over extended periods of time. The same flower and leaves can be dried using a variety of drying techniques to increase their beauty and aesthetic significance in order to get around this problem.

Simple drying methods can produce dry flowers by reducing the water content while preserving the colour and shape of the flowers to the greatest extent possible. The drying techniques produce flowers, foliage, and other products that can be successfully used to prepare a variety of floral decorations and craft items.

India's Status with Dry Flowers

One of the leading countries in this sector is India. It is a promising post-harvest technology that can be used to enhance the ornamental qualities of plant and floral parts.

India has abundant natural resources, including a diverse range of flora, which presents a significant opportunity for the dried flower sector. It guarantees that the different ornamental goods are of the highest quality from a functional, physical, and sensory perspective while using the least amount of energy.

India is blessed with abundant biodiversity. There are many different types of decorative trees, shrubs, climbers, herbaceous plants, fleshy mushrooms, lichens, mosses, and more in the Indian flora.

Dry Flower Product

In India alone, potpourri is the largest segment of the dried flower market, with a valuation of 55 crores. Typically, it is a blend of dried, sweet-smelling plant parts that include stems, roots, leaves, blossoms, and seeds.

The fragrant oils found in plants are the source of potpourri. Perfuming herbs include scented geranium, mint, marjoram, verbena, anise, fennel, achillea [yarrow], rosemary, sage, lavender, artemisia, thyme, and basil.

The fruits and plants should be completely dried while drying. Otherwise, powdery mildew will become an issue.

Flowers that have been dried and compressed can be utilized to make home decor items. When used properly, they can be used to create decorative wall hangings, greeting cards, covers, floral cards, floral patterns, flower balls, calendars, festive decorations, and other artistic displays.

Dry flower products can be used to create floral albums for botanical studies that involve plant identification. a small-scale or cottage business that uses dehydrated foliage, blossoms, fruits, pods, seeds, and other plant parts to create evaporate flower home decor items in an inconspicuous manner.

Products made from dried flowers can be arranged artistically and shielded from dust, wind, and ambient humidity by covering them with plastic or clear glass.

Products that have been dehydrated and sealed in a glass container can be utilised as interior decor. In order to gain the advantage of value addition, the dried flower sector can be linked to several secondary industries, such as candles, ribbon and laces, brass, etc., by working together.



Why Do Dry Flowers Still Bloom Beyond Time?

Dried flowers look beautiful and can keep longer than fresh flowers in a vase, but they also require less care. The cost of exquisitely arranged dried flowers may be slightly higher, but they are quite durable and may even last for many years.

The ability to remain intact and be cherished for years is what makes dried flowers so alluring.

Egyptians placed dried flowers in graves and utilized them to make scent. In middle age, they were utilized as medications.

Victorian women used dried flowers and created floral garlands. Flowers are still dried to create art and preserve memories for use in unique jewel designs.

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The Hidden Enemy of Okra: Biology and Integrated Management of the Shoot and Fruit Borer, *Earias vittella* (Fabricius)

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Ishika Agrahari¹, Mukesh Kumar Mishra², Raju Kumar Verma³

¹M. Sc. Scholar, Department of Entomology, Banda University of Agriculture and Technology, Banda 210001, U.P., India.

²Assistant Professor, Department of Entomology, Banda University of Agriculture and Technology, Banda 210001, U.P., India.

³Research Scholar, Department of Entomology, Banda University of Agriculture and Technology, Banda 210001, U.P., India.

Abstract

Okra (*Abelmoschus esculentus* L.), known as lady's finger or bhindi, is a nutrient rich vegetable, belonging to the Malvaceae family. It is very commonly cultivated during the *Kharif* season and in summers in the tropical and subtropical regions of India, where it suffers significant damage from the shoot and fruit borer, *Earias vittella* and *E. insulana* (Lepidoptera Noctuidae), which can cause up to 70% loss. The life cycle of *E. vittella* lasts 35-40 days, beginning with an embryonic stage of 3-5 days, followed by six larval instars with an incubation period of 12-18 days during which the larva bore into shoots and fruits, then 7-10 days as pupae, and occasional emergence of small ochreous-white moths at temperatures between 25-28°C. Integrated Pest Management (IPM) combines several techniques, including cultural practices, mechanical traps, biological control, and chemical control. For Okra, recommended protection measures include the use of pheromone traps, the biological activity of *Trichogramma chilonis*, spraying Neem Seed Karnal extract at 45 days after sowing, and applying an appropriate insecticide at days after sowing.

Introduction

Okra (*Abelmoschus esculentus* L.) is a popular vegetable crop, also known as lady's-finger or bhindi, and belongs to the family Malvaceae. It is an Ethiopian vegetable called the "Queen of Vegetable's" widely cultivated in tropical and subtropical regions. The warm - season crop requires a prolonged warm environment, and is grown during the *Kharif* and summer seasons. Okra is an excellent source of vitamins A, B, and C and contains essential minerals such as calcium, phosphorus, potassium, iron, and iodine as well as proteins, carbohydrates, fats, dietary fiber, antioxidants, ascorbic acid, and folate. Due to its nutritional and economic importance, it plays a significant role in both household consumption and market trade. Despite its value, okra is highly susceptible to insect pests throughout its growth stages. More than 70 insect species have been reported to attack okra. Among these, the shoot and fruit borer, *Earias vittella* (Fabricius) (Lepidoptera: Noctuidae), also known as the spotted bollworm, is considered the most damaging pest. This pest causes significant yield losses, up to 70%, by damaging shoots and fruits at various crop stages. Infestation typically begins early in the crop cycle, with reported damage ranging from 21.33% to 43.99% in shoots and 21.00% to 51.30% in fruits. Symptoms include withered, drooping terminal shoots, shedding of buds boreholes in fruits, deformed and stunted growth, and larvae feeding inside shoots and bolls, leading to premature drop and potential fungal infections, which cause a significant decline in yield.

Taxonomic Classification of Okra Shoot & Fruit Borer

Kingdom: Animalia

Phylum: Arthropoda

Class: Insecta

Order: Lepidoptera

Family: Noctuidae

Scientific name: *Earias vittella* (Fabricius).

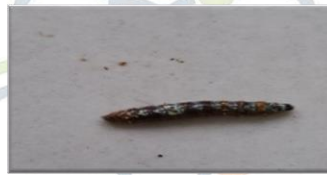
Life cycle: The insect undergoes four developmental stages to complete its life cycle, namely egg, larva, pupa, and adult.

Egg: Oviposition occurs at night, the female lays 2-3 eggs singly or in clusters on tender leaves, fruits, shoot tips, or flower buds, usually on the undersurface. The fecundity of a female is 200-400 eggs. Eggs are spherical, bluish or greenish, crowned and sculpted on the surface. The incubation period is 3-5 days.



Egg of *Earias vittella*

Larva (Caterpillar): After hatching from eggs, young larvae are light creamy white with dark brown head capsule and bore into shoots, causing wilting. In later stages, they attack buds, flowers, and fruits, which show holes plugged with excreta. A full grown larva is about 16-20 mm long, brownish with longitudinal white streaks on the dorsal side of the body, and has three pairs of legs on the thoracic segments. There are six larval instars, and total larval development takes 12-18 days.



Larvae

Pupa: Mature larvae stop feeding, become sluggish, and contract. They pupate on the plant or rarely in the soil among fallen leaves, making a boat-shaped, grayish silken cocoon about 8 to 13 mm in length for pupation. The pupa is pale to dark brown, stout and formed inside the cocoon. The pupal period is 7-10 days.



Pupa

Adult: Adult moths emerge during the night or early morning hours. They are small, with a head and thorax ochreous white, and measure 13-15 mm in length. The forewings are pale white with a broad wedge-shaped horizontal green patch in the middle. The hind wings are creamy white. Males and females are distinguished by size (males smaller than females) and by the female having a V shape at the end of the anal part, while male has thick hairs at the anal end. The total life cycle is about 35-40 days, and five to six overlapping generations completed in a year. Warm and humid weather with an optimum temperature of 25°C to 28°C favors growth and development.



Adult

Damage Symptoms: The caterpillar damages plants by boring into tender terminal shoots during the vegetative stage and into tender fruits during fruit formation. Damaged shoots exhibit wilting, drooping, and drying of the top portion. In fruits, larvae feed inside creating small circular holes filled with excreta, which deform and discolour the fruits, unfit for consumption. Buds and flowers also show borehole symptoms leading to their shedding. In cases of severe infestation, plants become weak and show stunted growth. Both quality and quantity of fruit production are reduced.


Damage symptom

Infested fruit

Integrated Pest Management Strategies

Cultural Method:

- Remove and destroy infested fruits, shoots, buds, and flowers to reduce the larval population in the field.
- Remove alternate hosts such as *Hibiscus cannabinus*, *H. abelmoschus*, and *Abutilon indicum*.
- Grow resistant varieties such as AE 57, PMS 8, Parkins Long Green, PKX 9275 and Karnal Special.
- Avoid continuous planting of Malvaceous crops (cotton, okra) to break the pest cycle.

Mechanical Method:

- Set up light traps to monitor moths and their egg laying @ 12per hactre.
- Install pheromone traps @10-12 per hectare to monitor and mass-trap adult males, changing lures every 15-20 days.
- Install bird perches @10 per acre to encourage predatory birds.

Biological Method:

- Release egg parasitoid *Trichogramma chilonis* @ 1.0-1.5 lakh per hactre and larval parasitoid *Chelonus blackburnii*.
- Release first instar larvae of *Chrysoperla carnea* @ 1 lakh/ha.
- Apply *Bacillus thuringiensis* @ 2 g/liter or *Beauveria bassiana* @ 5-10 ml/liter to control larvae.

Chemical Method:

- Spray Neem Seed Kernel Extract (NSKE) 5% or Azadirachtin 0.03%.
- The most effective, modern and high-performing insecticides include:
- Spray Emamectin benzoate 5% SG @ 3.0 g/10 L or Flubendiamide 39.35% SC @ 40-50 ml/acre or Spinetoram 11.7% SC @ 168-188 ml/acre or Indoxacarb 14.5% SC @ 200 ml/acre or Chlorantraniliprole 18.5% SC @ 60 ml/acre.
- Spray the chemical in evening hours and rotate insecticides to prevent resistance development. Avoid synthetic pyrethroids to prevent pest resurgence.

Recommended IPM Module

Pheromone trap (10/ha) + *T. chilonis* (1 lakh/ha) + 5% NSKE at 45 DAS + first insecticide spray at 60 DAS.

Conclusion

The shoot and fruit borer, *Earias vittella* (Fabricius), remains one of the most significant constraints in okra cultivation due to its continuous infestation and high yield loss potential. This rapid life cycle and overlapping generations make keep chemical control alone neither effective nor sustainable. Combining cultural, mechanical, biological, and chemical methods provides effective and eco-friendly control with an integrated pest management approach. Key practices include removing infested plant part, using pheromone traps, releasing natural enemies, applying biopesticides, and using selective insecticides as needed. Adoption of this recommended IPM module ensures sustainable okra production with improved yield and quality, as well as enhanced environmental safety.

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Uses of Remote Sensing, Geographic Information Systems, and Artificial Intelligence in Agriculture

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Veegala Ramesh Babu¹, Pandurang Raghunath Divte¹, Lavanya A. K¹

¹I.C.A.R- Central Research Institute for Jute and Allied Fibres, Barrackpore, Kolkata 700121, West Bengal, India.

Introduction

Modern agriculture is increasingly adopting advanced technologies to improve productivity, reduce costs, and ensure sustainable use of natural resources. Among these technologies, Remote Sensing (RS), Geographic Information Systems (GIS), and Artificial Intelligence (AI) play an important role in transforming traditional farming into smart and precision agriculture. The integration of Remote Sensing, GIS, and AI has revolutionized agriculture by enabling precision farming, better resource management, early warning systems, and data-driven decision-making. These technologies help increase crop production while minimizing environmental impacts, making agriculture more efficient, profitable, and sustainable for the future.

Remote Sensing (RS) and Geographic Information Systems (GIS) in Agriculture

Agriculture is one of the major sectors in Indian economy. India being a world's largest producer of rice, wheat and pulses, must keep up its pace with growing digital technologies. Over the past few decades, Remote Sensing and GIS have grown exponentially in many sectors for visualisation, monitoring, management and potential development. Remote Sensing and GIS technology enable agencies to get reliable information of natural and man-made features, or processed and interpreted appropriately phenomenon occurring over the earth's surface without making any physical contact. Nowadays, farmers rely on these technological improvements.

Remote Sensing (RS)

Remote Sensing is the science of collecting information about the Earth's surface without direct contact, using satellites, drones, or aircraft. In agriculture, it is widely used to monitor crops and environmental conditions over large areas. Remote sensing works by capturing reflected radiation from crops and soil. Healthy vegetation reflects light differently than stressed or diseased plants, which allows early detection of problems. One important technique is the Normalized Difference Vegetation Index (NDVI), which measures plant health based on how plants absorb and reflect light. Brief descriptions of Remote Sensing services provided by WRMS are given below.

1. Crop Sown Area Estimation: Crop sown area estimation is one of the major sections in agriculture Remote Sensing activities, which is done for entire country. Remote Sensing plays a crucial role in mapping and monitoring of various crops sown area estimation. Satellite data such as Sentinel-1, 2, Landsat-8, World View-3, LISS-IV and more provide precise level crop sown area and helps in crop loss assessment due to various catastrophic disasters. WRMS estimates the crops and vegetables sown area of paddy, cotton, wheat, pulses, potato, peas and more.

2. Normalized Difference Vegetation Index (NDVI): This is primarily used for the assessment of vegetation dynamics, particularly in determining the crop health status. With NDVI, the possibility of understanding the crop phenology escalates as it explains the crop chronology and their relationship with weather and climate (season). NDVI is measured using mathematical calculation of spectral bands within the satellite image which measures healthiness of vegetation, as it has a robust correlation with green biomass indicating a healthy vegetation or crop.

3. Crop Diseases Identification: Remote Sensing technology provides spatially distribution of information of diseases and pests over a large area with relatively low cost. With the help of satellite imagery and spatial analysis techniques, crop infected areas are identified like Mealybug, Plant Hopper, and White Fly to get an overview for evaluating the potentially infected areas.

4. Soil properties: Soil properties are crucial in farm management practices as it has direct impact on the yield output. Change in farming system and land management results in soil change which compromises the current and future capacity for primary production and provision of crops and by micro-nutrition's mapping as soil is a very important aspect of agriculture with characteristics like soil pH, soil organic matter, soil texture among many others. These characteristics infer information about soil condition by observing what happens on the surface in terms of vegetation growth. On the other hand, water content available within the soil is a very important factor that is taken into consideration by soil moisture mapping.

5. Flood Impact: Every year in Kharif season, majority of agriculture area is damaged due to flash flood or excessive rainfall. Satellite Remote Sensing provides significant information through the use of satellite imagery along with ground-based data collected from ground surveying teams, to compute precise damage assessment. In case of flood due to

rainfall, the excess amount of water caused by the precipitation affects the agricultural area where the water drainage system is absent causing inundation. Flood due to overflow ultimately forms small tributaries and joins the river, creating a situation of flood in the vicinity of river banks and river plains. The damage assessment of flood can significantly improve the role of land use planning in managing flood risk.

6. NATCAT Modelling: Natural Catastrophe modelling is a system to estimate the real time or possible forecast of risk assessment, using the probabilistic approach to predict the outcome and behaviour of natural hazards. This includes risk mapping and measuring hazard through computer simulated catastrophe models where scientific studies and historical occurrences are linked with advance information technology and geographic information system (using Remote Sensing & GIS). Flood risk maps are prepared depending on the estimated depth of inundation of flood. The estimation is commonly derived from various hydrological and remotely sensed data where the process ensures that areas having higher depth of inundation will be assigned a high 'hazard denomination'.

7. Drone Image Analysis for Crop Damage Assessment: Drone image analysis is very useful in micro level-crop assessment for crop loss due to hailstorm, horticulture tree counting, diseases and many more. The accuracy of drone image data is directly related to the spatial resolution of the input imagery as the spatial resolution is very high ranging from 50cm and increase as per the requirement.

Geographic Information System (GIS)

Geographic Information System (GIS) is a computer-based system used to collect, store, analyze, and display spatial (geographical) data. GIS integrates multiple layers of information such as soil type, topography, rainfall, and crop data to create detailed maps and support decision-making.

Applications in agriculture:

- a. **Soil mapping:** Identifies soil types and fertility levels
- b. **Land-use planning:** Helps decide what crops to grow and where
- c. **Irrigation management:** Designs efficient irrigation systems
- d. **Farm mapping:** Divides land into management zones
- e. **Yield prediction:** Uses historical and spatial data to forecast production

Integration of Remote Sensing and GIS

Remote sensing provides real-time data, while GIS organizes and analyzes that data for practical use. Together, they form the backbone of modern precision farming.

Combined benefits:

- a. Accurate crop monitoring and management
- b. Efficient use of water, fertilizers, and pesticides
- c. Better yield forecasting and planning
- d. Early warning for pests, diseases, and disasters
- e. Improved sustainability and resource conservation

Example: A farmer uses satellite data (remote sensing) to detect low vegetation health in part of a field. This data is then analyzed in GIS to locate the exact area and determine the cause (e.g., poor soil nutrients). The farmer then applies fertilizer only in that specific zone instead of the entire field saving cost and improving yield.

Limitations:

- a. High initial cost of technology
- b. Need for technical knowledge and training
- c. Dependence on data accuracy and availability
- d. Limited access in some rural areas.

Artificial Intelligence (AI) in Agriculture

Artificial intelligence (AI) is transforming agriculture by helping farmers make faster, data-driven decisions. In farming, AI combines technologies like machine learning, computer vision, sensors, drones, robotics, and satellite imagery to improve productivity, reduce costs, and support sustainable farming.

Major Applications of AI in Agriculture

1. Precision Farming: Artificial intelligence (AI) helps farmers apply the right amount of water, fertilizer, and pesticides exactly where they are needed, improving the efficiency of farming practices. Technologies such as soil analysis using sensors, GPS-guided tractors, and variable-rate irrigation systems allow farmers to monitor field conditions and manage resources accurately. These AI-based methods help increase crop yield, reduce the waste of water and chemicals, and lower the environmental impact of agriculture, making farming more productive and sustainable.

2. Crop Monitoring and Disease Detection: AI-powered cameras and drones help farmers detect crop problems such as plant diseases, nutrient shortages, pest attacks, and water stress. Using computer vision and AI, these systems analyze images of crops and provide early warnings, allowing farmers to take timely action and minimize crop damage. Common examples include drone-based imaging and satellite crop monitoring systems.

3. Smart Irrigation: AI systems evaluate factors such as weather conditions, soil moisture levels, crop types, and evaporation rates. Based on this analysis, they automatically adjust irrigation schedules to optimize water usage. This technology is particularly useful in drought-prone areas, where efficient water management is essential.

4. Autonomous Farm Machinery: AI is increasingly applied in agriculture through self-driving tractors, robotic harvesters, and automated weed control machines. These technologies reduce reliance on manual labor while improving speed and operational efficiency. A well-known example is the John Deere Autonomous Tractor, which can perform farming tasks with minimal human intervention.

5. Predictive Analytics: AI models are used to forecast crop yields, weather-related risks, market price trends, and potential pest outbreaks. These predictions help farmers make better decisions about when to plant, manage crops, and harvest, improving overall planning and reducing uncertainty.

6. Livestock Management: AI is used in livestock monitoring through wearable sensors, smart camera systems, and behavioral analysis. These technologies help track animal health, detect signs of illness at an early stage, and improve feeding and care management, leading to healthier livestock and better farm productivity.

7. Supply Chain and Market Intelligence: AI enhances food storage and supply chain systems by improving transportation logistics, demand forecasting, and price prediction. These capabilities help reduce food waste, optimize distribution, and increase profitability across the agricultural value chain.

Technologies Used in AI Agriculture

Common technologies include:

1. Machine Learning (ML)
2. Deep Learning
3. Internet of Things (IoT)
4. Drones
5. Robotics
6. Satellite Imaging
7. Big Data Analytics

Popular AI Apps for Agriculture

1. CropIn:

- a. Uses AI + satellite data + weather info
- b. Helps with crop monitoring, yield prediction, and risk management
- c. Useful for large farms and agribusinesses
- d. It analyzes farm data to give actionable insights and improve productivity.

2. Plantix:

- a. One of the most widely used farmer apps
- b. Farmers take a photo of crops
- c. AI detects diseases, pests, and nutrient deficiencies
- d. Especially popular among small farmers because it's simple and mobile-based.

3. AI Chatbots (like Darli / Bharat-VISTAAR)

- a. Provide real-time farming advice
- b. Work in multiple languages
- c. Help with fertilizers, weather, crop planning
- d. These tools bring expert knowledge directly to farmers' phones.

Conclusion

Remote sensing and GIS are revolutionizing agriculture by making it more scientific, precise, and data-driven. They help farmers monitor crops efficiently, reduce risks, optimize resources, and increase productivity, playing a vital role in ensuring food security and sustainable farming.

Artificial intelligence is transforming agriculture by making farming more efficient, productive, and sustainable. From crop monitoring and smart irrigation to predictive analytics and supply chain optimization, AI helps farmers make better decisions, reduce resource waste, and increase yields. Overall, AI is playing a key role in improving food security and supporting modern, data-driven farming practices.

From Fragrance to Pest Control: The Hidden Power of Essential Oils

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Repaka Harika¹, Kota Sahithi Chowdary¹, Gopu Sushma²

¹Ph. D Scholar, Indira Gandhi Krishi Vishwavidyalaya, Raipur.

²Ph. D Scholar, Professor Jayashankar Telangana Agricultural University.

Abstract

The excessive use of synthetic pesticides in agriculture has resulted in insecticide resistance, environmental contamination, destruction of beneficial organisms, and pesticide residues in food products. These concerns have intensified the search for safer and sustainable alternatives for pest management. Essential oils, volatile aromatic compounds extracted from plants such as neem, basil, peppermint, thyme, citronella, eucalyptus, and lemongrass, are emerging as promising botanical insecticides. These plant-derived compounds exhibit insecticidal, repellent, fumigant, antifeedant, ovicidal, and growth-regulating properties against a wide range of agricultural pests. Unlike conventional pesticides that often target a single physiological pathway, essential oils contain multiple bioactive compounds with diverse modes of action, thereby reducing the likelihood of rapid resistance development. Recent advances in nano-formulations and encapsulation technologies have significantly improved the stability and field performance of essential oil-based pesticides. However, limitations such as high volatility, short residual activity, inconsistent composition, and commercialization challenges still restrict their large-scale adoption. This article discusses the role of essential oils in crop protection, their mechanisms of action, recent scientific developments, environmental implications, formulation technologies, and future prospects in sustainable agriculture. Essential oils may not completely replace synthetic insecticides, but they can become important components of integrated pest management programs in future farming systems.

Keywords: Essential oils, botanical insecticides, sustainable agriculture, integrated pest management, crop pests, biopesticides, nano-formulations.

Introduction

Insects are among the most destructive enemies of agricultural crops worldwide. Every year, insect pests cause enormous economic losses by damaging field crops, vegetables, fruits, and stored products. Since the Green Revolution, farmers have depended heavily on synthetic insecticides for crop protection. Although these chemicals have helped improve agricultural productivity, their indiscriminate use has created several ecological and health-related concerns.

One of the major consequences of excessive insecticide use is the development of insecticide resistance in major pests such as the brown planthopper (*Nilaparvata lugens*), cotton bollworm (*Helicoverpa armigera*), diamondback moth (*Plutella xylostella*), and whiteflies (Isman, 2020). Synthetic pesticides also contaminate soil and water ecosystems, destroy beneficial insects such as pollinators and parasitoids, and leave harmful residues in food products (Pavela and Benelli, 2016).

These growing concerns have encouraged researchers to search for environmentally safe alternatives. Among the most promising solutions are plant-derived essential oils, which are increasingly recognized as eco-friendly “green pesticides” (Popescu and Gostin, 2024). Essential oils represent the natural chemical defense systems of plants and possess strong insecticidal activities against various agricultural pests.

What Are Essential Oils?

Essential oils are concentrated volatile liquids extracted from aromatic plants through methods such as steam distillation, hydrodistillation, solvent extraction, or cold pressing. They contain complex mixtures of secondary metabolites including terpenoids, phenols, aldehydes, alcohols, ketones, and esters (Regnault-Roger et al., 2012).

Plants naturally produce these compounds as defensive chemicals against herbivorous insects, pathogens, and environmental stress. Several aromatic plants have shown remarkable insecticidal properties.

Plant Source	Major Compound	Biological Activity
Neem	Azadirachtin	Antifeedant, growth regulator
Clove	Eugenol	Neurotoxic, fumigant
Thyme	Thymol	Contact toxicity
Peppermint	Menthol	Repellent
Lemongrass	Citral	Fumigant, repellent
Eucalyptus	1,8-cineole	Respiratory toxicity
Basil	Linalool	Feeding deterrent
Citronella	Citronellal	Repellent

Unlike conventional pesticides that usually contain a single active ingredient, essential oils contain multiple compounds acting synergistically. This multi-component nature reduces the chances of rapid resistance development in insects (Kesraoui et al., 2022).

Mechanisms of Action Against Insects

Essential oils affect insects through several physiological and behavioral mechanisms.

Neurotoxic Effects: Many essential oil compounds interfere with the insect nervous system by disrupting neurotransmission. They may inhibit acetylcholinesterase activity, affect octopamine receptors, interfere with gamma-aminobutyric acid (GABA) receptors, or alter ion channel functioning (Popescu and Gostin, 2024). Compounds such as thymol, eugenol, and menthol are particularly known for their neurotoxic effects. Exposure to these compounds causes paralysis, abnormal movement, and eventually insect death.

Repellent Activity: Insects rely heavily on olfactory signals to locate host plants, food sources, mates, and oviposition sites. Essential oils disrupt these chemical communication systems. Citronella, peppermint, eucalyptus, and basil oils are highly effective repellents against aphids, whiteflies, mosquitoes, and storage pests (Nerio et al., 2010). This repellent activity is especially useful in reducing pest colonization in crop ecosystems.

Fumigant Toxicity: Due to their volatile nature, essential oils can act as natural fumigants. Their vapors enter the insect respiratory system through spiracles and disrupt respiration and nervous system functioning. Several studies have reported strong fumigant activity of thyme, clove, and lemongrass oils against storage pests such as: Red flour beetle (*Tribolium castaneum*), Rice weevil (*Sitophilus oryzae*), Maize weevil (*Sitophilus zeamais*) (Tripathi et al., 2009; Moutassem et al., 2024).

Antifeedant and Oviposition Deterrent Effects

Certain essential oils reduce feeding activity and discourage egg laying by insects. Neem-derived compounds are especially known for disrupting feeding behavior and reproduction (Isman, 2020). These effects help reduce crop damage without necessarily causing immediate insect mortality.

Growth Regulatory Effects

Essential oils may interfere with insect growth and development by affecting hormonal regulation during molting and metamorphosis. Larvae exposed to essential oils often exhibit: Delayed development, Improper molting, Malformed pupae, Reduced adult emergence (Pavela and Benelli, 2016).

Essential Oils Against Major Agricultural Pests

Rice cultivation suffers heavily from pests such as brown planthopper, green leafhopper, and stem borers. Scientists are increasingly exploring botanical oils against these pests to reduce dependence on synthetic insecticides. Essential oils from citronella, basil, eucalyptus, and lemongrass have shown promising toxicity and repellent effects against rice pests (Kesraoui et al., 2022). Caterpillar pests cause severe crop losses globally. Essential oils have demonstrated effectiveness against: *Spodoptera litura*, *Helicoverpa armigera*, *Agrotis ipsilon* and *Plutella xylostella*. Basil and thyme oils have shown strong larvicidal and feeding deterrent activity against these pests (Assadpour et al., 2024). Stored grain insects significantly reduce grain quality and quantity during storage. Essential oils provide several advantages in storage systems: Strong fumigant action, Low residue accumulation, Reduced mammalian toxicity, Eco-friendly nature. Clove, cinnamon, thyme, and eucalyptus oils have shown remarkable effectiveness against storage beetles and moths (Tripathi et al., 2009).

Advantages of Essential Oils in Pest Management

- 1. Eco-Friendly and Biodegradable:** Essential oils degrade rapidly in the environment and leave minimal harmful residues in soil, water, and food products (Kesraoui et al., 2022).
- 2. Reduced Resistance Development:** Because essential oils contain multiple active compounds acting on different target sites, insects are less likely to develop resistance quickly compared with conventional insecticides (Isman, 2020).
- 3. Safety to Humans and Animals:** Many essential oils are relatively safer to mammals when properly used. This makes them suitable for organic farming and residue-free crop production.
- 4. Compatibility with Integrated Pest Management:** Essential oils can be integrated with: Biological control agents, Pheromone traps, Resistant crop varieties, Cultural practices, Precision agriculture technologies (Pavela and Benelli, 2016).

Challenges Limiting Their Adoption

Despite their advantages, essential oils still face several practical limitations.

- 1. High Volatility:** Essential oils evaporate rapidly under sunlight and high temperatures, reducing their persistence under field conditions (Popescu and Gostin, 2024).
- 2. Short Residual Activity:** Compared with synthetic pesticides, essential oils generally provide short-term protection and may require repeated applications.
- 3. Variability in Chemical Composition:** The chemical composition of essential oils varies depending on: Plant species, Soil conditions, Climate, Harvesting stage, Extraction method. This inconsistency affects their reliability and standardization (Gostin and Popescu, 2024).
- 4. Potential Effects on Beneficial Organisms:** Although considered safer, some essential oils may still affect pollinators, parasitoids, and predatory insects if improperly used (Gostin and Popescu, 2024).

Nano-Technology: Improving Essential Oil Efficiency

Recent advances in nano-technology are helping overcome many limitations associated with essential oils. Scientists are developing: Nanoemulsions, Nanoencapsulation systems, Polymeric nanoparticles, Controlled-release formulations. These technologies protect essential oils from: Rapid evaporation, UV degradation, Oxidation. Benefits include: improved stability, enhanced insecticidal activity, better field persistence, reduced dosage requirements (Ayllón-Gutiérrez et al., 2024). Nano-formulated peppermint, thyme, and citronella oils have shown significantly improved efficacy against agricultural pests.

Future Prospects in Sustainable Agriculture

The global demand for eco-friendly pest management solutions is increasing rapidly. Essential oils are expected to play an important role in future sustainable agriculture systems. Future research is focusing on: Standardized formulations, Synergistic mixtures, Nano-delivery systems, Precision application technologies, Controlled-release formulations. Scientists are also combining essential oils with reduced doses of synthetic insecticides to improve efficacy while minimizing environmental impact (Aioub et al., 2024). The future of crop protection will likely involve integrating essential oils with: Biological control, RNAi-based technologies, Semiochemicals, AI-based pest monitoring systems, Climate-smart agriculture.

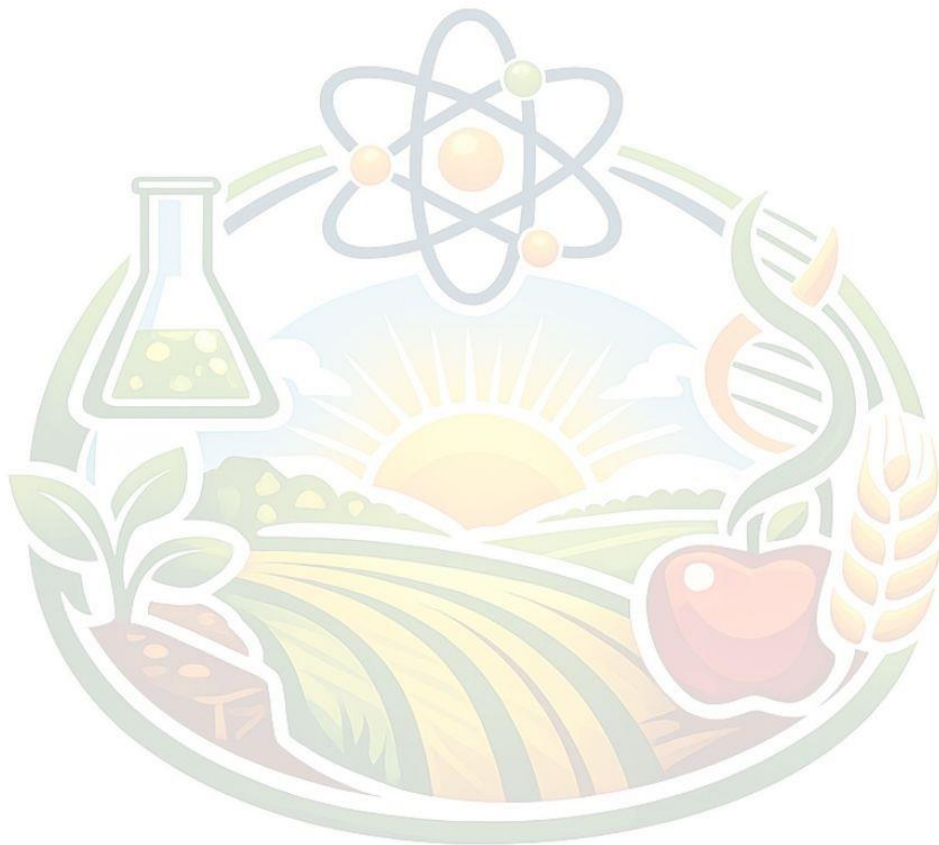
Conclusion

Essential oils are emerging as promising natural alternatives for crop pest management. Their insecticidal, fumigant, repellent, antifeedant, and growth-regulating activities make them valuable tools for sustainable agriculture. They offer several advantages including biodegradability, reduced environmental contamination, lower residue accumulation, and reduced chances of rapid resistance development. However, challenges such as high volatility, inconsistent composition, short residual activity, and commercialization barriers still limit their widespread adoption. Advances in nano-formulation technologies and improved delivery systems are helping overcome many of these obstacles. Although essential oils may not completely replace synthetic insecticides in the near future, they can significantly reduce agriculture's dependence on harmful chemicals when integrated into modern pest management strategies. Nature's aromatic compounds may soon become powerful allies in protecting crops while preserving environmental health.

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Artificial Intelligence and Machine Learning in Smart Agriculture

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Suraj N Gund¹, Rutuja S. Pisal², Dr. Amol S. Solanke³

¹Ph. D. Scholar, Department of Agril. Botany, Mahatma Phule Krishi Vidyapeeth, Rahuri, Ahilyanagar.

¹Ph. D. Scholar, Department of Horticulture, Mahatma Phule Krishi Vidyapeeth, Rahuri, Ahilyanagar.

³Asst. Prof. Affiliated to Vasantao Naik Marathwada Krishi Vidyapeeth, Parbhani.

Abstract

Agriculture is becoming increasingly complex due to climate variability, resource limitations, pest and disease pressures, and fluctuating market conditions. In this changing scenario, Artificial Intelligence (AI) and Machine Learning (ML) are emerging as valuable tools for improving farm decision-making and resource-use efficiency. These technologies help transform farm-level data into practical recommendations for irrigation scheduling, crop health monitoring, pest and disease detection, yield forecasting, and climate-smart advisories.

This article presents a simple overview of AI and ML in the context of smart agriculture, explaining their basic concepts, major types, data requirements, and real-world applications. It also highlights the tools and technologies supporting AI-based farming and discusses their economic, environmental, and social benefits. For Indian agriculture, particularly under smallholder and rainfed conditions, AI and ML offer significant potential to reduce risk, optimize inputs, and improve productivity. The article concludes that AI and ML are not merely advanced technologies for the future, but practical solutions that can contribute to more resilient, efficient, and sustainable agricultural systems.

Keywords: Artificial Intelligence, Machine Learning, Smart Agriculture, Precision Farming, Crop Management, Yield Prediction.

Introduction

Agriculture today is no longer guided only by experience and tradition. Farmers must make many decisions each season—when to sow, irrigate, spray, harvest, and market their produce. These decisions are becoming more difficult because of changing weather, limited resources, pest outbreaks, and unstable market prices.

In this situation, Artificial Intelligence (AI) and Machine Learning (ML) are emerging as practical tools for modern farming. They help convert field data into useful recommendations, making farm management more precise and efficient. For Indian agriculture, especially in rainfed and smallholder farming systems, AI and ML can support better crop management, reduce risk, save inputs, and improve productivity.

These technologies are not just futuristic ideas. They are already being used for disease detection, irrigation planning, yield forecasting, weather advisories, and input management. If used properly, AI and ML can make agriculture smarter, more resilient, and more profitable.

Understanding AI and ML in Simple Terms

AI refers to machines or computer systems that can perform tasks that normally require human intelligence, such as identifying patterns, making decisions, and solving problems. In agriculture, AI can help recognize crop diseases from images, guide farm machinery, and provide digital advisories to farmers.

ML is a branch of AI that learns from data. Instead of being programmed for every situation, ML models improve by analyzing examples. For example, if a system is shown many images of healthy and diseased leaves, it can gradually learn to identify plant diseases on its own.

A simple way to understand ML is to compare it with learning to drive. At first, instructions are needed, but with practice and feedback, performance improves. In the same way, ML systems become better as they receive more reliable data.

Major Types of Machine Learning in Agriculture

1. Supervised Learning: This method works like learning with an answer sheet. The model is trained using labeled data. For example, images of leaves may be tagged as “healthy” or “infected.” Once trained, the system can classify new images correctly. It is commonly used for disease detection, pest identification, and yield prediction.

2. Unsupervised Learning: In this method, the data are not labeled. The model finds hidden patterns or groups on its own. For example, it can group fields with similar soil moisture or nutrient status. This is useful for field zoning, farmer segmentation, and identifying unusual patterns.

3. Reinforcement Learning: This method learns through trial and error. The system takes actions and improves based on rewards or penalties. For example, an irrigation system can learn the best watering schedule by observing crop response and water use over time. This approach is useful in irrigation and resource optimization.

The Data Behind Smart Farming

AI and ML depend on data, and agriculture generates data from many sources. These include:

1. Soil and moisture sensors
2. Weather stations
3. Drones and satellite images
4. Mobile phone photographs
5. Farm machinery records
6. Market and price information
7. Research and breeding datasets

However, good decisions depend on good-quality data. If the data are incomplete, delayed, or inaccurate, recommendations may also be unreliable. Therefore, proper data collection, cleaning, storage, and validation are essential for successful smart agriculture.

What AI and ML Actually Do on the Farm

1. Precision Agronomy: AI helps farmers apply the right input, at the right time, in the right amount. It can guide fertilizer use, irrigation, and pesticide application based on field-specific needs. This reduces waste, lowers costs, and improves efficiency.

2. Crop Health Monitoring: Computer vision and image-based ML models can identify pests, diseases, and nutrient deficiencies at an early stage. This helps farmers take action before the problem becomes severe.

3. Yield Prediction: ML models can estimate crop yield using weather, crop growth, and management data. Such predictions help in harvest planning, storage preparation, and market decisions.

4. Irrigation Scheduling: AI-based irrigation tools use soil moisture, crop stage, and weather forecasts to suggest when and how much water to apply. This improves water-use efficiency, especially under drought conditions.

5. Weed and Pest Management: AI can identify weed species and pest damage through images and support targeted spraying or control measures. This reduces unnecessary chemical use and saves labor.

6. Climate-Smart Advisories: By analyzing weather and climate data, AI tools can provide warnings about heat stress, drought, excess rainfall, or disease-favorable conditions, helping farmers plan in advance.

7. Beyond Crops: AI is also useful in livestock and fisheries, where sensors and smart monitoring systems can track animal health, feed efficiency, and water quality.

Technologies Supporting AI in Agriculture

The success of AI in farming depends on both **hardware** and **software**.

Hardware

- a. Smartphones
- b. Soil and weather sensors
- c. Drones
- d. Satellites
- e. GPS-enabled tractors and machinery
- f. Edge devices for local data processing

Software

- a. Mobile advisory apps
- b. GIS and remote sensing platforms
- c. Machine learning tools
- d. Cloud-based data systems
- e. Digital dashboards and APIs

Together, these technologies create a connected farming system where decisions can be made more accurately and quickly.

Benefits of AI and ML in Agriculture

Economic Benefits: AI helps reduce the cost of fertilizer, irrigation, pesticides, and labor. It can also improve productivity and support better market timing, ultimately increasing profitability.

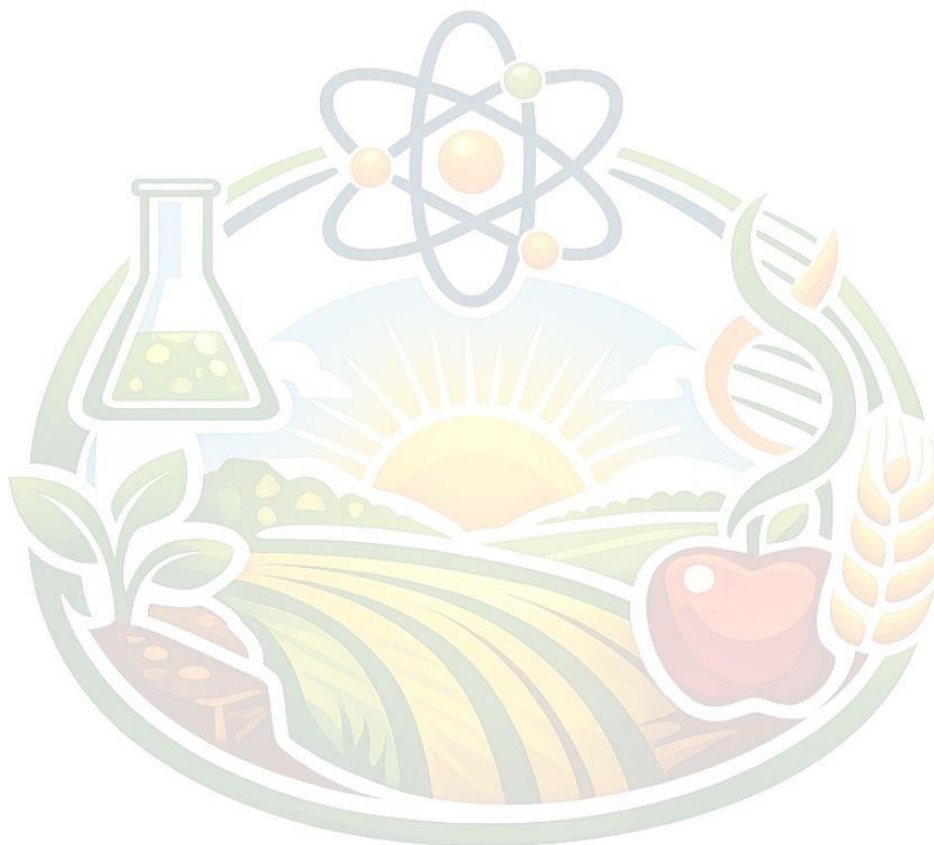
Environmental Benefits: By optimizing the use of water and chemicals, AI reduces waste, runoff, and environmental damage. It supports more sustainable farming practices.

Social and Knowledge Benefits: Perhaps the biggest advantage is that farmers gain confidence in decision-making. Data-based advisories can improve awareness, encourage community learning, and support wider adoption of improved practices.

Conclusion

Artificial Intelligence and Machine Learning are gradually changing the way agriculture is practiced. They help farmers make better decisions using data rather than guesswork. From disease detection and irrigation scheduling to yield forecasting and climate advisories, these tools have the potential to improve both productivity and sustainability.

For countries like India, where agriculture faces challenges from climate variability, labor shortages, and limited resources, AI and ML can play an important role in building a smarter and more resilient farming system. The real challenge now is not whether these technologies work, but how effectively they can be made accessible, affordable, and useful at the farm level.

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“Seeds Without Seeds”: Exploring the Science, Technology and Future of Synthetic Seeds in Plant Biotechnology

Article ID: 73723

V. Shajeeda Banu¹, Awadhesh Kumar Pal¹, Rima Kumari¹, Pankaj Kumar¹, Anil Kumar Singh¹, Duniya Ram Singh¹

¹Bihar Agricultural University, Sabour, Bhagalpur, Bihar-813210.

Introduction: Transforming the Way, We Propagate Plants

Seeds have been the cornerstone of agriculture since the beginning of civilization. Traditionally, seeds are formed through sexual reproduction and serve as the primary means of plant propagation. However, with the advancement of plant biotechnology, scientists have developed an innovative alternative known as synthetic seeds. These are artificially produced propagules that mimic natural seeds in structure and function but are generated through laboratory techniques rather than natural fertilization. Synthetic seed technology represents a major breakthrough because it combines the precision of tissue culture techniques with the practicality of seed-based propagation. This approach is particularly significant in modern agriculture, where there is an increasing demand for uniform planting material, rapid multiplication of elite varieties and conservation of valuable plant genetic resources.

Scientific Concept of Synthetic Seeds

Synthetic seeds, also referred to as artificial seeds, are defined as encapsulated plant propagules capable of developing into complete plants under suitable conditions. These propagules are typically somatic embryos, although other tissues such as shoot buds, nodal segments, or embryogenic callus can also be used depending on the species. From a scientific perspective, synthetic seeds consist of three major components. The first is the propagule, which serves as the biological unit capable of plant regeneration. The second component is the encapsulation matrix, usually composed of sodium alginate, which provides mechanical protection and structural integrity. The third component is the artificial endosperm, which includes nutrients, sugars and growth regulators necessary for the initial growth and development of the propagule. Unlike natural seeds, synthetic seeds do not have a protective seed coat or a naturally developed endosperm. However, these functions are artificially replicated using biocompatible materials and nutrient formulations.

Biological Principles Underlying Synthetic Seed Technology

The foundation of synthetic seed technology lies in the concept of totipotency, which states that every plant cell has the inherent ability to regenerate into a complete plant under appropriate environmental and nutritional conditions. This remarkable property is the basis of all plant tissue culture techniques. Another key principle is somatic embryogenesis, a process in which somatic (non-reproductive) cells undergo reprogramming to form embryo-like structures. These somatic embryos closely resemble zygotic embryos in morphology and developmental stages, passing through globular, heart-shaped, torpedo and cotyledonary stages. The bipolar nature of somatic embryos, having both shoot and root meristems, makes them ideal candidates for synthetic seed production.

The encapsulation process is governed by physicochemical interactions, particularly the ion exchange reaction between sodium alginate and calcium ions, resulting in the formation of calcium alginate gel. This gel creates a semi permeable barrier that allows the diffusion of gases and nutrients while protecting the encapsulated propagule from mechanical damage.

Methodology of Synthetic Seed Production

The production of synthetic seeds involves a series of carefully controlled steps that integrate biological and chemical processes. The process begins with the selection and sterilization of explants, such as leaves, stems, or immature embryos, to ensure contamination free cultures. These explants are then cultured on a nutrient medium, typically Murashige and Skoog (MS) medium, supplemented with specific plant growth regulators. Auxins such as 2,4-Dichlorophenoxyacetic acid (2,4-D) are commonly used to induce callus formation, followed by the development of somatic embryos.

The embryos are subsequently transferred to a hormone free or cytokinin rich medium to promote maturation. Once mature embryos are obtained, they are suspended in a sterile solution of sodium alginate, usually at a concentration of 2-5%. This mixture is then dropped into a calcium chloride solution, where rapid ion exchange leads to the formation of calcium alginate beads encapsulating the embryos. These beads are hardened for a specific duration and then washed to remove excess salts. The encapsulated beads can be used immediately or stored under controlled conditions. When placed on a suitable growth medium or soil, the synthetic seeds germinate and develop into complete plantlets.

Factors Influencing the Success of Synthetic Seeds

The efficiency of synthetic seed technology is influenced by a number of biological, chemical and environmental factors. One of the most critical factors is the developmental stage of the somatic embryo. Mature embryos with well defined structures exhibit higher germination and conversion rates compared to immature ones. The composition of the encapsulation matrix also plays a crucial role. The concentration of sodium alginate determines the strength and permeability of the bead, while calcium chloride concentration affects the degree of cross-linking and hardness. An optimal balance is essential to ensure both protection and adequate nutrient diffusion. The presence of nutrients and growth regulators within the encapsulation matrix significantly influences early plant development. Additionally, storage conditions such as temperature, humidity and duration impact the viability of synthetic seeds. Low temperatures, typically around 4°C, are often used to prolong shelf life. Genotype is another important factor, as different plant species exhibit varying responses to somatic embryogenesis and encapsulation. Oxygen availability and gas exchange through the matrix are also critical for maintaining metabolic activity.

Advantages of Synthetic Seed Technology

Synthetic seeds offer numerous advantages that make them highly attractive for agricultural and biotechnological applications. One of the primary benefits is the ability to achieve clonal propagation, ensuring genetic uniformity across all plants produced. This is particularly important for maintaining the quality and consistency of elite cultivars. Another significant advantage is the production of disease free planting material, as the entire process is conducted under sterile conditions. Synthetic seeds also enable year round production, independent of seasonal constraints, which is a major limitation in conventional seed production. From a practical standpoint, synthetic seeds are easy to handle, transport and store, making them suitable for large scale distribution. They also reduce the dependency on traditional propagation methods such as cuttings or grafting, which can be labour intensive and time consuming.

Applications Across Sectors

Synthetic seed technology has wide ranging applications in agriculture, horticulture, forestry and biotechnology. In agriculture, it enables the rapid multiplication of high yielding and stress tolerant crop varieties. In horticulture, it is used for the propagation of ornamental plants and fruit crops, ensuring uniformity and quality. In forestry, synthetic seeds facilitate the large scale propagation of tree species, which is essential for afforestation and reforestation programs. The technology is also highly valuable in the conservation of endangered and rare plant species, as it allows for the preservation and multiplication of germplasm. In the field of medicinal plants, synthetic seeds ensure the production of plants with consistent phytochemical profiles, which is crucial for pharmaceutical applications. Additionally, synthetic seeds can serve as delivery systems for genetically engineered plants, opening new avenues in plant biotechnology.

Future Prospects and Innovations

The future of synthetic seed technology is promising, with ongoing research focused on overcoming current limitations. Advances in nanotechnology and biomaterials are expected to improve encapsulation efficiency and durability. The development of synthetic endosperm substitutes may enhance nutrient availability and germination rates. Integration with modern tools such as CRISPR-based gene editing and metabolic engineering could further expand the applications of synthetic seeds. Additionally, the use of cryopreservation techniques may enable long term storage and conservation of synthetic seeds. Automation and scaling up of production processes are also being explored to make the technology commercially viable.

Conclusion: A Step Toward Sustainable and Smart Agriculture

Synthetic seed technology represents a powerful fusion of biology, chemistry and engineering, offering a sustainable solution for plant propagation in the modern era. By providing a means to produce uniform, disease-free and high-quality planting material, it addresses some of the most pressing challenges in agriculture and biotechnology. As research continues to advance, synthetic seeds are expected to play a vital role in enhancing crop productivity, conserving biodiversity and supporting bio-based industries. They truly symbolize a new generation of seeds, engineered not just for growth, but for the future of sustainable agriculture.

Shifting Cultivation: Ecological, Socio-economic and Sustainability Perspectives

Article ID: 73724

Hiranmayee Nayak¹, M C Behera¹, T L Mohanty¹

¹Department Silviculture and Agroforestry, College of Forestry, OUAT.

Abstract

Shifting cultivation is a traditional land-use system practiced by tribal communities, involving the clearing of vegetation, short-term cropping, and a fallow period for natural regeneration. It plays an important role in ensuring food security, maintaining biodiversity, and preserving indigenous knowledge systems. Under traditional long fallow cycles, the system is ecologically sustainable; however, increasing population pressure and land scarcity have led to shortened fallow periods, resulting in soil degradation and reduced productivity. Therefore, sustainable management practices such as agroforestry integration and improved fallow management are essential to balance ecological stability and livelihood needs.

Introduction

Shifting cultivation is one of the earliest forms of agriculture, dating back to the Neolithic period. It involves clearing forest vegetation, cultivating crops for a short duration, and allowing the land to lie fallow for natural regeneration (Spencer, 1966). The practice is prevalent in tropical regions of Asia, Africa, and Latin America and is locally known as *Jhum* in India, *Ladang* in Indonesia, and *Milpa* in Central America (Conklin, 1957). Despite being labelled as primitive, shifting cultivation is a complex ecological and socio-cultural system that supports millions of indigenous people worldwide (Mertz *et al.*, 2009).

Characteristics of Shifting Cultivation

1. Shifting cultivation involves the clearing of natural vegetation through the slash-and-burn method, where biomass is cut and burned to prepare the land for cultivation. The cropping period in shifting cultivation is relatively short, typically lasting between one to three years, after which the land is abandoned (Singh *et al.*, 2024).
2. This system traditionally includes a long fallow period ranging from 10 to 25 years, allowing the land to regenerate naturally. Farmers practice mixed cropping, growing a variety of crops simultaneously to ensure food security and reduce risk. The system relies on low external inputs and primarily uses traditional tools and indigenous knowledge for cultivation.
3. The fallow phase plays a crucial role in restoring soil fertility through natural ecological processes such as nutrient cycling, organic matter accumulation, and biomass regeneration (Nye & Greenland, 1960).

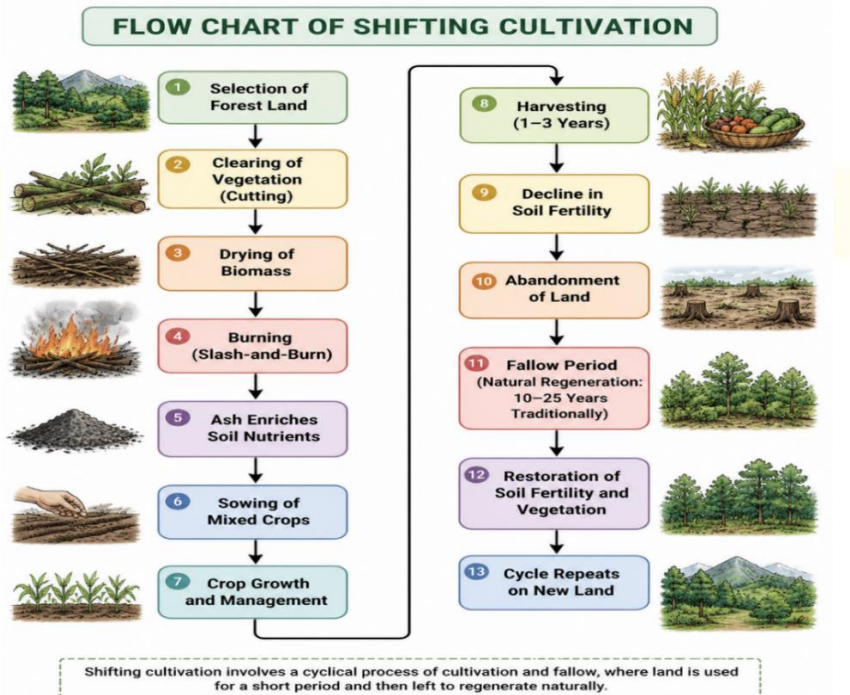


Fig 1: Steps of Shifting Cultivation

Ecological Implications

1. Positive Impacts: Under traditional conditions with sufficiently long fallow periods, shifting cultivation can be ecologically sustainable:

- It promotes secondary forest succession, which helps in the regeneration of vegetation.
- It contributes to the maintenance of biodiversity by creating a mosaic of habitats at different stages of succession (Nayak, *et al.*, 2024)
- It enhances soil organic matter through the accumulation of plant residues during the fallow phase.
- It supports efficient nutrient recycling, thereby maintaining soil fertility (Kleinman *et al.*, 1995).

2. Negative Impacts: When the fallow period is shortened due to external pressures, shifting cultivation can lead to several ecological problems:

- It causes a decline in soil fertility due to insufficient time for nutrient replenishment. It increases soil erosion, especially on sloping lands where vegetation cover is reduced.
- It leads to a loss of biodiversity as natural regeneration is disrupted. It contributes to forest degradation and environmental instability (FAO, 2015).

Socio-Economic Significance

Shifting cultivation is closely linked with the livelihoods and cultural identity of tribal communities:

- It ensures food security for communities living in remote and inaccessible regions. It provides diversified agricultural outputs, including cereals, pulses, vegetables, and minor forest produce.
- It helps in preserving traditional ecological knowledge that has been developed over generations. It supports socio-cultural practices, rituals, and community-based resource management systems (Cairns, 2015).

In India, particularly in the North-Eastern region and parts of Odisha, shifting cultivation continues to be a primary source of livelihood for many indigenous communities.

Indian Scenario

In India, shifting cultivation is predominant in the North-Eastern states such as Mizoram, Nagaland, Meghalaya, and Assam. It is also practiced in the Eastern Ghats, including parts of Odisha and AP.

Table 1: Status of Shifting Cultivation in India:

State	Local Name	Status / Extent	Key Characteristics	References
Nagaland	Jhum	Highest proportion of land under shifting cultivation in NE India; majority of rural households depend on it	Shortened fallow cycles (5-10 years), high dependence on forest land	Suman & Sarkar (2020)
Manipur	Jhum	Extensive practice in hill districts; significant area under rotational farming	Declining jhum area but increasing fragmentation of plots	Singh et al. (2019)
Mizoram	Jhum	Dominant land-use system; practiced by majority tribal population	Transition towards settled agriculture but still widespread	Thong et al. (2018)
Meghalaya	Jhum	Moderate to high extent; practiced in Garo, Khasi hills	Jhum area fluctuates (0.79-2.39% of total area annually)	Dutta et al. (2023)
Assam	Jhum	Practiced in tribal hill regions; declining trend due to policy interventions	Increasing marginalization and reduced productivity	Choudhury & Sundriyal (2003)
Tripura	Jhum	Significant livelihood source for tribal communities	Supports food security and socio-economic stability	Datta et al. (2014)
Arunachal Pradesh	Jhum	Widely practiced across tribal communities; large forest dependency	Long tradition but under transition due to modernization	Prakash (2018)
Odisha	Podu	Practiced in districts like Koraput, Rayagada, Kandhamal	Short fallow cycles (<5-7 years), linked with tribal livelihoods	Panda & Sarkar (2017))
Andhra Pradesh	Podu	Practiced in tribal belts of Eastern Ghats	Increasing pressure due to land scarcity and policy restrictions	Panda & Sarkar (2017))

Madhya Pradesh / Chhattisgarh	Bewar / Dahiya	Limited and declining practice	Transition to settled agriculture due to forest policies	FAO (2015)

Strategies for Sustainable Management

Several strategies can be adopted to improve the sustainability of shifting cultivation systems:

1. Integration of agroforestry systems can enhance productivity and ecological stability.
2. Improved fallow management using nitrogen-fixing species can accelerate soil fertility restoration. Adoption of soil and water conservation techniques can reduce land degradation. Livelihood diversification can reduce dependency on shifting cultivation alone. Policy support that incorporates indigenous knowledge and practices can promote sustainable land-use systems.

Conclusion

Shifting cultivation is a dynamic land-use system that integrates ecological processes with socio-cultural practices. While it has sustained communities for centuries, modern pressures have altered its sustainability. Rather than elimination, adaptive management strategies should be adopted to enhance its ecological and economic viability.

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Antixenosis: A Natural Way to Manage Insect Pests in Pigeonpea

Article ID: 73725

Raushan Kumar¹, Arjun Kumar Agarwal², Binay Kumar¹, Radhe Shyam Yadav³

¹Department of Entomology, Birsa Agriculture University, Kanke, Ranchi, Jharkhand (India)- 834006.

²Department of Genetics and Plant Breeding, Birsa Agriculture University, Kanke, Ranchi, Jharkhand (India)- 834006.

³Department of Agronomy, Birsa Agriculture University, Kanke, Ranchi, Jharkhand (India)- 834006.

Abstract

Pigeonpea is a vital pulse crop, but its productivity is severely affected by insect pests, especially pod borers like *Helicoverpa armigera* and *Maruca vitrata*. Overreliance on chemical pesticides has created environmental and health concerns, making sustainable alternatives essential. Antixenosis, a natural plant defence mechanism, reduces pest infestation by discouraging insect feeding and egg-laying through physical, chemical, and phenological traits. Features such as trichomes, pod hardness, defensive compounds, and growth timing make plants less attractive to pests. This eco-friendly approach lowers pesticide use, supports biodiversity, and fits well within Integrated Pest Management, offering a long-term, sustainable solution for pigeonpea cultivation.

Introduction

Pigeonpea (*Cajanus cajan*) is one of the most important pulse crops cultivated across tropical and subtropical regions, particularly in countries like India where it serves as a major source of protein in daily diets. Despite its significance, pigeonpea productivity is often limited by a wide range of insect pests that attack the crop at different growth stages, especially during flowering and pod formation. Among these, the most destructive are the pod borers such as *Helicoverpa armigera* and *Maruca vitrata*, which can cause severe yield losses by feeding on flowers and developing pods. Traditionally, farmers rely heavily on chemical pesticides to control these pests; however, excessive and indiscriminate use of chemicals has led to several problems including pesticide resistance, environmental pollution, resurgence of pests, and health hazards. In this context, the concept of antixenosis, or non-preference, has emerged as an effective, eco-friendly, and sustainable approach to insect pest management in pigeonpea (Painter, 1951).

Understanding Antixenosis (Non-Preference)

Antixenosis refers to a type of host plant resistance in which plants possess certain characteristics that discourage or repel insects, thereby preventing them from selecting the plant for feeding, oviposition (egg laying), or shelter. Unlike other forms of resistance such as antibiosis, which affects the biology or survival of insects, antixenosis primarily influences insect behaviour (Kogan & Ortman, 1978). In simple terms, the plant becomes unattractive or unsuitable, prompting the insect to avoid it and move to a more favourable host. This behavioural resistance is highly valuable because it reduces pest infestation at an early stage, often before any significant damage occurs.

The mechanism of antixenosis involves a complex interaction between plant traits and insect sensory responses. Insects rely on visual, tactile, and chemical cues to identify suitable host plants. When these cues are unfavourable, insects may fail to recognize the plant as a host or may actively avoid it after initial contact. In pigeonpea, antixenosis is mainly expressed in the pods, which are the primary target of major insect pests.

Major Insect Pests of Pigeonpea Pods

Pigeonpea is attacked by a number of insect pests, but pod borers are the most damaging. The gram pod borer, *Helicoverpa armigera*, is a highly polyphagous pest that feeds on a wide range of crops. Its larvae bore into pods and consume developing seeds, causing direct yield loss. Similarly, the legume pod borer, *Maruca vitrata*, damages flowers and pods by webbing them together and feeding inside, making control difficult (Sharma *et al.*, 1999). These pests are known for their high reproductive capacity and adaptability, which makes their management challenging. Antixenosis offers a promising solution by reducing the attractiveness of pigeonpea pods to these pests.

How Plants Defend Themselves Naturally

Plants are not passive victims of insect attack; they have evolved a variety of defence mechanisms to protect themselves. These defences can be broadly classified into morphological (physical), biochemical (chemical), and phenological (timing-related) traits. In the case of antixenosis, these traits work together to alter insect behaviour, making the plant less desirable. Instead of killing the insect, the plant simply discourages it from feeding or laying eggs, thereby reducing infestation levels.

Role of Pod Morphology in Antixenosis

Morphological traits of pigeonpea pods play a crucial role in determining insect preference. One of the most important features is trichomes, or hair-like structures present on the surface of pods. Dense and long trichomes act as a physical barrier, making it difficult for insects to land, move, or lay eggs (Duffey, 1986). In some cases, glandular trichomes may also secrete sticky substances that trap or repel insects.

Another important trait is pod wall thickness and hardness. Pods with thick and tough walls are less susceptible to penetration by larvae, discouraging pests from selecting them for feeding. Similarly, surface texture and waxiness influence insect behaviour by affecting their ability to grip and move on the pod surface. Smooth or waxy surfaces reduce insect attachment, making it harder for them to feed or oviposit.

Biochemical Traits: Invisible Chemical Defences

In addition to physical traits, pigeonpea pods contain a variety of biochemical compounds that play a significant role in antixenosis. These include secondary metabolites such as phenols, tannins, flavonoids, and alkaloids, which can act as repellents, feeding deterrents, or oviposition inhibitors. When insects come into contact with these compounds, their sensory receptors detect unfavourable signals, leading to rejection of the plant.

Higher levels of phenolic compounds have been associated with reduced preference by *H. armigera* larvae (Sharma and Ortiz, 2002). Conversely, susceptible varieties often contain higher amounts of sugars and amino acids, which act as feeding stimulants.

On the other hand, the presence of certain primary metabolites like sugars and amino acids can increase plant attractiveness by acting as feeding stimulants. Therefore, resistant varieties often have lower levels of such compounds and higher concentrations of defensive chemicals.

Another important aspect is the production of volatile organic compounds (VOCs), which serve as chemical signals that guide insects during host selection. Resistant pigeonpea varieties may emit volatiles that are less attractive or even repellent to pests, reducing the likelihood of infestation. These chemical defences operate at both short and long distances, influencing insect behaviour even before physical contact occurs.

Phenological Traits: Escaping Pest Attack

Phenological traits refer to the timing of plant growth stages such as flowering and pod formation. These traits play a critical role in antixenosis by creating a mismatch between crop stages and pest activity. For example, early-maturing pigeonpea varieties may complete their podding stage before peak pest populations develop, thereby escaping damage.

The duration and synchrony of pod formation also influence insect preference. Varieties with a short and uniform podding period provide a limited window for pest attack, while those with prolonged or staggered podding offer continuous opportunities for infestation. By selecting appropriate sowing times and varieties, farmers can exploit phenological traits to reduce pest pressure naturally.

Benefits of Antixenosis to Farmers

Antixenosis offers numerous advantages that make it an attractive option for pest management. First and foremost, it reduces the need for chemical pesticides, leading to lower production costs and minimizing environmental pollution. It also helps preserve beneficial insects such as pollinators and natural enemies, which play an important role in maintaining ecological balance.

Since antixenosis does not exert direct selection pressure on pests, the risk of resistance development is relatively low compared to chemical control methods. Moreover, it provides a long-term and sustainable solution, as resistant plant varieties can be used season after season without additional input costs.

Integration with Integrated Pest Management (IPM)

Antixenosis is most effective when used as part of an Integrated Pest Management (IPM) strategy. IPM combines multiple approaches such as cultural practices, biological control, and the use of resistant varieties to manage pests in an environmentally friendly manner. By incorporating pigeonpea varieties with strong antixenosis traits, farmers can significantly reduce pest populations and enhance the effectiveness of other control methods.

For example, adjusting sowing dates, maintaining field sanitation, and encouraging natural enemies can complement the effects of antixenosis, leading to better pest control and higher yields.

Future Scope and Research

The development of pigeonpea varieties with enhanced antixenosis traits is an active area of research. Plant breeders and scientists are working to identify genetic sources of resistance and incorporate them into high-yielding varieties. Advances in biotechnology and molecular breeding techniques are expected to accelerate this process, making it possible to develop crops that are both productive and pest-resistant.

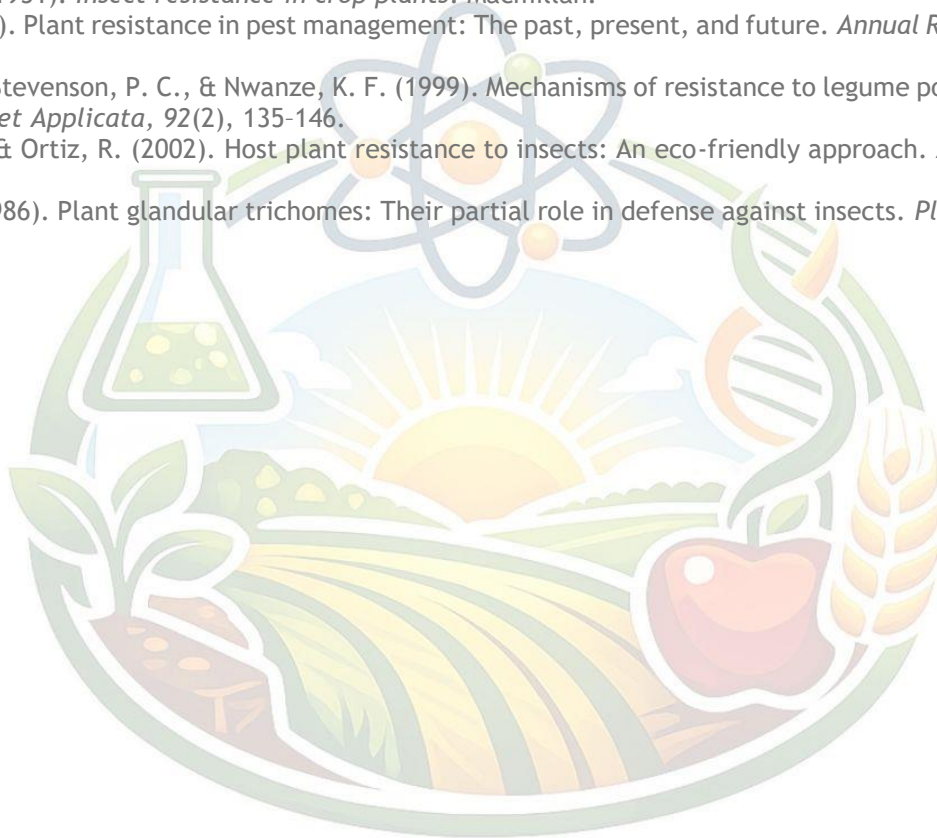
In addition, a better understanding of plant-insect interactions and the underlying mechanisms of antixenosis can lead to the discovery of new strategies for pest management. This will be particularly important in the face of climate change, which is likely to alter pest dynamics and increase the challenges faced by farmers.

Conclusion

Antixenosis represents a powerful and sustainable approach to insect pest management in pigeonpea. By influencing insect behaviour through morphological, biochemical, and phenological traits, pigeonpea plants can effectively reduce pest infestation without relying on harmful chemicals. This natural defence mechanism not only protects the crop but also supports environmental conservation and economic viability for farmers. Promoting the use of antixenosis-based resistant varieties, along with integrated pest management practices, can play a crucial role in ensuring stable and sustainable pigeonpea production in the future.

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Plant Stress in Vegetable Crops: Causes, Physiological and Biochemical Responses

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Arusha Sharma¹

¹Ph.D. Research Scholar, Department of Vegetable Science, Chaudhary Charan Singh Haryana Agricultural University, Hisar, Haryana, India.

Introduction

Plant stress refers to any unfavorable environmental condition or biological factor that adversely affects plant growth, development, productivity, or survival. In vegetable crops, stress is a major limiting factor that significantly reduces yield, quality, and nutritional value. Under stress conditions, plants experience disruption in normal physiological and biochemical processes, which ultimately affects their overall performance. In natural and agricultural ecosystems, plants are constantly exposed to various stress factors. To survive, they have evolved complex defense mechanisms, including physiological adjustments, biochemical changes, and molecular responses. Understanding plant stress and its different types is essential for developing strategies to improve crop productivity and resilience.

Characteristics of Plant Stress

Stress in plants is associated with several visible and invisible changes that impair normal functioning. Some key characteristics include:

1. Reduction in plant growth and development
2. Decrease in productivity and yield
3. Disturbance in physiological processes such as photosynthesis, respiration, transpiration, nutrient uptake, and water transport
4. Production of reactive oxygen species (ROS) like superoxide radicals, hydrogen peroxide, and hydroxyl radicals
5. Activation of defense mechanisms to cope with stress
6. Alteration in plant hormone levels, especially abscisic acid (ABA)
7. Disruption of metabolic activities.

One of the most critical effects of stress is the overproduction of ROS, which can damage cellular structures if not regulated by antioxidant systems.

Classification of Stress in Vegetable Crops

Plant stress in vegetable crops is broadly classified into two major categories:

1. **Abiotic Stress:** Abiotic stress is caused by non-living environmental factors such as temperature, water availability, salinity, and nutrient imbalance.
2. **Biotic Stress:** Biotic stress is caused by living organisms such as insects, pathogens, nematodes, and weeds.

Abiotic Stress in Vegetable Crops

Drought Stress: Drought stress occurs when soil moisture becomes insufficient to meet the water requirements of plants and is considered one of the most serious constraints in vegetable production. It usually results from low rainfall, high evaporation rates, improper irrigation practices, and sandy soils with poor water-holding capacity. Under drought conditions, plants respond by closing their stomata to reduce water loss through transpiration. However, this also limits carbon dioxide uptake, thereby reducing photosynthesis and overall growth. Water stress further affects nutrient absorption and transport within the plant. At the biochemical level, drought induces the accumulation of osmoprotectants such as proline and stimulates the production of abscisic acid (ABA), which helps plants regulate water loss. Antioxidant enzyme activity also increases to protect cells from oxidative damage caused by reactive oxygen species. Morphologically, drought-stressed plants often exhibit reduced leaf size, shorter plant height, and lower root and shoot biomass, ultimately leading to yield reduction.

Temperature Stress: Temperature is a key environmental factor regulating plant metabolism, growth, and development. Any deviation from the optimum temperature range can adversely affect vegetable crops. Temperature stress can broadly be classified into cold stress and heat stress depending upon whether plants are exposed to temperatures below or above their tolerance limits.

Cold Stress: Cold stress occurs when plants are exposed to temperatures below their optimum growth range. Low temperatures disrupt various physiological and metabolic processes, resulting in reduced nitrogen uptake and assimilation, increased oxidative damage, membrane instability, and accumulation of osmolytes that help maintain cellular water balance. Some plants also synthesize antifreeze proteins that prevent ice crystal formation within tissues. Certain vegetable crops such as cabbage and kale possess natural adaptive mechanisms like thicker leaves and

accumulation of sugars, which lower the freezing point of plant cells and provide protection from frost injury. Based on frost sensitivity, crops are classified into hardy, half-hardy, tender, and very tender groups. Hardy crops such as cabbage, spinach, onion, and peas can tolerate lower temperatures, whereas crops like tomato, chilli, cucumber, brinjal, and watermelon are highly sensitive to frost.

Heat Stress: Heat stress occurs when temperatures rise beyond a critical limit, causing irreversible damage to plant growth and productivity. It is increasingly significant due to climate change, heat waves, and high solar radiation. Elevated temperatures disrupt source-sink relationships, reducing assimilate partitioning and yield. Plants respond by accumulating osmolytes like proline and sugars to maintain cellular balance. Heat stress also alters hormonal levels, particularly increasing abscisic acid and ethylene, which act as stress signals. Additionally, plants produce heat shock proteins (HSPs) to protect cellular structures. However, excessive heat leads to overproduction of reactive oxygen species, resulting in oxidative stress and cellular damage.

Salinity Stress: Salinity stress develops when excessive salts accumulate in the soil, limiting the plant's ability to absorb water and nutrients. Common causes include irrigation with saline water, poor drainage systems, and cultivation in coastal or salt-affected soils. Initial symptoms of salinity stress resemble drought and include mild wilting, leaf yellowing, and reduced growth. As salt concentration increases, leaf burn, premature senescence, and severe stunting may occur. Salinity imposes osmotic stress, reducing water uptake by roots and disturbing nutrient balance. To survive, plants accumulate compatible solutes such as sugars, amino acids, and organic acids, which help in osmotic adjustment and maintenance of cellular turgor. Some relatively salt-tolerant vegetable crops such as beet and asparagus exhibit structural adaptations like smaller, thicker leaves with waxy cuticles to reduce water loss and salt damage.

Waterlogging Stress: Waterlogging stress occurs when soil becomes saturated with excess water, creating oxygen-deficient conditions in the root zone. Since roots require oxygen for respiration, prolonged flooding inhibits root metabolic activities, reduces nutrient uptake, and increases susceptibility to root diseases. Early symptoms include pale green or yellow leaves due to oxygen starvation, followed by reduced growth, leaf drop, and root decay. Some vegetable crops adapt to waterlogged conditions by developing specialized air spaces known as aerenchyma or adventitious roots, which facilitate oxygen transport to submerged tissues.

Nutrient Stress: Nutrient stress results from either deficiency or toxicity of essential mineral nutrients required for normal plant growth. In vegetable crops, nutrient deficiencies often produce characteristic symptoms that can serve as diagnostic indicators. For instance, calcium deficiency causes blossom end rot in tomato and tip burn in cabbage, while molybdenum deficiency leads to whiptail in cauliflower. Boron deficiency is associated with fruit cracking in tomato, whereas nitrogen deficiency causes yellowing of older leaves in crops such as lettuce, cabbage, and spinach. Magnesium deficiency commonly manifests as interveinal chlorosis, where leaf veins remain green while surrounding tissues turn yellow.

Biotic Stress in Vegetable Crops

Insect Stress: Insects are among the most destructive biotic stress factors affecting vegetable crops. They damage plants directly by feeding on leaves, stems, roots, fruits, or plant sap and indirectly by transmitting diseases. Common insect pests in vegetables include aphids, whiteflies, thrips, and fruit borers. Sap-sucking insects weaken plants by extracting essential nutrients, causing curling, yellowing, and stunted growth. Feeding damage also reduces photosynthetic area, while several insect vectors play a crucial role in transmitting viral diseases, significantly lowering crop productivity.

Disease Stress: Plant diseases caused by fungi, bacteria, and viruses are major constraints in vegetable production. Fungal pathogens are among the most widespread and reproduce through spores that spread via air, water, soil, or infected plant material. Bacterial pathogens usually enter plants through natural openings such as stomata or through wounds caused by insects or mechanical injury. Viral diseases are particularly problematic because viruses depend entirely on host cells for multiplication and are commonly transmitted by insect vectors such as aphids and whiteflies. These pathogens interfere with plant metabolism, reduce growth, and affect both yield and quality.

Nematode Stress: Nematodes are microscopic roundworms that inhabit soil and attack plant root systems. They cause considerable economic losses in vegetable crops by impairing nutrient and water absorption. Root-knot nematodes are among the most common nematode pests and induce gall formation on roots. Infected plants typically show poor growth, stunted appearance, nutrient deficiency symptoms, and increased susceptibility to secondary infections. Since root damage reduces the efficiency of water and mineral uptake, nematode-infested plants often appear weak and unproductive.

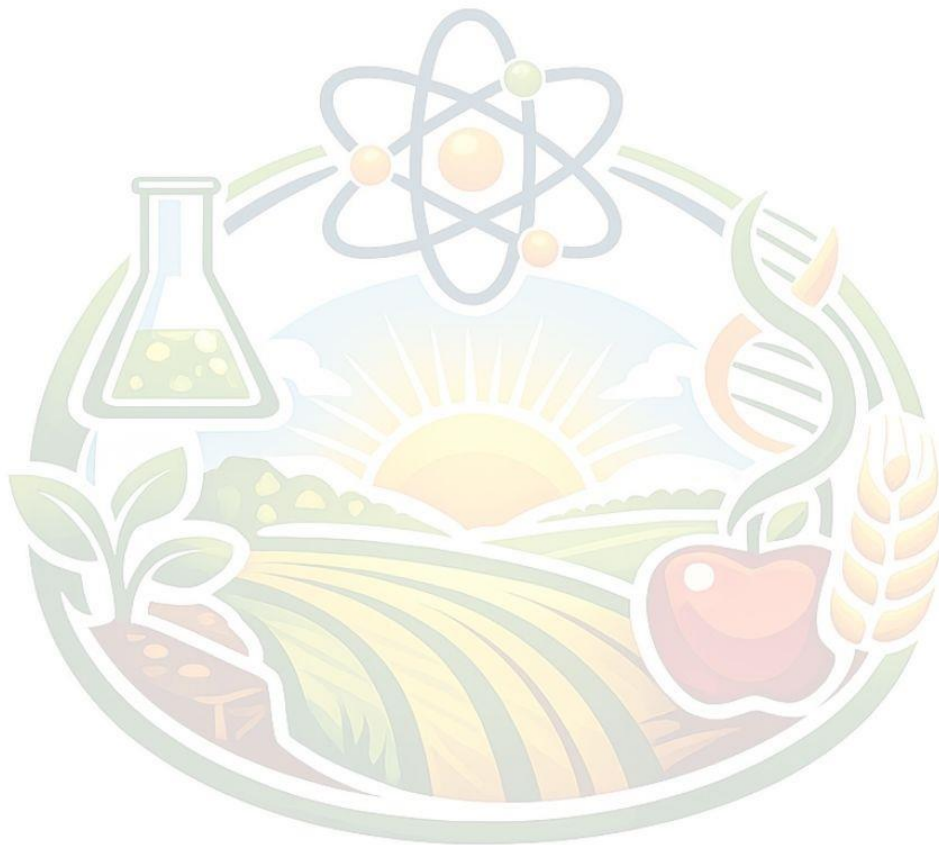
Conclusion

Plant stress, whether abiotic or biotic, poses a significant challenge to vegetable production worldwide. These stresses disrupt physiological, biochemical, and metabolic processes, ultimately reducing crop yield and quality. However, plants have evolved various adaptive mechanisms such as antioxidant systems, osmolyte accumulation, and structural modifications to cope with stress conditions. A comprehensive understanding of different types of stress and their effects is essential for developing effective management strategies. Adoption of stress-tolerant varieties, improved agronomic

practices, and advanced technologies can help mitigate the adverse effects of stress and ensure sustainable vegetable production in the face of changing environmental conditions.

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Farm Record System in India: A Foundation for Scientific and Profitable Farming

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Dr. Sravanthi Kolla¹

¹Assistant Professor, Dept. of Agricultural Economics, Agricultural College, Palem.

Introduction

Agriculture is the backbone of the Indian economy, supporting the livelihoods of millions of farmers across the country. In recent years, Indian agriculture has undergone significant changes due to rising input costs, market fluctuations, labour shortages, and climate variability. Under such conditions, farmers require better planning and management practices to improve farm productivity and profitability. One of the most effective tools for achieving this objective is the maintenance of systematic farm records. Farm record keeping refers to the organized documentation of all farm-related activities, including production operations, input use, labour employment, sales, income, and expenditures. Just as business enterprises maintain financial and operational records, farmers also need accurate records to evaluate farm performance and make informed decisions.

Importance of Farm Records

Farm records play an important role in modern farm management. They help farmers estimate the cost of cultivation, compare profitability across crops, identify unnecessary expenditures, and plan future agricultural activities more effectively. Proper record keeping also supports farmers in obtaining institutional credit, crop insurance, subsidies, and government assistance. In addition, farm records provide valuable information for researchers, extension workers, cooperatives, and policymakers to understand farming systems and improve agricultural programmes. Scientific agriculture and precision farming practices increasingly depend upon reliable farm data, making record maintenance essential for sustainable agricultural development.

Daily Farm Diary

The daily farm diary is one of the most basic and useful records maintained by farmers. This diary contains the day-to-day activities performed on the farm, such as sowing, irrigation, fertilizer application, pesticide spraying, harvesting, and machinery use. Farmers may also record weather conditions, pest and disease incidence, and important decisions related to crop management. The daily farm diary serves as a memory aid and helps farmers monitor crop progress throughout the season. It also acts as a reference document for future planning and evaluation of farm operations.

Example:

Date	Activity Performed	Remarks
10 June 2026	Paddy nursery sowing completed	Good soil moisture
18 June 2026	Applied 50 kg urea	Light rainfall received
25 June 2026	Pest incidence observed	Stem borer noticed

Crop-Wise Input Register

Another important record is the crop-wise input register. This register records the quantity and cost of all inputs used for each crop separately. Inputs such as seeds, fertilizers, pesticides, herbicides, irrigation charges, and machinery expenses are entered systematically. Maintaining this register enables farmers to calculate the actual cost of cultivation for different crops and assess input efficiency. It also helps farmers avoid excessive use of fertilizers and pesticides, thereby reducing production costs and minimizing environmental damage. Crop-wise input records are particularly useful for comparing the profitability of alternative cropping systems and improving resource management.

Example:

Crop	Input Used	Quantity	Cost (₹)
Cotton	Hybrid seed	2 packets	1,800
Cotton	DAP fertilizer	100 kg	3,200
Cotton	Pesticide spray	3 litres	2,100
Cotton	Tractor ploughing	5 hours	4,000

Labour Employment Register

Labour is a major component of agricultural production costs in India, especially in labour-intensive crops such as paddy, cotton, and sugarcane. Therefore, maintaining a labour employment register is highly important. This register contains details regarding the number of labourers employed, the nature of work performed, wage rates, and the duration of employment. Family labour contribution may also be recorded. Such records help farmers estimate labour requirements

during peak agricultural seasons and evaluate labour costs for different operations. The labour register also assists in labour planning and mechanization decisions.

Example:

Date	Work Performed	No. of Labourers	Wage Rate (₹/day)	Total Cost (₹)
15 July 2026	Paddy transplantation	10	400	4,000
20 August 2026	Weeding operation	6	350	2,100
10 October 2026	Cotton picking	8	450	3,600

Sales Register

The sales register is another essential component of the farm record system. It contains details regarding the sale of agricultural produce and by-products, including quantity sold, date of sale, market price, buyer information, transportation charges, and total income received. This register helps farmers monitor market trends and compare prices across different markets and seasons. By analyzing sales records, farmers can identify profitable marketing channels and improve marketing decisions. Proper sales records also help in calculating farm income and net returns accurately.

Example:

Date	Produce Sold	Quantity	Price per Quintal (₹)	Total Income (₹)
15 November 2026	Maize	25 quintals	2,300	57,500
20 December 2026	Cotton	18 quintals	7,000	1,26,000

Income and Expenditure Register

An income and expenditure register provides a comprehensive summary of all farm receipts and expenses during a production period. Income may include earnings from crop sales, livestock products, machinery rentals, government subsidies, and other farm-related activities. Expenditures include costs incurred on seeds, fertilizers, labour wages, electricity, irrigation, machinery repairs, and other operational expenses. This register functions as the financial statement of the farm and helps farmers determine whether the farming enterprise is generating profit or loss. It also assists in budgeting, financial planning, and credit management.

Example:

Particulars	Amount (₹)
Total income from crops	2,50,000
Income from milk sales	40,000
Total expenditure on inputs	1,60,000
Labour expenses	45,000
Net farm income	85,000

Asset and Investment Register

In addition to operational records, farmers should maintain an asset and investment register. This register contains information regarding land holdings, farm machinery, irrigation equipment, livestock, farm buildings, and other long-term investments. Details such as purchase year, purchase value, and depreciation may also be recorded. The asset register helps farmers assess the overall value of farm resources and plan future investments. It is also useful while applying for bank loans, insurance claims, and government schemes.

Example:

Asset	Year Purchased	Value (₹)
Tractor	2022	7,00,000
Borewell	2021	1,50,000
Sprayer	2023	12,000
Dairy animals	2024	1,20,000

Challenges in Maintaining Farm Records

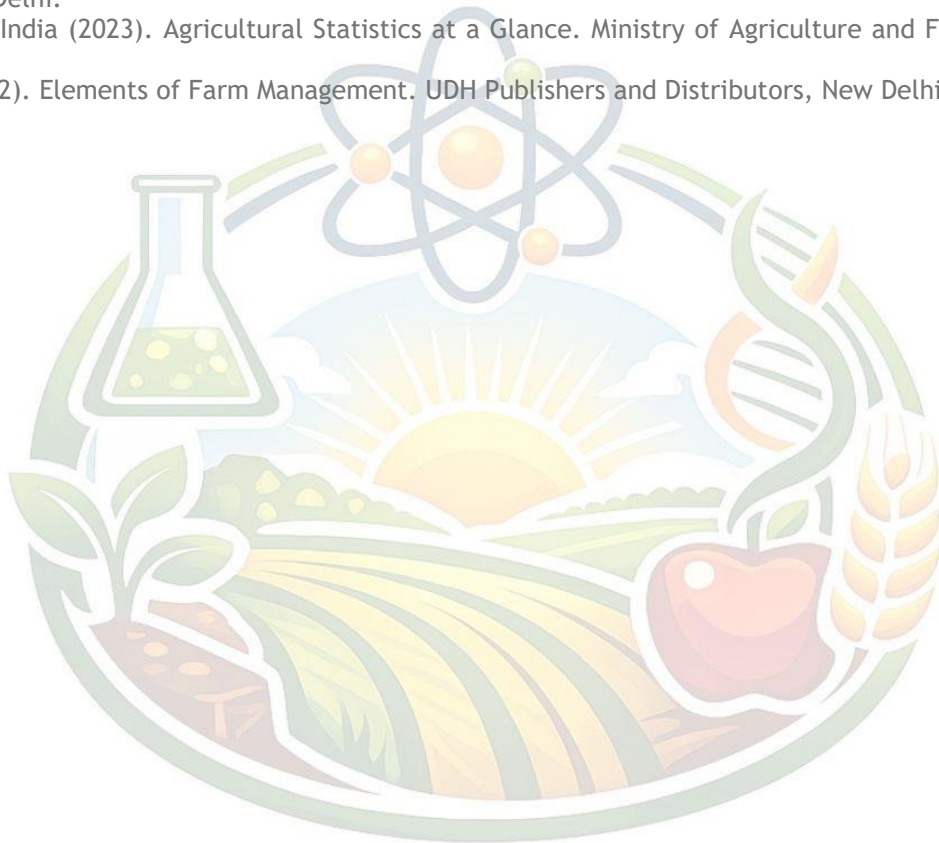
Despite the numerous advantages of farm record maintenance, many Indian farmers still do not maintain systematic records due to factors such as illiteracy, lack of awareness, small landholdings, and dependence on memory-based management. However, increasing digital literacy, smartphone penetration, and the availability of mobile-based farm management applications are creating new opportunities for improving record-keeping practices among farmers. Agricultural universities, Krishi Vigyan Kendras (KVKs), Farmer Producer Organizations (FPOs), cooperatives, and extension agencies have an important role in creating awareness and providing practical training on farm record maintenance.

Conclusion

Farm records are not merely notebooks containing farm expenses and activities; they are powerful management tools that support scientific decision-making and sustainable agricultural development. Proper maintenance of farm records helps farmers improve efficiency, reduce production costs, increase profitability, and strengthen financial planning. In the era of commercial agriculture and digital farming, systematic farm record keeping is becoming increasingly essential for Indian farmers. Promoting farm record systems through training programmes, extension services, and digital technologies can significantly contribute to the modernization and sustainability of Indian agriculture.

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Different Pigment Responsible for Colour Development in Different Vegetables and their Importance

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Puspita Das¹

¹Ph.D. Research Scholar (Vegetable Science), Department of Vegetable Science, Bidhan Chandra Krishi Vishwavidyalaya, Mohanpur, Nadia, West Bengal, Pin-741252.

Abstract

Vegetable colours are developed by natural pigments such as chlorophyll, carotenoids, anthocyanins, betalains, and flavonoids. Chlorophyll imparts green colour in spinach and broccoli, while carotenoids provide yellow, orange, and red shades in carrot, tomato, and pumpkin. Anthocyanins are responsible for purple and blue colours in brinjal and red cabbage, whereas betalains produce red and yellow pigments in beetroot. These pigments not only enhance visual appeal and consumer preference but also possess significant nutritional and antioxidant properties. They play an important role in human health by reducing oxidative stress and preventing chronic diseases. Therefore, vegetable pigments are valuable for both quality improvement and nutritional security.

Keywords - Antioxidant, Betalains, Chlorophyll, Pigment, Vegetable.

Introduction

Vegetables are important components of the human diet because they provide vitamins, minerals, carbohydrates, proteins, dietary fiber, and several bioactive compounds. One of the most attractive features of vegetables is their wide range of colours, including green, yellow, orange, red, purple, blue, and white. These colours are produced by natural pigments present in plant tissues. Pigments are chemical compounds capable of absorbing certain wavelengths of light and reflecting others, thereby giving vegetables their characteristic colours.

The colour of vegetables plays an important role in consumer preference, market value, and nutritional quality. Brightly coloured vegetables are often associated with freshness, health benefits, and superior quality. Besides contributing to appearance, pigments also perform several physiological functions in plants and provide numerous health benefits to humans. Many pigments possess antioxidant, anti-inflammatory, anticancer, and immune-boosting properties.

The major pigments responsible for colour development in vegetables include chlorophylls, carotenoids, anthocyanins, betalains, flavonoids, and anthocyanin. Each pigment group contributes specific colours and functions. Understanding these pigments is important for horticulture, food science, nutrition, and vegetable breeding programs.

Chlorophyll

Chlorophyll is the green pigment present in plants and is mainly responsible for photosynthesis. It captures sunlight and converts it into chemical energy. Chlorophyll is found in chloroplasts of plant cells. There are mainly two types of chlorophyll - Chlorophyll-a and Chlorophyll-b. Chlorophyll-a is bluish green, while chlorophyll-b is yellowish green.

Vegetables Containing Chlorophyll - Spinach, Broccoli, Cabbage, Peas, Coriander leaves, Fenugreek, Green beans, Lettuce.

Importance of Chlorophyll-

- Role in Photosynthesis - Chlorophyll absorbs light energy required for photosynthesis, helping plants produce food.
- Nutritional Importance - Green vegetables rich in chlorophyll are excellent sources of Magnesium, Iron, Vitamins A, C, K and Dietary fiber.
- Antioxidant Properties - Chlorophyll acts as an antioxidant and helps protect cells from oxidative damage.
- Detoxification - It may help remove toxins and harmful substances from the body.
- Health Benefits - Consumption of green vegetables reduces the risk of Anemia, Heart diseases and Digestive disorders.

Factors Affecting Chlorophyll - Heat during cooking may destroy chlorophyll. Acidic conditions convert chlorophyll into pheophytin, causing dull olive-green colour. Proper storage helps maintain green colour.

Carotenoids

Carotenoids are yellow, orange, and red pigments found in many vegetables and fruits. They are fat-soluble pigments synthesized in plastids.

Types of Carotenoids - Beta-carotene, Lycopene, Lutein and Zeaxanthin.

Vegetables Containing Carotenoids - Yellow and Orange Vegetables like carrot, pumpkin, sweet potato, yellow capsicum. Red vegetables like Tomato and Red pepper.

Importance of Carotenoids

- Provitamin A Activity** - Beta-carotene is converted into vitamin A in the human body and helps maintain good vision, healthy skin and immune function.
- Antioxidant Activity** - Carotenoids neutralize free radicals and reduce oxidative stress.
- Prevention of Diseases** - They help lower the risk of cancer, cardiovascular diseases and eye disorders.
- Lycopene Benefits** - Lycopene in tomatoes is associated with reduced risk of prostate cancer and heart diseases.
- Eye Protection** - Lutein and zeaxanthin protect eyes from age-related macular degeneration.

Factors Affecting Carotenoids - Carotenoids are relatively stable during cooking. Light and oxygen exposure may reduce pigment concentration.

Anthocyanins

Anthocyanins are water-soluble pigments responsible for red, purple, and blue colours in vegetables and fruits. They belong to the flavonoid group.

Vegetables Containing Anthocyanins - Red cabbage, purple cauliflower, purple carrot, brinjal (eggplant), purple sweet potato and red onion.

Importance of Anthocyanins:

- Antioxidant Properties** - Anthocyanins are powerful antioxidants that protect cells from damage.
- Anti-inflammatory Effects** - They help reduce inflammation in the body.
- Cardiovascular Protection** - Anthocyanins improve blood circulation and heart health.
- Cancer Prevention** - These pigments may inhibit the growth of cancer cells.
- Anti-aging Benefits** - Anthocyanins slow down cellular aging and improve skin health.

Effect of pH on Anthocyanins - Anthocyanin colour changes with pH like Acidic conditions - red, Neutral conditions - purple, Alkaline conditions - blue. This property is important in food processing and preservation.

Betalains

Betalains are nitrogen-containing pigments responsible for red and yellow colours. They are found mainly in plants of the Caryophyllales order.

Types of Betalains:

- Betacyanins** - red-violet colour
- Betaxanthins** - yellow colour

Vegetables Containing Betalains - Beetroot, Amaranthus.

Importance of Betalains:

- Antioxidant Activity** - Betalains protect the body from oxidative stress.
- Anti-inflammatory Properties** - They help reduce inflammation and improve immunity.
- Natural Food Colouring** - Betalains are used as natural food dyes in beverages, candies, and processed foods.
- Detoxification** - They support liver function and detoxification processes.
- Health Benefits** - Consumption of beetroot improves blood circulation and physical performance.

Stability of Betalains - Betalains are sensitive to heat, light and oxygen. Proper storage is required to maintain colour quality.

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Flavonoids and Anthoxanthins

Flavonoids are a large group of plant pigments with antioxidant properties. Anthoxanthins are flavonoid pigments responsible for white, cream, or pale yellow colours.

Vegetables Containing Anthoxanthins - Cauliflower, Onion, Potato, Turnip, White radish.

Importance of Flavonoids and Anthoxanthins:

- Antioxidant Function** - They protect cells from free radical damage.
- Disease Prevention** - Regular consumption reduces the risk of diabetes, hypertension and heart diseases.
- Anti-inflammatory Effects** - Flavonoids help control inflammatory responses.
- Immune Support** - They strengthen the immune system.
- Food Quality** - These pigments contribute to the colour and quality of vegetables.

Effect of Cooking - Anthoxanthins may become more yellow under alkaline conditions and remain white in acidic conditions.

Importance of Vegetable Pigments

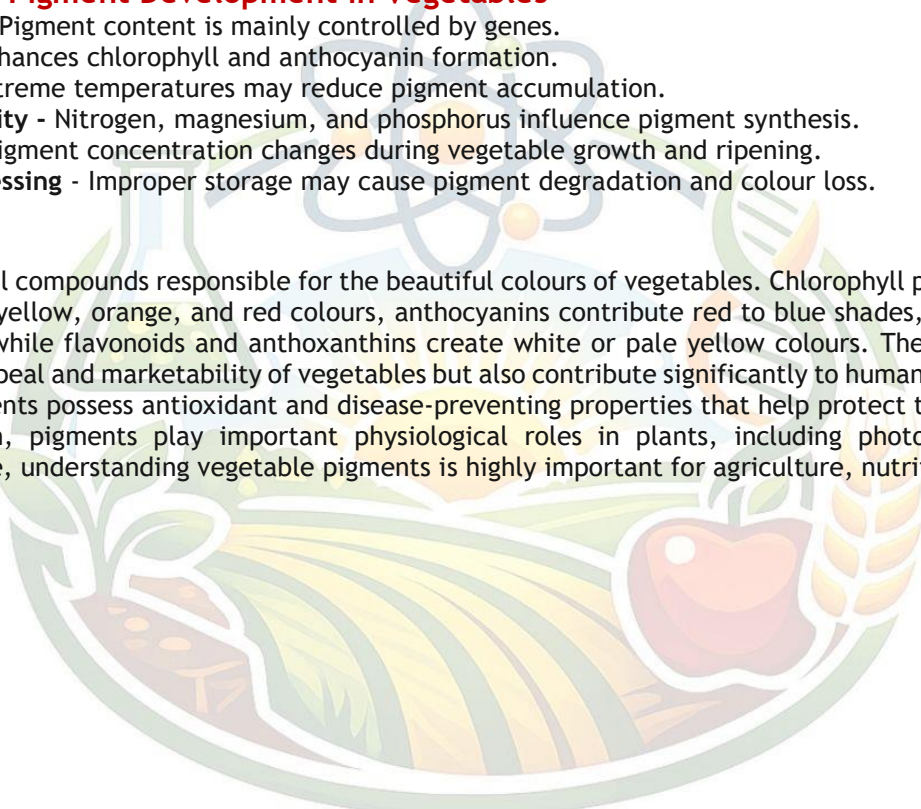
1. **Consumer Attraction** - Colour is the first quality parameter noticed by consumers. Bright and attractive vegetables have better market demand.
2. **Nutritional Significance** - Pigments provide essential nutrients such as Vitamin A, Vitamin C, minerals and antioxidants.
3. **Health Benefits** - Pigments help prevent chronic diseases by reducing oxidative stress and improving immunity.
4. **Role in Plant Physiology** - Pigments participate in photosynthesis, pollination and Protection against environmental stress.
5. **Industrial Applications** - Natural pigments are increasingly used as food colourants in place of synthetic dyes.
6. **Breeding and Crop Improvement** - Plant breeders develop coloured vegetable varieties with higher nutritional value and improved consumer preference.

Factors Affecting Pigment Development in Vegetables

1. **Genetic Factors** - Pigment content is mainly controlled by genes.
2. **Light** - Sunlight enhances chlorophyll and anthocyanin formation.
3. **Temperature** - Extreme temperatures may reduce pigment accumulation.
4. **Nutrient Availability** - Nitrogen, magnesium, and phosphorus influence pigment synthesis.
5. **Maturity Stage** - Pigment concentration changes during vegetable growth and ripening.
6. **Storage and Processing** - Improper storage may cause pigment degradation and colour loss.

Conclusion

Pigments are essential compounds responsible for the beautiful colours of vegetables. Chlorophyll provides green colour, carotenoids produce yellow, orange, and red colours, anthocyanins contribute red to blue shades, betalains impart red and yellow colours, while flavonoids and anthoxanthins create white or pale yellow colours. These pigments not only improve the visual appeal and marketability of vegetables but also contribute significantly to human nutrition and health. Most vegetable pigments possess antioxidant and disease-preventing properties that help protect the body from chronic illnesses. In addition, pigments play important physiological roles in plants, including photosynthesis and stress protection. Therefore, understanding vegetable pigments is highly important for agriculture, nutrition, food processing, and human health.



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Bird Repellents for Sustainable Agriculture

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Krishna J. Bhuva¹, Ashish Nayi¹, Jalpa J. Dand¹, R. R. Waghunde¹

¹All India Network Project on Vertebrate Pest Management: Agricultural Ornithology, AAU, Anand- 388 110 (Gujarat).

Abstract

Damage caused by bird activity on agricultural crops pose a serious threat to farming systems by directly consuming grains, fruits and seeds. Their feeding activity leads to significant crop damage, resulting in reduced yield, marketing value and economic losses for farmers. In many cases, birds attack crops at critical growth stages, further lowering productivity and affecting the overall quality and market value of the produce. Various bird repellent strategies ranging from traditional scare methods to advanced intelligent systems have been developed to mitigate their impact. However, the effectiveness of these methods are often limited by habituation, environmental concerns and species-specific behavior. This article provides a review of bird repellents, including visual, auditory, chemical, physical and advanced automated technologies based on drones, sensors and the Internet of Things (IoT) for sustainable and eco-friendly agriculture.

Keywords - Bird repellents, crop damage, IoT, crop protection.

Introduction

Birds can cause severe damage to agricultural crops, leading to substantial economic losses for farmers. To address this issue, a wide range of bird deterrent methods have been developed over time. These methods include traditional practices such as scarecrows, reflective objects and noise-making devices, as well as modern innovations like ultrasonic repellents and solar-powered electronic systems (Hernadi *et al.*, 2025). Although conventional techniques may provide immediate protection, their effectiveness often declines over time as birds become habituated to them. Therefore, both traditional visual and auditory approaches, along with advanced technological solutions, are being explored to improve long-term efficiency in bird pest management (Wan Mohamed *et al.*, 2020). Out of the total, 25 species of (2%) birds cause damage to human interests. Across different agro-ecological zones, birds are responsible for considerable economic losses in various crops, particularly during their vulnerable growth stages. The level of damage varies depending on factors such as bird population density, the extent of cultivated area, cropping patterns, seasonal conditions, and the physiological condition of the birds. Managing these depredatory birds differs significantly from conventional pest control methods (Chellappan *et al.*, 2023). Moreover, the Indian Wildlife (Protection) Act, 1972 restricts the use of methods that involve trapping, harming, or killing most bird species, including those that are endangered or protected. Birds play a dual role in agro-ecosystems, functioning both as beneficial and harmful organisms. Many species act as natural predators, feeding on insect pests and rodents, thereby contributing to biological pest control and maintaining ecological balance. Conversely, certain bird species are depredatory, causing direct damage to crops by feeding on grains, fruits and seeds, which can lead to significant yield losses for farmers. Thus, the role of birds in agriculture is complex, as they provide ecological benefits while also posing challenges to crop production (Dhindsa and Saini, 1994). The role of birds in natural regulation of a polyphagous lepidopteran pest - *Helicoverpa armigera* in wheat crop was documented in Gujarat and opined that the birds preferred to feed on insects rather than maturing wheat grains (Borad and Parasharya, 2018). Crop losses caused by bird depredation differ widely across geographical regions and seasons, mainly due to variations in the number and types of bird species involved (Patel, 2013).

Over the years, various bird repellent methods have been developed. However, many traditional techniques lose effectiveness due to habituation, where birds adapt to repeated stimuli and no longer respond to deterrents. It's interesting to note that only around 2% (05 out of 1000) of avian species in India have been found inflicting damage to horticultural and agricultural crops (Priya *et al.*, 2022). Accurately quantifying the costs and benefits of bird activities in agriculture remains challenging. Nevertheless, their harmful impacts can be reduced while promoting the valuable ecosystem services. Hence, there is a need to adopt sustainable management approaches to effectively balance these cost benefit trade-offs.

Types of Depredatory Bird Repellents

Visual Repellents: The Management of bird pests has been one of the difficult areas to tackle due to the highly intelligent, adaptable and mobile nature of birds and the need to preserve the ecological balance.

a. Methods usually employed in the fields for bird menace are beating empty tins, using scarecrows, tying polythene bags and reflective and metallic strips, CDs, hanging predatory eye ball, stringing thread, models of predatory birds (owl, hawk) on the poles and using sound producing crackers.



b. Reflective ribbon: More effective and easily adaptable by the farmers in the field for scaring the birds. The inter distance between the two ribbons should be about 5-8 meters. The ribbon needs to be twisted at every one meter and be given support at every 5 m. During sunshine, the brightness and humming noise produced due to wind, scares bird like Rose-ringed Parakeet, House Crow and Myna on the crops viz., sunflower, jowar, bajra, maize, safflower, pomegranate and guava.



c. Scarers: Farmers use scarecrows to create the illusion of human presence and deter birds from fields (Marsh *et al.*, 1992).

d. These tactics create fear by simulating predators or unusual movements. However, birds quickly learn that these objects are harmless, leading to reduced effectiveness over time (Yauri *et al.*, 2023).

Auditory Repellents:

a. An automatic cracker station can be employed to deter depredatory birds. The device emits sounds at regular intervals, which function as auditory repellents and help keep birds away from the area. One-hectare area can be covered with this method.

b. Pre-recorded distress and alarm calls of different bird species are amplified with the help of speakers to drive away the birds from the fields. This method is very effective on orchards and small acreage crops.

c. Electronic systems can produce high-frequency or species-specific sounds that disturb birds without harming them (Varriano *et al.*, 2025).

Physical and Mechanical Repellents:

a. **Use of nets:** The use of nets to keep birds away from fruit crops. Nets are potentially 100% effective, non-toxic, noiseless, and reusable (Stuckey, 1973).



- b. The rice seedlings can be protected from the damage of purple moorhen by using net of various kinds viz., nylon, polythene and polythene coated iron with mesh size of $\frac{1}{4}$ to $\frac{3}{4}$ inches (Chellappan and Ranjith, 2022).
- c. Crop screening: This method involves planting tall forage sorghum along the edges of sunflower fields to act as a barrier. It was developed based on observations of birds feeding behavior.
- d. Wrapping of maize cobs: Covering the maize cobs by wrapping of leaves around them.



- e. Reduce the parakeet and crow damage to negligible level. Being hidden and camouflaged the wrapped cobs escape to locate by the birds and thus crop is protected. The process is much less time-consuming than scaring, extremely straightforward and material-free. The grain yield is not negatively impacted. By using this method (Rao and Dubey, 2016).

Chemical Repellents:

- a. Use of Botanical Pesticides: Use of botanical pesticides with Neem formulations 10 ml/L of water at the time of milk stage on the crop, repel the birds from cropped area, if necessary the applications can be repeated after 10 days.
- b. Methyl anthranilate is offered as volatilizing paint-on liquids, blocks and pouches as well as a fog or spray for perches and roosts. It can also be used on a range of crops and irritates the trigeminal nerve, which makes it toxic to birds (Avery *et al.*, 1996; Linz *et al.*, 2011).

Habitat Modification:

- a. Birds are more likely to forage on the edges of fields than in the center, so reconfiguring fields to increase the area to perimeter ratio could help reduce crop damage. Removing natural habitat around fields can actually increase crop damage and food safety concerns, because birds have less access to alternative food sources, perches and roosts.
- b. Many bird species are closely linked to specific habitats and modifying conditions within agricultural ecosystems can help reduce or prevent crop damage caused by them. Parakeet populations were successfully reduced when the nests entrances were sealed. Planting fruit-bearing trees within and around cultivated fields can attract many grain-feeding birds during their fruiting season, thereby reducing their damage to crops at critical growth stages.
- c. Lure crop method: Availability of alternative food is an important factor in determining bird damage to commercial crops. The presence of sorghum screens around maize fields provide protection from parakeets since parakeets prefer sorghum over maize as revealed by their food preferences in captivity. Damage by weaver birds to paddy can be reduced by keeping small tracts of pearl millet near paddy fields as an alternative food. Naturally occurring plant species around farm area, such as palas, (*Butea monosperma*) attracts many depredatory species during flowering stage and thus reduces bird visit to crop area (Kler, 2010).

Advanced Bird Repellent Technologies

IoT-Based Smart Repellent Systems: This system will use the YOLO11m algorithm to identify birds in real time, then activate a sound repellent device (bell.mp3) through an IoT module. This system is designed to respond quickly to the presence of birds in fields, thereby reducing crop damage and increasing crop productivity (Hirzi *et al.*, 2025).

Ultrasonic Repellent Systems

Ultrasonic repeller: Ultrasonic waves are generated, which are not within the spectrum audible to humans. It is a common way that manages to make birds uncomfortable, preventing them from gathering in the area to be protected. Usually, its use AC or DC power supply is required by batteries.

Laser-Based Systems

1. Lasers include light-emitting devices such as pointers and light guns that can be flashed in fields and at perched or roosting birds. Lasers are most effective at dusk and dawn when ambient light levels are low. Repeated targeting of roosting by lasers has been reported to successfully clear roosts (Varriano *et al.*, 2025).

2. Sensors: Technology of laser sensor is effective for remote bird control and is based on a high frequency light beam and optical filters. This allows for keeping the infrastructure of the companies and the crops protected from damage by birds without causing them harm (Yauri, *et al.*, 2023).

3. PIR sensor: It is a passive infrared sensor that interacts with the energy sources of the animals. This sensor captures the variation of environmental radiation and can be used to detect intruders (Ruban *et al.*, 2025).

4. Drones or unmanned aerial vehicles (UAVs), can be used to harass and drive off birds from fields. Drones, especially when paired with auditory cues such as predator noises or distress calls, can present a more realistic threat to birds than other scaring devices, but as with other kinds of predator decoys, they may be more effective at deterring some bird species than others (Holevinski *et al.*, 2007).

Conclusion

Bird repellents are vital for protecting crops and sustaining agricultural productivity, but traditional methods alone are often ineffective in the long run due to bird habituation. Modern technologies such as IoT, drone and ultrasonic devices provide more efficient and eco-friendly alternatives, yet no single solution works in all situations. Therefore, an integrated and adaptive approach combining conventional and advanced methods and modifying them over time is essential for effective, long-term bird pest management while maintaining ecological balance.

Note

All the information presented here fully complies with national and state-level wildlife conservation laws. This article does not encourage any form of harm or illegal activities against them.

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From Waste to Watts: Biogas as India's Sustainable Solution to Agricultural Waste and Energy Insecurity

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Avinash C¹, Shevakula Manasa¹

¹Ph.D. Scholar, Division of Environmental Sciences, ICAR - Indian Agricultural Research Institute, New Delhi.

Abstract

India generates large quantities of agricultural residues annually, much of which is openly burned, causing severe air pollution and greenhouse gas emissions. Biogas technology offers a sustainable solution by converting organic waste into clean and renewable energy through anaerobic digestion. This article highlights the production process, composition, applications, and environmental benefits of biogas in India. It also discusses major government initiatives such as GOBAR-Dhan, SATAT, and the National Bioenergy Programme that promote biogas development. In addition to reducing stubble burning and improving air quality, biogas supports rural livelihoods, enhances soil fertility through digestate application, and strengthens national energy security.

The Agricultural Waste Crisis in India

India is one of the largest agricultural producers, generating approximately 600 million tonnes of crop residues annually. Of this, 141 million tonnes are surplus, and out of which 92 million tonnes are burned in open fields, primarily in states such as Punjab, Haryana, and Uttar Pradesh during post-harvest seasons (Bimbraw, 2019). This practice of stubble burning releases particulate matter (PM_{2.5} and PM₁₀), carbon monoxide, black carbon, and greenhouse gases into the atmosphere, contributing to severe air quality degradation. Govardhan et al. (2023) quantified that stubble-burning activities in north-western India in 2021 contributed significantly to Delhi's air pollution episodes, and it is continuing every year, particularly during the onset of winter (Oct-November).

Biogas production is among the most environmentally and economically viable methods for converting surplus agricultural residues into value-added products. The dual benefit of energy generation and nutrient recovery makes biogas an ideal technology for a country like India, where both energy security and agricultural waste management are critical challenges.

What is Biogas?

Biogas is a combustible mixture of gases produced by the microbial decomposition of organic matter in the absence of oxygen. The process is known as anaerobic digestion (AD). The feedstocks include cattle dung, crop residues, kitchen waste, vegetable waste, agro-industrial waste, and sewage sludge.

Composition and Properties: Methane (CH₄) gas is the primary component of biogas, constituting 55-65% of its volume, followed by CO₂ (30-40%), as shown in Table 1. The energy content of biogas is approximately between 16 MJ/m³ and 28 MJ/m³, making it a clean fuel for multiple applications (IEA, 2026).

Table 1. Chemical Composition of Biogas:

Component	Chemical Formula	Percentage (%)
Methane	CH ₄	55-65%
Carbon dioxide	CO ₂	30-40%
Hydrogen	H ₂	1-5%
Nitrogen	N ₂	1%
Water vapour	H ₂ O	0.1%
Hydrogen sulfide	H ₂ S	0.1%
Others	Various	0.1%

Stages of Anaerobic Digestion

Biogas is produced through a sequential four-stage biochemical process carried out by microbial communities inside an anaerobic digester maintained at mesophilic conditions (25-35°C).

Stage I (Hydrolysis): Complex organic polymers such as carbohydrates, proteins, and lipids are broken down by hydrolytic bacteria into simpler, soluble monomers such as sugars, amino acids, and fatty acids.

Stage II (Acidogenesis): The soluble monomers produced during hydrolysis are fermented by acidogenic bacteria into volatile fatty acids (VFAs) such as lactic acid, acetic acid, and propionic acid, along with hydrogen and carbon dioxide.

Stage III (Acetogenesis): Acetogenic bacteria convert the VFAs into acetic acid (acetate), H₂, and CO₂, which are the direct precursors to methane production.

Stage IV (Methanogenesis): Methanogenic archaea are the most environmentally sensitive microbial group in the digester, converting acetate, carbon dioxide, and hydrogen into methane and water. This final stage determines the gas yield and quality of the biogas produced.

Applications for Biogas

Biogas is a versatile renewable energy source with applications in domestic, agricultural, industrial, and transportation sectors. Table 2 shows the fuel equivalence of 1 m³ of biogas.

1. Cooking and thermal energy: The most widespread use of biogas in India is as a clean cooking fuel in rural households, replacing firewood, dung cakes, and kerosene. This reduces indoor air pollution, which is responsible for premature deaths in India.

2. Electricity generation: Biogas can be used to run generators for community-level electricity production, supporting irrigation pumps, agro-processing units, and rural households.

3. Compressed Biogas (CBG) for transportation: Biogas purified and upgraded to more than 98% methane becomes CBG, a direct substitute for CNG in vehicles. The HPCL CBG plant in Badaun, Uttar Pradesh, utilizes 100 metric tonnes of rice straw daily to produce 14 tonnes of CBG and 65 tonnes of nutrient-rich manure (PIB, 2024).

4. Industrial feedstock: Methane extracted from biogas serves as a raw material for producing chemicals such as methanol and hydrogen, making it valuable for industrial decarbonization.

5. Digestate as biofertilizer: The slurry remaining after digestion is a rich source of macro and micronutrients. Kapoor et al. (2020) emphasized that biogas slurry application to fields not only improves soil health but also reduces chemical fertilizer consumption.

Table 2. Fuel Equivalence of 1 m³ of Biogas:

Conventional Fuel	Quantity Equivalent
Kerosene	0.62 litre
Fire-wood	3.47 kg
Cow dung cake	12.29 kg
Electricity	4.69 kWh
CNG	0.9 m ³
Petrol	0.5 litre
Diesel	0.6 litre

Source: Surendra et al. (2013)

India's Policy Landscape: Schemes and Targets

Recognizing biogas as a critical pillar of renewable energy and waste management strategy, the Government of India has launched several flagship schemes. In 2024, India's biogas market size was estimated at approximately USD 1.6 billion, projected to reach USD 3.5-4.9 billion by 2032 (FBI, 2026). Also, India currently has over 5 million household biogas plants.

1. GOBAR-Dhan Scheme: Galvanizing Organic Bio-Agro Resources Dhan was launched in 2018. As of 2025, 583 biogas plants are functional under GOBAR-Dhan, with a total installed capacity of 19,837 m³ of biogas and 3,11,086 kg of commercial CBG (DTE, 2023).

2. SATAT Scheme: The Sustainable Alternative Towards Affordable Transportation initiative, managed by the Ministry of Petroleum and Natural Gas, promotes CBG as a transport fuel. It targets 5,000 CBG plants producing 15 million MT per annum by 2023-24 (PIB, 2022).

3. National Bioenergy Programme: Phase I of the NBP, notified by MNRE in 2022, has an approved budget of ₹100 crore specifically for the Biogas Programme supporting small (1-25 m³/day) to medium-scale plants (up to 2,500 m³/day) (MNRE, 2026).

4. National Policy on Biofuels (2018, revised 2022): The policy sets a target of 20% ethanol blending (E20) by 2025-26 and 5% biodiesel blending by 2030, with biogas positioned as a complementary component of India's overall bioenergy strategy.

Environmental and Socioeconomic Benefits

Beyond energy production, biogas systems deliver substantial environmental and socioeconomic benefits that align with India's Nationally Determined Contributions under the Paris Agreement. India has committed to reducing the emissions intensity of its GDP by 45% by 2030 compared to 2005 levels, and biogas can contribute meaningfully.

GHG emission reduction: Every tonne of agricultural waste diverted from open burning to anaerobic digestion avoids the direct emission of CO₂, CH₄, and N₂O.

Soil health and fertilizer savings: Digestate application reduces dependence on synthetic chemical fertilizers, improving organic carbon, microbial activity, and water-holding capacity of soils.

Rural employment and livelihoods: The biogas value chain creates decentralized employment in rural areas. The HPCL Badaun CBG plant alone provides direct and indirect employment to hundreds of agricultural labourers and farmers in the surrounding region (PIB, 2024).

Air quality improvement: Replacing stubble burning with biogas production directly addresses one of India's most pressing public health emergencies.

Conclusion

Biogas has significant potential to address India's dual challenge of agricultural waste management and energy insecurity. By converting crop residues and organic wastes into renewable energy, biogas reduces open-field burning, greenhouse gas emissions, and dependence on fossil fuel imports. The technology also contributes to improved soil health, rural employment, and sustainable agricultural practices through the use of nutrient-rich digestate. With proper policy support, infrastructure, and public awareness, biogas can become an important component of India's transition toward a cleaner and more sustainable energy future.

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Role of Digital Platforms in Agricultural Marketing and Price Discovery

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Puja Sinha¹

¹Research Scholar, Department of Agricultural Economics and Statistics, Chandra Shekhar Azad University of Agriculture & Technology, Kanpur, Uttar Pradesh.

Abstract

Agricultural marketing in India has historically been constrained by inefficiencies such as fragmented markets, information asymmetry, and the dominance of intermediaries, resulting in low price realization for farmers. The emergence of digital platforms has introduced a structural transformation in the marketing ecosystem by enabling transparent transactions, real-time price dissemination, and direct farmer-buyer linkages. This study critically examines the role of digital platforms in improving marketing efficiency and strengthening price discovery mechanisms. Using secondary data and analytical insights, the paper highlights that digital initiatives such as e-NAM have significantly reduced price dispersion, improved farmers' bargaining power, and enhanced market integration. However, constraints such as digital illiteracy, infrastructural gaps, and institutional limitations continue to restrict their full potential. The study concludes that digital platforms can play a transformative role in increasing farmers' income, provided supportive policies and infrastructure are strengthened.

Keywords: Digital Agriculture, Price Discovery, Market Efficiency, e-NAM, Information Asymmetry, Farmer Income.

Introduction

Agricultural marketing is a crucial determinant of farmers' income and overall agricultural development. In India, the traditional marketing system is largely governed by regulated markets (APMCs), where farmers often face challenges such as lack of competition, delayed payments, and exploitation by intermediaries. One of the major issues in this system is inefficient price discovery, caused by limited access to market information and restricted market participation.

Digital platforms have emerged as a solution to these challenges by integrating markets and improving transparency. With the introduction of electronic trading systems, mobile-based applications, and online marketplaces, farmers now have access to real-time price information and a wider range of buyers. These developments have significantly improved the efficiency of agricultural markets and strengthened price discovery mechanisms.

Concept of Price Discovery in Agriculture

Price discovery refers to the process through which the price of a commodity is determined based on demand and supply interactions in a competitive market. In traditional agricultural markets, price discovery is often distorted due to:

1. Information asymmetry
2. Limited number of buyers
3. Collusion among traders
4. Lack of transparency in bidding

Digital platforms address these issues by ensuring open and competitive bidding, thereby leading to more accurate and fair price determination.

Role of Digital Platforms in Agricultural Marketing

- 1. Market Integration:** Digital platforms integrate geographically dispersed markets into a unified system. This reduces regional price disparities and ensures that farmers receive competitive prices irrespective of their location.
- 2. Real-Time Market Information:** Access to real-time data on prices, arrivals, and demand conditions enables farmers to make informed decisions regarding when and where to sell their produce.
- 3. Reduction of Intermediaries:** By facilitating direct transactions between farmers and buyers, digital platforms reduce the role of middlemen, thereby increasing the farmer's share in the consumer's rupee.
- 4. Improved Supply Chain Efficiency:** Digital platforms streamline logistics, storage, and transportation, reducing post-harvest losses and ensuring timely delivery of produce.
- 5. Access to Wider Markets:** Farmers are no longer restricted to local mandis and can sell their produce across states, enhancing competition and price realization.

Impact on Price Discovery Mechanism

Digital platforms significantly improve price discovery through:

1. Transparent Bidding Systems: Ensures fair competition among buyers
2. Reduction in Price Dispersion: Uniform prices across markets
3. Efficient Information Flow: Eliminates uncertainty in pricing
4. Demand-Supply Matching: Better alignment of production with market demand

Studies indicate that farmers using digital platforms often receive 5-15% higher prices compared to traditional markets due to improved transparency and competition.

Empirical Insights

Table 1: Comparison of Traditional vs Digital Marketing Systems:

Aspect	Traditional System	Digital Platform
Market Access	Localized	National/Global
Price Information	Delayed	Real-time
Intermediaries	High	Reduced
Transparency	Low	High
Farmer Share in Consumer Price	40-50%	60-75%

Constraints in Adoption

Despite the advantages, the adoption of digital platforms is limited due to:

1. Digital Illiteracy: Many farmers lack the skills to use digital tools
2. Infrastructure Gaps: Poor internet connectivity in rural areas
3. Institutional Weakness: Inefficient implementation of digital policies
4. Trust Issues: Hesitation in adopting online transactions
5. Small Landholdings: Limited marketable surplus reduces participation.

Policy Implications

To enhance the effectiveness of digital platforms, the following measures are recommended:

1. Strengthening rural digital infrastructure
2. Providing training programs for farmers
3. Promoting awareness about digital marketing tools
4. Encouraging public-private partnerships
5. Ensuring secure and transparent transaction systems

Conclusion

Digital platforms have the potential to revolutionize agricultural marketing by improving efficiency, transparency, and price discovery. They empower farmers with better market access, reduce dependency on intermediaries, and enhance income levels. However, their success depends on addressing key challenges related to infrastructure, awareness, and institutional support. A coordinated approach involving government intervention, technological innovation, and farmer participation is essential to fully realize the benefits of digital agriculture.

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Breeding for Climate Resilience in Major Fruit Crops - Advances and Challenges

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Shri. V. N. Patil¹, Dr. V. D. Tayade², Dr. V. G. Kalpande³, Nicky Bansod⁴

¹Assistant Professor of Horticulture, Bhausaheb Fundkar Government College of Agriculture, Buldhana (Dr. PDKV., Akola).

²Assistant Professor (C) of Horticulture, Bhausaheb Fundkar Government College of Agriculture, Buldhana (Dr. PDKV., Akola).

³Assistant Professor of Agricultural Botany, Bhausaheb Fundkar Government College of Agriculture, Buldhana (Dr. PDKV., Akola).

⁴Assistant Professor of Agricultural Entomology, SVGI, College of Agriculture, Jalgaon Jamod (MS).

Abstract

Climate change has emerged as one of the most serious threats to global fruit production systems. Rising temperatures, erratic rainfall, prolonged droughts, salinity, flooding, and the increasing incidence of pests and diseases are adversely affecting the productivity, quality, and sustainability of fruit crops worldwide. Fruit crops are particularly vulnerable because of their perennial nature and sensitivity to environmental fluctuations during flowering, fruit set, and fruit development. Breeding for climate resilience has therefore become a major priority in horticultural research. Recent advances in conventional breeding, molecular breeding, genomics, marker-assisted selection, genome editing, and phenomics have accelerated the development of stress-tolerant fruit crop cultivars. Important traits such as drought tolerance, heat tolerance, salinity resistance, water-use efficiency, and disease resistance are increasingly being incorporated into breeding programs. Major fruit crops including mango, banana, citrus, grapevine, apple, guava, papaya, pomegranate, and strawberry are being improved for climate resilience through integrated breeding approaches. However, challenges such as long juvenile periods, complex genetics, polyploidy, narrow genetic diversity, and strong genotype × environment interactions continue to limit breeding efficiency. This review discusses the impact of climate change on fruit crops, physiological and genetic mechanisms of stress tolerance, conventional and advanced breeding strategies, recent technological advances, crop-specific breeding efforts, major challenges, and future prospects for developing climate-resilient fruit cultivars.

Introduction

Climate change is increasingly affecting agricultural and horticultural production systems across the world. Rising atmospheric temperatures, changing rainfall patterns, frequent droughts, floods, salinity intrusion, and extreme weather events are significantly influencing crop growth and productivity. Fruit crops are highly sensitive to climatic variations because their flowering, pollination, fruit set, ripening, and quality are strongly influenced by environmental conditions. Consequently, climate variability has become a major constraint in sustainable fruit production.

Fruit crops contribute significantly to global nutritional security, farm income, export earnings, and livelihood generation. However, increasing climatic stress is threatening orchard productivity and fruit quality. Temperature rise has altered flowering patterns and chilling requirements in temperate fruit crops, while tropical fruit crops are increasingly experiencing heat stress, water scarcity, and sunburn injuries. Moreover, climate change has increased the prevalence of insect pests and diseases in many fruit-growing regions.

Breeding climate-resilient fruit crops is therefore essential for ensuring sustainable horticultural production under changing climatic conditions. Climate-resilient cultivars possess the ability to tolerate abiotic and biotic stresses while maintaining stable yield and fruit quality. Advances in molecular biology, genomics, and biotechnology have revolutionized fruit breeding programs and improved the efficiency of developing stress-tolerant cultivars. Recent studies have emphasized the importance of integrating conventional breeding with modern genomic tools for developing climate-resilient crops capable of tolerating multiple stresses simultaneously (Sugumar et al., 2024).

Climate Change and its Impact on Fruit Crops

Climate change affects fruit crops at physiological, biochemical, molecular, and developmental levels. Fruit crops require specific climatic conditions for optimum growth and fruiting, and even slight deviations can cause substantial reductions in productivity and fruit quality.

Temperature Stress: Increasing temperature is one of the most severe consequences of climate change. High temperature affects flowering, pollen viability, fruit set, fruit growth, and ripening. In temperate fruit crops such as apple, pear, peach, and plum, inadequate winter chilling due to warmer winters causes irregular flowering and reduced fruit set. In tropical and subtropical fruit crops such as mango, banana, papaya, and citrus, elevated temperatures lead to floral abnormalities, fruit sunburn, and poor fruit quality. Heat stress damages chloroplast membranes and

photosynthetic enzymes, resulting in reduced photosynthesis and increased respiration. Excessive heat also accelerates fruit ripening and reduces storage life.

Drought Stress: Water scarcity is becoming increasingly severe due to declining rainfall and depleting groundwater resources. Drought stress reduces stomatal conductance, photosynthesis, nutrient uptake, and cell expansion. Consequently, fruit size, yield, and quality decline significantly. In mango and citrus, drought stress causes flower and fruit drop, while in banana it reduces bunch weight and fruit filling. Drought also alters hormonal balance and root growth dynamics. Improvement of water-use efficiency, osmotic adjustment, and root architecture are important targets in drought-resilient breeding programs.

Salinity Stress: Salinity is an emerging problem in irrigated fruit-growing regions. Excess accumulation of salts in soil causes osmotic stress, ion toxicity, oxidative damage, and nutrient imbalance. Fruit crops such as citrus, grapevine, strawberry, and banana are particularly sensitive to salinity stress. Salt injury reduces plant vigor, leaf area, fruit size, and overall productivity. Breeding for salinity tolerance involves improving ion exclusion mechanisms, antioxidant activity, and osmo-protectant accumulation.

Flooding and Waterlogging: Climate change has increased the frequency of heavy rainfall and flooding events. Waterlogging reduces oxygen availability in the root zone and impairs root respiration and nutrient absorption. Papaya, banana, and several tropical fruit crops are highly susceptible to waterlogging injury.

Pest and Disease Incidence: Changing climatic conditions favour the spread and survival of insect pests and pathogens. Increased humidity and temperature create favourable conditions for many fungal, bacterial, and viral diseases. Climate change has also facilitated the emergence of new pest biotypes and pathogen races. Diseases such as citrus greening, Fusarium wilt of banana, anthracnose, powdery mildew, bacterial blight, and viral diseases are becoming more severe under changing climatic conditions.

Physiological Mechanisms of Climate Resilience

Climate-resilient fruit crops possess several adaptive physiological and biochemical mechanisms that enable them to survive under stress conditions.

- 1. Photosynthetic Stability:** Stress-tolerant genotypes maintain higher photosynthetic activity under adverse environmental conditions through better chlorophyll retention and efficient stomatal regulation.
- 2. Root Architecture:** Deep and extensive root systems enhance water and nutrient absorption under drought conditions. Improved root plasticity is considered an important adaptive trait.
- 3. Osmotic Adjustment:** Accumulation of compatible solutes such as proline, glycine betaine, and soluble sugars helps maintain cell turgor during drought and salinity stress.
- 4. Antioxidant Defense System:** Abiotic stresses generate reactive oxygen species that damage cellular structures. Climate-resilient cultivars possess stronger antioxidant defence systems involving enzymes such as superoxide dismutase, catalase, and peroxidase.
- 5. Hormonal Regulation:** Plant hormones including abscisic acid, salicylic acid, cytokinins, and ethylene regulate stress responses and adaptation mechanisms in fruit crops.

Conventional Breeding Approaches

Conventional breeding remains an important strategy for improving climate resilience in fruit crops.

- 1. Germplasm Selection:** Selection of naturally adapted genotypes from local germplasm collections has been widely practiced in fruit crop improvement. Indigenous cultivars often possess valuable adaptive traits.
- 2. Hybridization:** Hybridization combines desirable traits from different parents to generate improved cultivars. Breeding programs in mango, grapevine, citrus, and guava have focused on combining stress tolerance with superior fruit quality.
- 3. Rootstock Breeding:** Rootstocks play a major role in imparting tolerance to drought, salinity, flooding, and diseases. Stress-tolerant rootstocks have significantly improved orchard performance in citrus and apple cultivation.
- 4. Mutation Breeding:** Mutation breeding creates novel genetic variability through physical or chemical mutagens. Mutation-derived variants with improved stress tolerance have been identified in banana and citrus. Despite its importance, conventional breeding in fruit crops is slow due to long juvenile periods, heterozygosity, self-incompatibility, and polyploidy.

Molecular Breeding and Genomic Approaches

Advances in molecular genetics and genomics have transformed fruit crop breeding.

- 1. Marker-Assisted Selection:** Marker-assisted selection enables breeders to identify desirable genotypes using DNA markers linked to stress-responsive genes. Molecular markers such as SSRs, SNPs, AFLPs, and RAPDs are widely used in

fruit breeding programs. Marker-assisted breeding accelerates the development of stress-tolerant cultivars by reducing dependency on phenotypic screening.

2. Quantitative Trait Loci Mapping: Quantitative trait loci mapping identifies genomic regions associated with important adaptive traits such as drought tolerance, heat tolerance, and disease resistance.

3. Genomic Selection: Genomic selection uses genome-wide marker information to predict breeding values and accelerate selection efficiency for complex traits.

4. Transcriptomics and Functional Genomics: Transcriptomic studies help identify stress-responsive genes and regulatory pathways involved in climate adaptation. RNA sequencing technologies have greatly enhanced the understanding of molecular responses to abiotic stress.

5. Genome Editing: Genome-editing technologies such as CRISPR/Cas systems enable precise modification of stress-responsive genes. Genome editing offers tremendous opportunities for developing fruit crops with enhanced tolerance to drought, heat, salinity, and diseases. Recent advances indicate that genomic tools and precision breeding technologies can substantially improve climate resilience in horticultural crops (Totawar et al., 2026).

High-Throughput Phenotyping and Artificial Intelligence

Modern breeding increasingly depends on high-throughput phenotyping technologies involving imaging systems, drones, sensors, robotics, and artificial intelligence. Phenotyping platforms enable rapid evaluation of physiological traits such as canopy temperature, chlorophyll fluorescence, root growth, and water-use efficiency under stress conditions. Artificial intelligence and machine learning algorithms are increasingly used for analyzing large datasets and predicting genotype performance under different climatic conditions.

Breeding Climate-Resilient Major Fruit Crops

1. Mango: Mango is highly susceptible to temperature fluctuations and drought stress. Heat stress during flowering reduces pollen viability and fruit set. Breeding objectives include regular bearing, heat tolerance, drought resistance, and disease resistance. Wild mango relatives and indigenous cultivars serve as valuable genetic resources for adaptive traits.

2. Banana: Banana production is threatened by drought, salinity, heat stress, and devastating diseases such as Fusarium wilt Tropical Race 4. Breeding programs aim to develop stress-tolerant hybrids through conventional and molecular approaches. Polyploidy and sterility remain major constraints in banana breeding.

3. Citrus: Citrus crops face severe challenges from salinity, drought, and citrus greening disease. Rootstock breeding has been highly successful in improving stress tolerance and orchard resilience.

4. Grapevine: Climate change affects berry composition, sugar accumulation, anthocyanin synthesis, and wine quality. Breeding efforts focus on drought tolerance, heat tolerance, and fungal disease resistance. Wild grape species provide important sources of adaptive genes.

5. Apple: Apple production is increasingly threatened by declining winter chilling due to rising temperatures. Breeding programs focus on low-chill cultivars, heat tolerance, and disease resistance. Genomic tools have accelerated early selection in apple breeding programs.

6. Guava: Guava possesses moderate adaptability to stress conditions, but drought and salinity significantly reduce productivity. Breeding programs aim to improve fruit quality, stress tolerance, and resistance to wilt disease.

7. Papaya: Papaya is highly sensitive to waterlogging and viral diseases. Breeding strategies focus on improving tolerance to abiotic stress and papaya ring spot virus.

8. Pomegranate: Pomegranate is comparatively drought tolerant and is considered a promising fruit crop under arid conditions. However, fruit cracking and bacterial blight remain major concerns.

9. Strawberry: Strawberry is highly sensitive to heat and salinity stress. Breeding efforts focus on improving heat tolerance, fruit firmness, shelf life, and disease resistance.

Role of Wild Relatives and Germplasm Resources

Wild relatives and traditional landraces possess valuable adaptive traits that are often absent in commercial cultivars. Germplasm conservation and characterization are therefore essential for climate-resilient breeding. Crop wild relatives provide genes for drought tolerance, salinity resistance, disease resistance, and environmental adaptability. Introgression breeding involving wild species has become increasingly important in fruit crop improvement.

Challenges in Breeding Climate-Resilient Fruit Crops

Several biological, technical, and economic constraints hinder the development of climate-resilient fruit cultivars.

- 1. Long Juvenile Periods:** Many fruit crops require several years before flowering and fruiting, making breeding programs extremely time-consuming.
- 2. Complex Genetic Architecture:** Fruit crops are often highly heterozygous and polyploid, complicating inheritance patterns and trait selection.
- 3. Genotype × Environment Interaction:** Environmental variability strongly influences the expression of adaptive traits, reducing selection efficiency.
- 4. Narrow Genetic Diversity:** Commercial cultivation often depends on a few elite cultivars, increasing vulnerability to climatic stresses.
- 5. Limited Genomic Resources:** Compared to cereals, genomic information and molecular markers are still limited in many fruit crops.
- 6. Regulatory Challenges:** Genome-edited crops face regulatory restrictions and public acceptance issues in several countries.
- 7. Phenotyping Constraints:** Accurate field phenotyping under variable climatic conditions remains a major challenge in breeding programs.

Future Prospects

Future breeding strategies for climate resilience will increasingly integrate genomics, phenomics, biotechnology, artificial intelligence, and systems biology approaches. Speed breeding, genomic prediction, gene editing, and multi-omics technologies are expected to accelerate the development of stress-resilient fruit cultivars. Integration of transcriptomics, proteomics, metabolomics, and epigenomics will improve understanding of stress adaptation mechanisms. Participatory breeding involving farmers and local communities may help identify region-specific resilient genotypes. Conservation and utilization of indigenous germplasm and wild relatives will remain crucial for sustainable fruit breeding. Climate-smart horticultural practices combined with resilient cultivars will be essential for maintaining productivity under changing climatic conditions. Studies have emphasized that developing climate-resilient crops capable of tolerating heat, drought, and salinity is essential for sustainable agriculture under future climate scenarios (Cabusora et al., 2024).

Conclusion

Climate change poses a major threat to global fruit production systems through increasing temperatures, water scarcity, salinity, flooding, and enhanced pest and disease pressures. Fruit crops are particularly vulnerable because of their perennial nature and environmental sensitivity. Breeding for climate resilience has therefore become a critical component of sustainable horticultural development. Conventional breeding approaches continue to play a significant role; however, integration with molecular breeding, genomics, genome editing, phenomics, and artificial intelligence has greatly enhanced breeding efficiency. Major fruit crops such as mango, banana, citrus, grapevine, apple, guava, papaya, pomegranate, and strawberry are increasingly being targeted for the development of resilient cultivars. Despite significant progress, several challenges including long breeding cycles, polyploidy, limited genomic resources, and environmental variability continue to restrict breeding advancements. Future research should focus on multi-stress tolerance, utilization of wild germplasm, precision breeding technologies, and interdisciplinary approaches to ensure sustainable fruit production under changing climatic conditions.

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Nanotechnology and Precision Tools for Targeted Pest and Disease Management

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Dr. Srujani Behera¹, Dr. Anupam Kumari², Dr. Ipsita Das³, Dr. Simly Das⁴

¹Assistant Professor (Plant Pathology), College of Agriculture, Odisha University of Agriculture and Technology, Bhubaneswar, Odisha.

²Assistant Professor -cum- Jr. Scientist, Dept. of Plant Pathology, B.P.S. Agricultural College, Purnea (BAU, Sabour).

³Assistant Professor, Department of Soil Science & Agricultural Chemistry, College of Agriculture, Odisha University of Agriculture and Technology, Chiplima.

⁴Assistant Professor (Nematology), College of Agriculture, Odisha University of Agriculture and Technology, Bhubaneswar, Odisha.

Abstract

The rapid growth of the global population and the increasing demand for sustainable food production have intensified the need for advanced crop protection technologies capable of minimizing losses caused by insect pests and plant diseases. Conventional chemical-based pest management strategies, although effective, have resulted in environmental contamination, pesticide resistance, destruction of beneficial organisms, and harmful impacts on human and animal health. In this context, nanotechnology and precision agriculture tools have emerged as revolutionary approaches for targeted pest and disease management. Nanotechnology facilitates the development of nanopesticides, nanosensors, nanoformulations, and controlled-release systems that improve pesticide efficiency and reduce environmental hazards. Precision agriculture technologies such as drones, remote sensing, artificial intelligence, machine learning, GPS, GIS, Internet of Things (IoT), robotics, and biosensors enable real-time monitoring, early disease diagnosis, and site-specific crop protection interventions. The integration of these advanced technologies has significantly improved the precision, sustainability, and effectiveness of pest and disease management strategies. This review comprehensively discusses the principles, applications, mechanisms, advantages, limitations, environmental implications, and future prospects of nanotechnology and precision tools in modern crop protection systems.

Introduction

Agriculture faces enormous challenges due to increasing incidences of insect pests, plant pathogens, nematodes, weeds, and climate-induced stresses. Crop losses caused by pests and diseases are responsible for severe reductions in agricultural productivity worldwide. Traditionally, chemical pesticides and fungicides have been the primary means of crop protection. However, the excessive and indiscriminate use of these chemicals has resulted in pesticide resistance, resurgence of secondary pests, environmental pollution, soil degradation, groundwater contamination, and toxic residues in food products. Moreover, conventional pesticides often affect non-target organisms including pollinators, predators, parasitoids, soil microorganisms, birds, and aquatic organisms (Kah et al., 2013).

Sustainable agriculture requires innovative crop protection technologies that are efficient, environmentally safe, and economically viable. Nanotechnology and precision agriculture have emerged as transformative scientific innovations capable of revolutionizing pest and disease management systems. Nanotechnology involves the manipulation and application of materials at the nanoscale level, generally ranging from 1 to 100 nanometers (Mishra et al., 2017). At this scale, materials exhibit unique physicochemical properties such as enhanced surface area, increased reactivity, improved stability, and superior delivery capabilities.

Precision agriculture refers to the use of advanced digital technologies for monitoring and managing spatial and temporal variability within agricultural fields. Precision crop protection focuses on applying pesticides and management inputs only where and when required. The integration of nanotechnology with precision tools provides unprecedented opportunities for targeted pest suppression, smart pesticide delivery, real-time disease detection, automated surveillance, and sustainable crop protection.

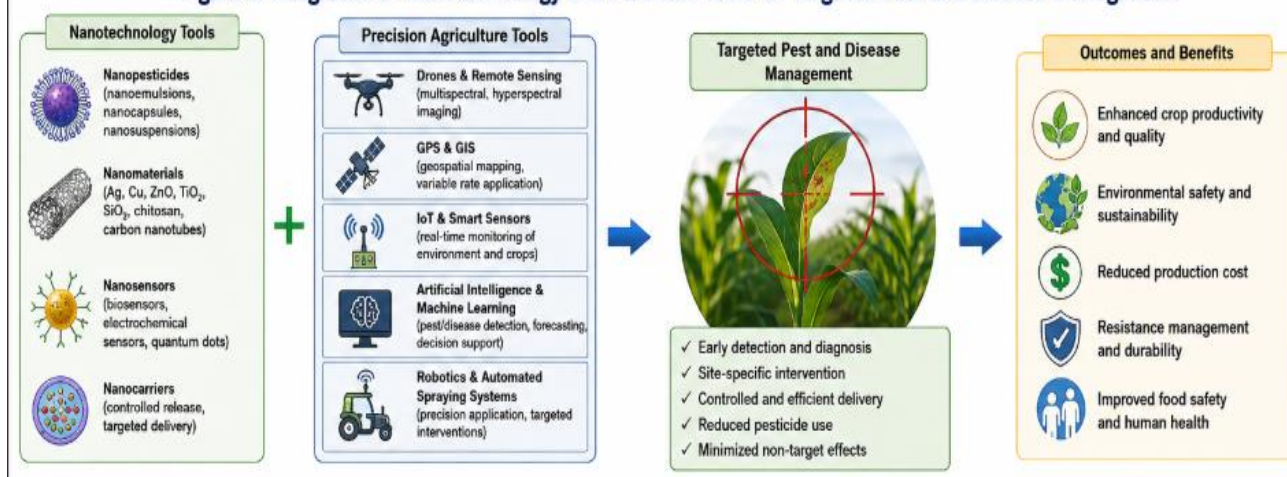
Nanotechnology in Crop Protection

Nanotechnology has gained considerable attention in agriculture because of its ability to improve pesticide efficiency and reduce environmental contamination. Nanomaterials possess unique optical, electrical, magnetic, and chemical properties that enhance their agricultural applications. In crop protection, nanotechnology is primarily used for developing nanopesticides, nanocarriers, nanosensors, and nano-enabled delivery systems. Nanoparticles improve the solubility and stability of active ingredients and facilitate controlled release mechanisms. Nanoformulations reduce volatilization, photodegradation, leaching, and off-target movement of pesticides. The small size of nanoparticles enhances their penetration into plant tissues and insect cuticles, thereby increasing pesticide efficacy (Kah et al., 2013).

Several types of nanomaterials are utilized in pest and disease management. Metallic nanoparticles such as silver, copper, zinc oxide, and titanium dioxide nanoparticles possess strong antimicrobial and insecticidal properties. Polymeric nanoparticles, chitosan nanoparticles, nanoemulsions, nanocapsules, carbon nanotubes, dendrimers, and mesoporous silica nanoparticles are increasingly employed as delivery systems for agrochemicals.

Nanotechnology-based crop protection strategies significantly reduce pesticide dosage requirements and improve the persistence of active ingredients. Controlled-release formulations ensure prolonged protection and minimize repeated pesticide applications. These innovations contribute to environmentally sustainable agriculture and reduced chemical pollution (Khot et al., 2012).

Figure 1. Integration of Nanotechnology and Precision Tools for Targeted Pest and Disease Management



Nano-Pesticides and Controlled Release Systems

Nano-pesticides are one of the most important applications of nanotechnology in agriculture. These formulations are designed to improve the efficiency, stability, and delivery of pesticides while minimizing environmental hazards. Nano-formulations include nanoemulsions, nanosuspensions, nanocapsules, polymeric nanoparticles, and encapsulated pesticide systems (Khot et al., 2012). Nanoencapsulation protects pesticides from degradation caused by sunlight, temperature, oxidation, and moisture. Controlled-release systems gradually release active ingredients over extended periods, thereby reducing the frequency of pesticide applications. This mechanism enhances bioavailability and minimizes pesticide losses through runoff and leaching.

Silver nanoparticles have demonstrated strong antifungal and antibacterial activity against numerous plant pathogens. Copper nanoparticles inhibit fungal spore germination and damage microbial cell membranes. Zinc oxide nanoparticles exhibit broad-spectrum antimicrobial properties and interfere with microbial metabolism. Silica nanoparticles are effective against insect pests by causing abrasion and desiccation of insect cuticles.

Nanoformulations of botanical pesticides and essential oils have also shown promising results in pest management. Encapsulation improves the stability, persistence, and efficacy of plant-derived bioactive compounds. Nanotechnology therefore provides opportunities for developing eco-friendly biopesticides with enhanced performance. Nanopesticides have been recognized as important tools for sustainable crop protection because they improve pesticide efficiency and reduce environmental contamination (Kah et al., 2013).

Precision Agriculture for Pest and Disease Management

Precision agriculture utilizes advanced technologies to monitor crop conditions and optimize agricultural operations. Precision pest management aims to apply pesticides only where infestation occurs, thereby reducing unnecessary chemical applications and improving efficiency (Kah et al., 2013).

Remote sensing technologies play a critical role in precision crop protection. Satellite imagery, hyperspectral imaging, thermal sensors, and multispectral cameras are used to monitor crop health and detect disease symptoms at early stages. Spectral signatures associated with plant stress help identify infected plants before visible symptoms appear. Geographic Information Systems and Global Positioning Systems enable spatial mapping of pest infestations and disease outbreaks. These technologies facilitate site-specific pesticide applications and improve resource-use efficiency.

Artificial intelligence and machine learning algorithms analyze large volumes of agricultural data generated from drones, sensors, and imaging systems. Deep learning models can accurately identify insect pests and plant diseases from digital images. Predictive analytics models also forecast disease outbreaks using environmental and climatic parameters. The integration of advanced digital technologies with precision agriculture is transforming site-specific crop protection and disease forecasting systems (Rai et al., 2025).

Role of Drones and Robotics in Precision Pest Management

Drones or unmanned aerial vehicles have become highly valuable tools in precision agriculture. Drones equipped with thermal, multispectral, and hyperspectral cameras provide rapid aerial surveillance of crop fields. These systems can identify disease hotspots, nutrient deficiencies, and insect infestations with high accuracy. Drone-based pesticide spraying ensures uniform application and reduces pesticide drift. Variable-rate spraying technologies optimize pesticide dosage according to crop conditions and infestation intensity. Drones also reduce labour requirements and minimize human exposure to toxic chemicals (Mishra et al., 2017).

Agricultural robotics integrated with artificial intelligence are increasingly used for automated scouting, precision spraying, and weed management. Autonomous robots equipped with computer vision systems can identify infected plants and selectively apply pesticides. These technologies significantly improve precision and reduce operational costs.

Nanosensors and Smart Disease Detection

Nanosensors are highly sensitive devices capable of detecting pathogens, toxins, environmental stresses, and physiological changes in plants. These sensors utilize nanomaterials such as gold nanoparticles, carbon nanotubes, graphene, and quantum dots for rapid and accurate detection. Nanosensors can identify pathogen-specific DNA, proteins, metabolites, and volatile organic compounds associated with plant diseases. Early detection enables timely intervention and prevents disease spread within agricultural fields.

Smart sensor networks integrated with IoT platforms provide real-time monitoring of crop health, temperature, humidity, soil moisture, and pathogen activity. Continuous monitoring improves disease forecasting and supports precision management decisions. The application of nanosensors and smart monitoring systems has significantly enhanced precision disease diagnostics and crop protection efficiency (Gogos et al., 2012).

Environmental Benefits and Sustainability

Nanotechnology and precision agriculture contribute substantially to environmental sustainability. Controlled-release nano-pesticides reduce pesticide losses and environmental contamination. Precision spraying minimizes excessive pesticide use and protects beneficial organisms including pollinators and natural enemies (Mishra et al., 2017). Site-specific crop protection reduces chemical residues in soil, water, and food products. Smart monitoring systems improve resource-use efficiency and support climate-resilient agriculture. Nano-enabled biopesticides and biodegradable nanomaterials provide environmentally safer alternatives to synthetic pesticides. The integration of nanotechnology with biological control agents also promotes sustainable integrated pest management systems. Nanoencapsulation improves the stability and effectiveness of microbial biocontrol agents and botanical pesticides.

Challenges and Limitations

Despite significant advancements, several challenges hinder the large-scale adoption of nanotechnology and precision tools in agriculture. High development costs, limited infrastructure, and lack of technical expertise restrict accessibility, particularly among smallholder farmers. The environmental fate and toxicity of nanoparticles remain major concerns. Nanoparticles may accumulate in soil and aquatic ecosystems and potentially affect non-target organisms. Comprehensive biosafety assessments and regulatory frameworks are therefore essential. Precision agriculture technologies require reliable internet connectivity, sophisticated equipment, and efficient data management systems. Limited awareness and insufficient farmer training further constrain adoption in developing countries. Standardization of nanoparticle synthesis, formulation stability, and field evaluation protocols also remains a significant challenge.

Future Prospects

Future developments in agricultural nanotechnology are expected to focus on biodegradable nanoparticles, smart nano-delivery systems, AI-integrated nanosensors, autonomous robotic systems, and precision disease forecasting models. Advances in machine learning, cloud computing, and IoT technologies will further improve real-time crop monitoring and decision-making systems. The integration of nanotechnology with genomics, CRISPR-based technologies, and RNA interference approaches may revolutionize targeted pest management in the future. Sustainable and climate-smart agriculture will increasingly depend on intelligent precision technologies for efficient crop protection and resource conservation.

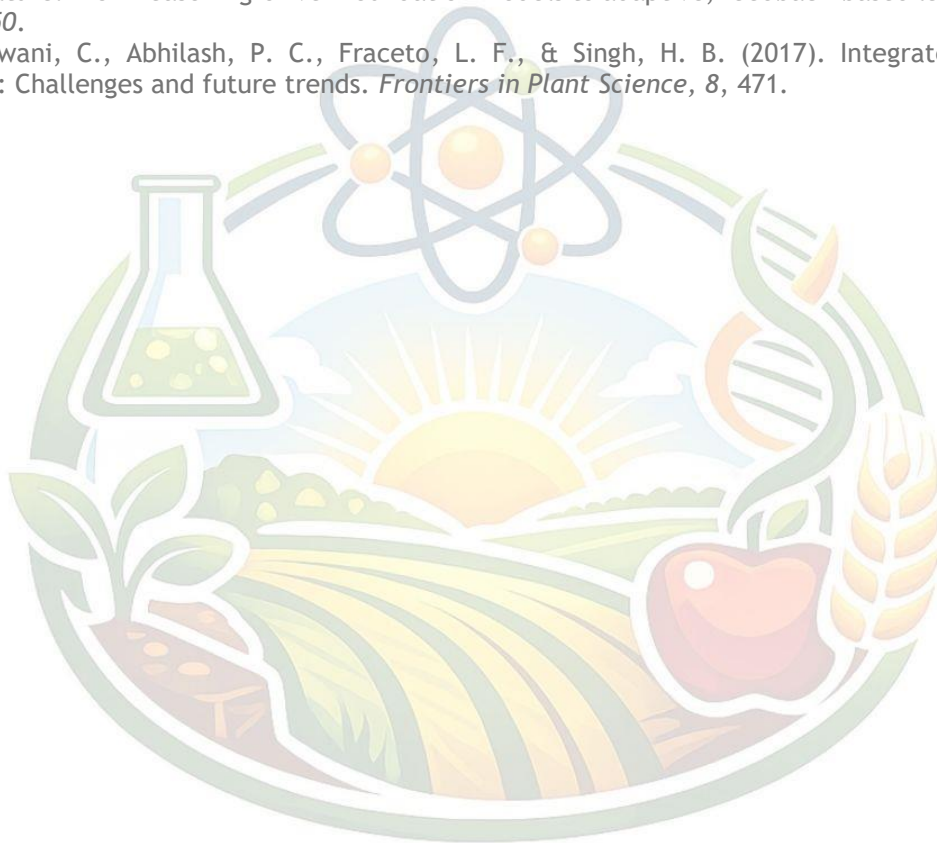
Conclusion

Nanotechnology and precision agriculture tools have emerged as revolutionary technologies for targeted pest and disease management in modern agriculture. Nanopesticides, nanosensors, smart delivery systems, drones, artificial intelligence, robotics, and IoT-based monitoring systems collectively improve the efficiency, precision, and sustainability of crop protection practices. These technologies reduce chemical usage, minimize environmental contamination, improve pesticide efficacy, and support climate-resilient agriculture. The integration of nanotechnology with precision agriculture provides powerful opportunities for early disease detection, site-specific pesticide application, automated

monitoring, and sustainable integrated pest management. However, challenges related to biosafety, environmental impacts, regulatory policies, and economic accessibility must be addressed carefully. Continued interdisciplinary research and responsible implementation will be essential for maximizing the benefits of these advanced technologies in sustainable agriculture.

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Integration of Biological Control Agents with Chemical and Cultural Practices in IPM

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Dr. Anupam Kumari¹, Dr. Srujani Behera², Dr. Paritosh Kumar³, Dr. Prity Sundaram⁴, Dr. Chunni Kumari⁵

¹Assistant Professor -cum- Jr. Scientist, Dept. of Plant Pathology, B.P.S. Agricultural College, Purnea (BAU, Sabour).

²Assistant Professor (Plant Pathology), College of Agriculture, Odisha University of Agriculture and Technology, Bhawanipatna.

³Assistant Professor-cum-Junior Scientist, Department of Plant Pathology, Jute Research Station, Katihar.

⁴Assistant Professor-cum-Junior Scientist, Department of Genetics and Plant Breeding, Bhola Paswan Shasrti Agriculture College, Purnea, Bihar.

⁵Assistant Professor cum-junior-Scientist (Entomology), Bhola Paswan Shasrti Agriculture College, Purnea, Bihar.

Abstract

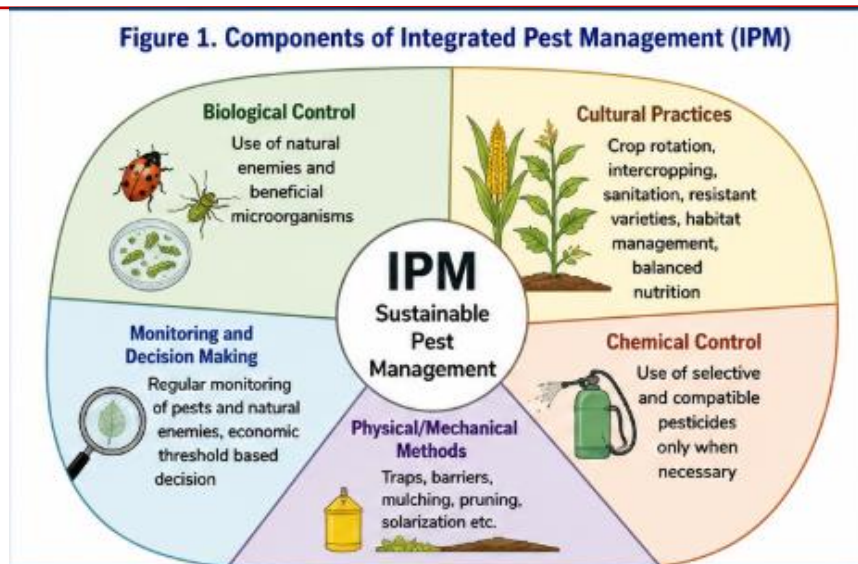
Integrated Pest Management (IPM) is recognized as one of the most effective and sustainable approaches for managing agricultural pests, diseases, nematodes, and weeds. Excessive dependence on synthetic pesticides has resulted in environmental pollution, pesticide resistance, resurgence of pests, destruction of beneficial organisms, and health hazards to humans and animals. Consequently, the integration of biological control agents with compatible chemical and cultural practices has gained considerable importance in modern agriculture. Biological control agents such as predators, parasitoids, entomopathogenic fungi, bacteria, viruses, and antagonistic microorganisms provide eco-friendly and long-term pest suppression. However, biological control alone may not always ensure complete protection under severe pest infestations. Therefore, combining biological control with selective pesticides and suitable cultural methods offers a balanced and effective pest management strategy. The integration of these approaches helps maintain pest populations below economic threshold levels while conserving ecological balance and biodiversity. Cultural practices including crop rotation, intercropping, sanitation, resistant varieties, habitat manipulation, and balanced nutrient management further strengthen the efficiency of biological agents. Selective chemical interventions are used only when necessary and in a manner compatible with beneficial organisms. This integrated strategy reduces pesticide dependence, delays resistance development, improves environmental safety, enhances crop productivity, and supports sustainable agriculture. The present review discusses the principles, importance, components, compatibility, benefits, challenges, and future prospects of integrating biological control agents with chemical and cultural practices in IPM systems.

Introduction

Agricultural crops are continuously threatened by a wide range of insect pests, plant pathogens, nematodes, and weeds that significantly reduce crop productivity and quality. For many decades, chemical pesticides remained the primary means of pest management because of their rapid and visible action. Although pesticides have contributed enormously to agricultural production, their indiscriminate and repeated use has created serious ecological and environmental problems. Continuous pesticide use has resulted in pesticide resistance, pest resurgence, secondary pest outbreaks, environmental contamination, destruction of natural enemies, toxic residues in food products, and adverse effects on human and animal health. These concerns have led to the development of Integrated Pest Management (IPM), which combines multiple compatible pest management strategies to achieve sustainable pest suppression (Kogan, 1998).

IPM is a holistic and environmentally sound approach that aims to maintain pest populations below economic injury levels rather than completely eradicating them. Among the different components of IPM, biological control occupies a central position because it utilizes natural enemies and beneficial microorganisms for suppressing pest populations. Biological control agents are environmentally safe, target-specific, and capable of providing long-term pest regulation. However, biological control alone may sometimes provide inconsistent results due to environmental conditions, delayed action, or high pest pressure. Therefore, integration of biological control agents with compatible chemical and cultural practices is considered essential for improving the overall effectiveness of IPM systems.

The integration approach seeks to create a balanced agroecosystem where biological agents are conserved and supported by suitable cultural practices, while selective pesticides are applied judiciously whenever pest populations exceed economic thresholds. Such integration not only improves pest management efficiency but also reduces ecological disturbances and promotes agricultural sustainability.



Concept and Principles of Integrated Pest Management

Integrated Pest Management is a scientific and ecological approach to pest management that combines various control measures in a coordinated and compatible manner. The major principles of IPM include pest prevention, monitoring, economic threshold-based decision making, conservation of natural enemies, and integration of multiple pest management tactics.

The basic objective of IPM is not complete elimination of pests but regulation of pest populations below levels that cause economic damage. Preventive measures such as crop rotation, resistant varieties, field sanitation, proper irrigation, and balanced fertilization form the first line of defense. Biological control agents are encouraged and conserved to provide natural suppression of pests. Chemical pesticides are used only when necessary and preferably in selective forms that minimize harm to beneficial organisms.

The integration of different management practices creates synergistic effects that improve the stability and sustainability of agricultural ecosystems. IPM therefore represents an ecologically balanced and economically viable alternative to conventional pesticide-dependent agriculture.

Figure 2. Compatibility of Pesticides with Biological Control Agents

Pesticide Group	Predators (e.g., <i>C. carnea</i> , Ladybird beetles)	Parasitoids (e.g., <i>Trichogramma</i> spp., <i>Encarsia</i> spp.)	Entomopathogenic Fungi (e.g., <i>B. bassiana</i> , <i>M. anisopliae</i>)	Remarks
Botanical pesticides (Neem, Azadirachtin)	●	●	●	Generally safe and compatible
Microbial pesticides (Bt, NPV)	●	●	●	Highly compatible and safe
Insect growth regulators (IGRs)	●	●	●	Generally safe if used as recommended
Spinosad	●	●	●	Relatively safe with minimal impact
Neonicotinoids (Imidacloprid, Thiamethoxam)	●	●	●	Harmful to natural enemies and microorganisms
Organophosphates (Chlorpyrifos, Dimethoate)	●	●	●	Highly toxic to beneficial organisms, should be avoided

● = Safe / Compatible

● = Moderately safe / Slight risk

● = Unsafe / Incompatible

Biological Control Agents in IPM

Biological control refers to the use of living organisms to suppress pest populations. Biological control agents include predators, parasitoids, entomopathogens, and antagonistic microorganisms.

Predators are free-living organisms that consume large numbers of prey throughout their lifetime. Common predators used in IPM include ladybird beetles, lacewings, spiders, predatory bugs, and predatory mites. Ladybird beetles

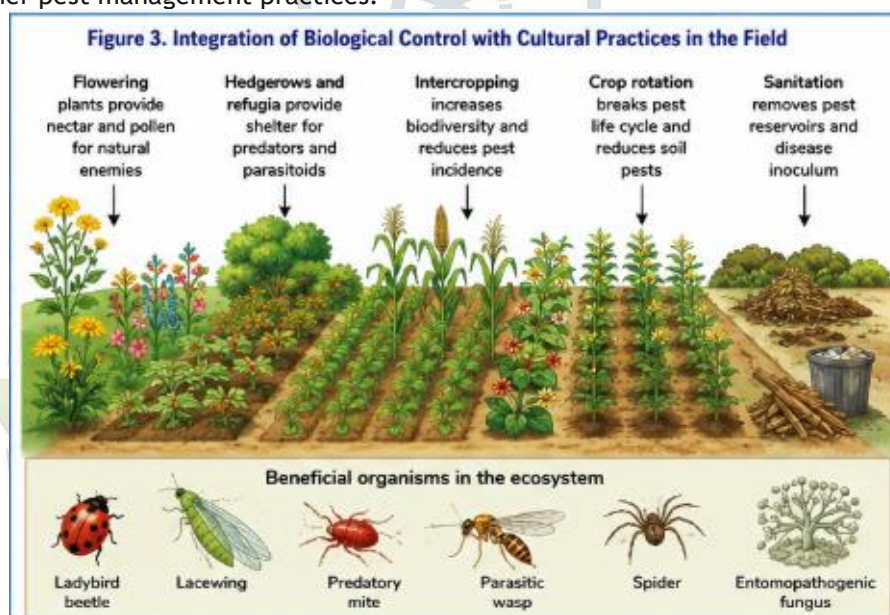
effectively control aphids, mealybugs, and scale insects, whereas lacewings suppress soft-bodied insect pests such as whiteflies, aphids, and thrips.

Parasitoids are insects whose immature stages develop within or on the body of host insects, ultimately killing them. Species of *Trichogramma* are widely used against lepidopteran pests by parasitizing their eggs. Similarly, *Encarsia formosa* is highly effective against whiteflies in greenhouse crops.

Entomopathogenic microorganisms include bacteria, fungi, viruses, and nematodes that infect and kill insect pests. *Bacillus thuringiensis* (Bt) is one of the most widely used microbial insecticides for controlling caterpillar pests. Entomopathogenic fungi such as *Beauveria bassiana* and *Metarhizium anisopliae* infect a wide range of insect pests under humid conditions. Nuclear Polyhedrosis Viruses (NPVs) are highly specific pathogens used against major lepidopteran pests.

Antagonistic microorganisms such as *Trichoderma harzianum*, *Pseudomonas fluorescens*, and *Bacillus subtilis* are extensively utilized against soil-borne and foliar plant pathogens. These microorganisms suppress pathogens through competition, antibiosis, mycoparasitism, and induction of systemic resistance in plants.

Biological control agents are environmentally safe and highly specific, making them valuable components of sustainable pest management systems. However, their effectiveness is strongly influenced by environmental conditions and compatibility with other pest management practices.



Integration of Biological Control with Chemical Practices

The integration of biological control agents with chemical pesticides is a crucial aspect of modern IPM systems. Although pesticides provide rapid suppression of pest populations, indiscriminate use can destroy beneficial organisms and disrupt ecological balance. Therefore, only selective and compatible pesticides are recommended within IPM programs.

Selective pesticides are designed to target pests while causing minimal harm to predators, parasitoids, and microbial biocontrol agents. Botanical pesticides such as neem-based formulations, microbial pesticides such as Bt, and insect growth regulators are often safer to natural enemies compared with broad-spectrum synthetic insecticides.

The timing and method of pesticide application are extremely important for conserving biological control agents. Pesticides should be applied only when pest populations exceed economic threshold levels. Spot applications, need-based spraying, and evening applications help reduce exposure of natural enemies to toxic chemicals.

Integration of biological and chemical approaches also contributes significantly to resistance management. Continuous application of the same pesticide group leads to the development of resistant pest populations. Biological control agents exert different modes of action, thereby reducing selection pressure and delaying resistance development. Thus, integrating biological control with selective pesticide use ensures long-term sustainability of pest management systems (Stenberg, 2017).

Compatibility studies between pesticides and biological control agents are essential before field application. Certain fungicides and insecticides may inhibit the growth and survival of beneficial microorganisms and parasitoids, while others remain relatively safe. Therefore, proper selection of pesticides based on compatibility testing is necessary for successful integration.

Integration of Biological Control with Cultural Practices

Cultural practices form an important preventive component of IPM and greatly enhance the effectiveness of biological control agents. Cultural methods modify the crop environment in ways that make it less favorable for pests while improving conditions for natural enemies.

Crop rotation is one of the oldest and most effective cultural practices. Rotating susceptible crops with non-host crops disrupts pest life cycles and reduces populations of soil-borne pathogens, nematodes, and insect pests. Crop rotation also improves soil fertility and supports beneficial microbial communities.

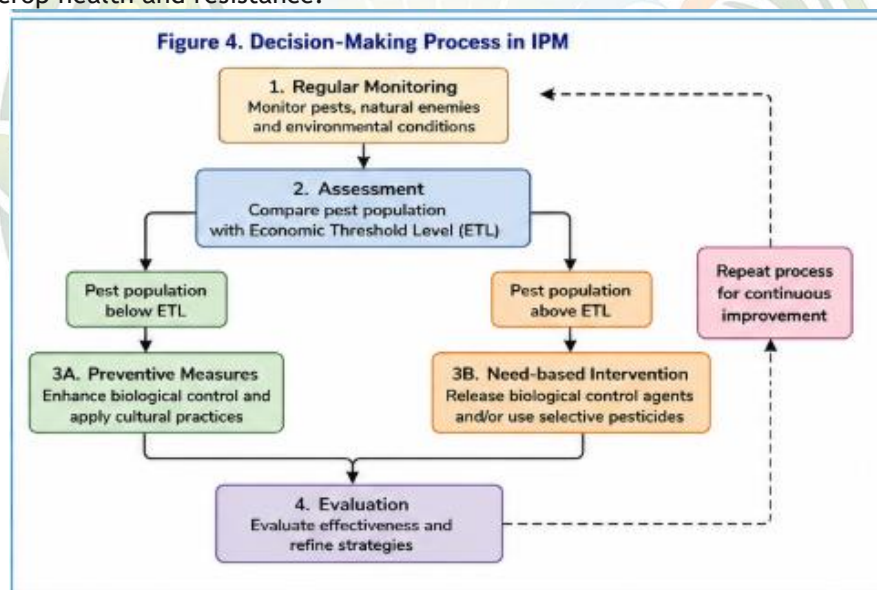
Intercropping and crop diversification increase biodiversity within agricultural ecosystems. Diversified cropping systems provide shelter, nectar, pollen, and alternative prey for predators and parasitoids. Flowering plants in intercropping systems often enhance the abundance and efficiency of natural enemies.

Field sanitation is another essential cultural practice. Removal of infected plant debris, alternate hosts, weeds, and diseased plant parts reduces pest reservoirs and disease inoculum. Proper sanitation lowers initial pest pressure and improves the performance of biological control agents.

The use of resistant varieties is an effective means of reducing pest establishment and multiplication. Resistant cultivars decrease pest damage and minimize dependence on pesticides. When combined with biological control agents, resistant varieties often provide additive or synergistic pest suppression effects.

Habitat manipulation and ecological engineering are increasingly used in modern IPM systems. Flowering strips, cover crops, hedgerows, and refugia provide food and shelter for natural enemies. Such ecological approaches improve biodiversity and stabilize agroecosystems. Ecological engineering has become highly successful in rice ecosystems where flowering plants support parasitoids and predators that naturally suppress insect pests (Gurr et al., 2003).

Balanced nutrient management and proper irrigation practices also influence pest incidence and natural enemy activity. Excessive nitrogen fertilization often increases crop susceptibility to insect pests and diseases, whereas balanced fertilization improves crop health and resistance.



Integration in Major Cropping Systems

Integrated approaches combining biological control agents with chemical and cultural practices have been successfully implemented in several cropping systems.

In rice ecosystems, conservation of spiders and parasitoids, use of resistant varieties, balanced fertilizer application, and selective insecticides have effectively reduced pesticide dependence and pest outbreaks. Biological agents such as *Trichogramma japonicum* and entomopathogenic fungi are increasingly incorporated into rice IPM programs.

Cotton cultivation historically depended heavily on synthetic pesticides, resulting in severe resistance and secondary pest outbreaks. Modern cotton IPM programs integrate Bt cotton, pheromone traps, predators, parasitoids, neem-based pesticides, and microbial biocontrol agents to reduce pesticide use and improve sustainability.

Vegetable crops are highly susceptible to insect pests and diseases due to their succulent nature and intensive cultivation practices. Integrated approaches involving crop rotation, resistant cultivars, biological agents, mulching, and protected cultivation systems have significantly improved vegetable pest management.

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Fruit orchards and plantation crops also benefit greatly from integrated pest management approaches. Pruning, sanitation, habitat management, pheromone trapping, and conservation of natural enemies contribute to sustainable pest suppression in perennial cropping systems.

Ecological and Environmental Benefits

Integration of biological control agents with cultural and chemical practices offers numerous ecological and environmental benefits. Reduced dependence on synthetic pesticides minimizes environmental contamination and protects non-target organisms such as pollinators, soil microorganisms, birds, and aquatic fauna.

Enhanced biodiversity within agricultural ecosystems improves ecological stability and resilience against pest outbreaks. Conservation of natural enemies reduces the likelihood of pest resurgence and secondary pest outbreaks. Soil health and water quality also improve because of reduced chemical contamination.

Integrated approaches contribute significantly to sustainable agriculture and environmental conservation. By promoting ecological balance and reducing chemical inputs, IPM systems support long-term agricultural productivity and ecosystem sustainability (Barzman et al., 2015).

Economic Benefits

Integrated pest management systems often reduce overall production costs by minimizing pesticide use and enhancing natural pest suppression. Reduced pesticide applications lower input expenses and decrease labor requirements associated with repeated spraying.

Biological control agents and cultural practices provide long-term pest suppression, thereby improving economic sustainability. Crops produced under IPM systems often have lower pesticide residues and higher market acceptability, particularly in export-oriented and organic markets. In addition, reduced environmental damage and improved ecosystem services contribute indirectly to long-term economic benefits for farmers and society.

Challenges in Integration

Despite its numerous advantages, integration of biological control agents with chemical and cultural practices faces several challenges. Limited availability of quality biocontrol agents, high production costs, inconsistent field performance, and inadequate awareness among farmers restrict widespread adoption. Environmental conditions such as temperature, humidity, and ultraviolet radiation may adversely affect survival and efficacy of biological control agents. In many regions, farmers still rely heavily on broad-spectrum pesticides that disrupt natural enemy populations and ecological balance. Insufficient extension services, lack of training programs, poor regulatory support, and inadequate commercialization infrastructure also hinder successful implementation of integrated approaches. Adoption of IPM practices often requires greater technical knowledge and continuous monitoring, which may limit adoption among small-scale farmers (Parsa et al., 2014).

Future Prospects

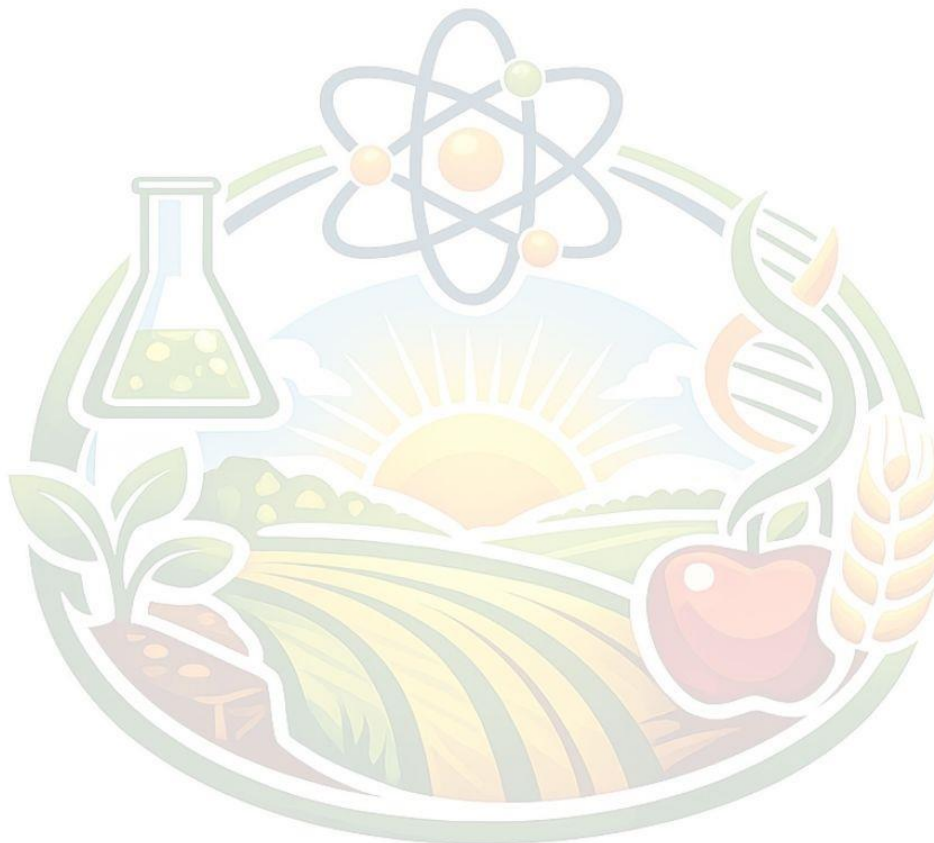
Rapid advances in biotechnology, microbial formulation technology, artificial intelligence, nanotechnology, and precision agriculture are creating new opportunities for integrated pest management. Improved formulations and delivery systems are enhancing the stability and effectiveness of biological control agents. Remote sensing technologies, drones, and artificial intelligence-based pest monitoring systems are improving pest surveillance and decision-making processes. Molecular and genomic tools are helping identify more efficient biological control agents and enhancing understanding of pest-natural enemy interactions. Climate-smart IPM approaches integrating resilient biological agents, ecological engineering, and adaptive cultural practices will become increasingly important under changing climatic conditions. Sustainable agriculture in the future will depend heavily on ecologically based pest management systems that harmoniously integrate biological, chemical, and cultural methods.

Conclusion

Integration of biological control agents with chemical and cultural practices represents one of the most effective and sustainable approaches for pest management in modern agriculture. Biological control agents provide environmentally safe and long-term suppression of pests, while cultural practices create unfavorable conditions for pest development and support ecological stability. Selective and compatible chemical interventions offer rapid pest suppression when required without severely affecting beneficial organisms. The integrated approach reduces pesticide dependence, delays resistance development, conserves biodiversity, improves environmental quality, and enhances economic sustainability. Successful implementation requires scientific understanding of pest ecology, compatibility among management practices, farmer awareness, and strong institutional support. Future agricultural systems must increasingly adopt integrated and ecologically balanced pest management strategies to ensure food security, environmental protection, and sustainable development. Strengthening research, farmer education, commercialization of biocontrol technologies, and policy support will play critical roles in promoting wider adoption of integrated pest management systems worldwide.

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Biological Control of Plant Diseases: Opportunities and Challenges

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Dr. Jasmee R. Patel¹, Dr. Dinesh H. Chaudhary², Dr. Mulji D. Jehani³, Dr. Vipulkumar Baldaniya⁴, Dr. Manjula G. Chaudhari⁵

¹Assistant Professor (Plant Pathology), KKIARS, Ganpat University, Kherva, Mahesana, Gujarat.

²Assistant Professor (Plant Pathology), Office of the Director of Research, Navsari Agricultural University, Navsari, Gujarat.

³Scientist (Plant Protection), Krushi Vigyan Kendra, SDAU, Deesa, Gujarat.

⁴Assistant Professor (Plant Physiology), KKIARS, Ganpat University, Kherva, Mahesana, Gujarat.

⁵Assistant Professor (Biochemistry), Department of Soil Science and Agricultural Chemistry, N. M. College of Agriculture, Navsari Agricultural University, Navsari, Gujarat.

Abstract

Plant diseases caused by fungi, bacteria, viruses, nematodes, and other phytopathogens are among the major constraints limiting agricultural productivity and global food security. Excessive dependence on chemical pesticides has led to environmental pollution, development of resistant pathogen strains, destruction of beneficial microorganisms, and harmful impacts on human and animal health. In this context, biological control of plant diseases has emerged as a sustainable, eco-friendly, and economically viable alternative for disease management. Biological control involves the use of beneficial microorganisms and natural antagonists to suppress plant pathogens through diverse mechanisms such as antibiosis, competition, parasitism, induced systemic resistance, and production of lytic enzymes. Various microbial agents including species of *Trichoderma*, *Pseudomonas*, *Bacillus*, *Gliocladium*, and mycorrhizal fungi have shown remarkable effectiveness against numerous plant diseases. The integration of biological control agents into integrated disease management systems has gained considerable attention due to increasing concerns regarding pesticide residues and environmental sustainability. Despite significant advancements, several challenges such as inconsistent field performance, environmental variability, formulation difficulties, limited shelf life, regulatory constraints, and farmer awareness continue to hinder large-scale adoption. Recent developments in molecular biology, genomics, nanotechnology, and microbial formulation technologies are creating new opportunities for enhancing the efficiency and commercialization of biocontrol agents. This review comprehensively discusses the concepts, mechanisms, types, important microbial agents, applications, opportunities, limitations, and future prospects of biological control of plant diseases with special emphasis on sustainable agriculture and integrated disease management strategies.

Introduction

Plant diseases have been a persistent threat to agricultural production since the beginning of crop cultivation. They reduce crop yield, impair quality, decrease market value, and create severe economic losses worldwide. Fungal pathogens alone are responsible for substantial yield losses in cereals, fruits, vegetables, plantation crops, and ornamental plants. Diseases such as wilt, blight, rust, smut, damping-off, root rot, leaf spot, powdery mildew, and bacterial wilt continue to challenge modern agriculture.

For several decades, synthetic fungicides and chemical pesticides have been the primary tools used for plant disease management. Although chemicals provide rapid and effective disease suppression, their continuous and indiscriminate use has resulted in numerous adverse consequences including environmental contamination, accumulation of toxic residues in food products, emergence of resistant pathogen populations, destruction of beneficial soil microorganisms, and risks to human health. Increasing public concern regarding environmental safety and sustainable agriculture has stimulated the search for alternative disease management approaches. Biological control of plant diseases represents one of the most promising eco-friendly alternatives to chemical disease management. It involves the use of living organisms or their products to suppress the activity and population of plant pathogens. The concept of biological control is based on natural ecological interactions occurring among microorganisms in the soil, rhizosphere, phyllosphere, and plant tissues. Beneficial microorganisms can inhibit pathogens directly or indirectly through diverse mechanisms.

The scientific foundation of biological control was extensively described by Cook and Baker (1983), who defined it as the reduction of inoculum density or disease-producing activities of a pathogen through one or more organisms other than humans. Since then, biological control has evolved into an important component of integrated disease management programs worldwide (Cook and Baker, 1983). Beneficial microorganisms not only suppress pathogens but also improve soil fertility, plant growth, nutrient uptake, and stress tolerance, thereby contributing to sustainable crop production systems. The growing demand for organic farming, residue-free food production, and environmentally sound agricultural practices has further increased interest in biological disease management. Several commercial biocontrol formulations based on fungi and bacteria are now available for agricultural use. Nevertheless, many scientific, technological, and

practical challenges remain unresolved, particularly regarding field efficacy, formulation stability, and large-scale commercialization.

Concept and Principles of Biological Control

Biological control refers to the suppression of plant pathogens and diseases using living organisms or biologically active natural substances. The principle of biological control is based on ecological balance within microbial communities. In natural ecosystems, pathogens rarely dominate because antagonistic microorganisms regulate their populations through competition and inhibitory interactions. Biological control agents may include fungi, bacteria, actinomycetes, viruses, protozoa, nematodes, or beneficial insects. These agents may act directly against pathogens or indirectly by stimulating plant defense mechanisms. The effectiveness of biological control depends upon environmental conditions, microbial interactions, host plant susceptibility, and pathogen biology.

The rhizosphere, which is the narrow region surrounding plant roots, is considered a highly active zone for biological interactions. Beneficial rhizosphere microorganisms colonize root surfaces and compete with pathogens for nutrients and ecological niches. Some microorganisms establish symbiotic relationships with plants and enhance their resistance against diseases. Modern biological control approaches emphasize sustainable disease management rather than complete eradication of pathogens. The objective is to maintain pathogen populations below economically damaging levels while preserving environmental integrity.

Historical Development of Biological Control

The history of biological control dates back to the nineteenth century when researchers observed natural antagonism among microorganisms. Early investigations demonstrated that certain soil microorganisms could suppress soil-borne pathogens. One of the earliest successful examples involved suppression of damping-off disease by antagonistic soil fungi. Later, extensive studies on suppressive soils revealed that microbial communities play a critical role in natural disease suppression. The pioneering work of Cook and Baker significantly advanced understanding of soil microbial ecology and biological disease suppression.

During the twentieth century, increasing awareness of the negative impacts of chemical pesticides accelerated research on microbial antagonists. Several bacterial and fungal biocontrol agents were isolated and evaluated against major plant pathogens. Commercialization of microbial biopesticides began during the latter half of the century, especially with species of *Trichoderma* and *Bacillus*. Recent advances in molecular biology, microbial genomics, metabolomics, and biotechnology have greatly enhanced understanding of microbial interactions and mechanisms of disease suppression. Modern biological control research now integrates microbial ecology, molecular genetics, nanotechnology, and precision agriculture for improved disease management strategies.

Types of Biological Control

- 1. Classical Biological Control:** Classical biological control involves introduction of natural antagonists into environments where pathogens have become problematic. The introduced organisms establish themselves and provide long-term disease suppression. This approach is commonly used against invasive pathogens.
- 2. Augmentative Biological Control:** Augmentative biological control involves mass multiplication and periodic application of beneficial microorganisms to enhance their population in the field. It includes inoculative and inundative releases of microbial antagonists.
- 3. Conservation Biological Control:** Conservation biological control focuses on preserving and enhancing naturally occurring beneficial microorganisms through habitat management, reduced pesticide usage, crop rotation, organic amendments, and conservation agriculture practices.

Mechanisms of Biological Control

- 1. Antibiosis:** Antibiosis refers to the production of antimicrobial compounds by beneficial microorganisms that inhibit or kill pathogens. Many species of *Pseudomonas*, *Bacillus*, and *Trichoderma* produce antibiotics, toxins, and secondary metabolites effective against plant pathogens. Antibiotic compounds such as phenazines, pyoluteorin, pyrrolnitrin, surfactin, and iturin play major roles in disease suppression. These metabolites interfere with cell wall synthesis, membrane integrity, and metabolic activities of pathogens.
- 2. Competition for Nutrients and Space:** Competition is one of the most important mechanisms in biological control. Beneficial microorganisms rapidly colonize ecological niches and consume available nutrients, thereby depriving pathogens of essential resources. Iron competition mediated through siderophore production is particularly important in rhizosphere interactions.
- 3. Hyperparasitism and Mycoparasitism:** Certain fungi directly parasitize pathogenic fungi. Species of *Trichoderma* coil around pathogen hyphae, penetrate cell walls, and degrade fungal structures using lytic enzymes such as chitinases and glucanases. This process is known as mycoparasitism.

4. Induced Systemic Resistance: Some beneficial microorganisms activate plant defense systems and enhance resistance against pathogens. This phenomenon is termed induced systemic resistance. Plants treated with beneficial microbes exhibit increased production of defense enzymes, phytoalexins, and pathogenesis-related proteins.

5. Production of Lytic Enzymes: Biocontrol microorganisms produce extracellular enzymes capable of degrading pathogen cell walls. Chitinases, cellulases, proteases, glucanases, and lipases play major roles in destruction of fungal pathogens.

6. Volatile Organic Compounds: Certain microbial antagonists release volatile compounds that inhibit pathogen growth and stimulate plant defense responses. These volatile metabolites contribute significantly to biological disease suppression.

Important Biological Control Agents

1. Fungal Biocontrol Agents:

a. *Trichoderma* spp.: Species of *Trichoderma* are among the most widely used fungal biocontrol agents. They suppress pathogens through mycoparasitism, antibiosis, competition, and induction of systemic resistance. *Trichoderma harzianum*, *T. viride*, and *T. asperellum* are extensively used against soil-borne pathogens such as *Rhizoctonia*, *Fusarium*, *Pythium*, and *Sclerotium*. These fungi are highly adaptable, fast-growing, and capable of colonizing root surfaces effectively. They also promote plant growth by improving nutrient availability and root development. Harman et al. highlighted the multifunctional role of *Trichoderma* in sustainable agriculture (Harman et al., 2004).

b. *Gliocladium* spp.: *Gliocladium* species exhibit strong antagonistic activity against several pathogenic fungi through production of antibiotics and hydrolytic enzymes. They are commonly used in greenhouse disease management.

c. *Ampelomyces quisqualis*: This hyperparasitic fungus attacks powdery mildew fungi and is used as a biological control agent in horticultural crops.

2. Bacterial Biocontrol Agents:

a. *Pseudomonas* spp.: Fluorescent pseudomonads are important rhizosphere bacteria known for disease suppression. They produce antibiotics, siderophores, hydrogen cyanide, and lytic enzymes. *Pseudomonas fluorescens* is widely used against wilt, root rot, damping-off, and foliar diseases. These bacteria also induce systemic resistance and enhance plant growth. Their effectiveness in suppressing soil-borne pathogens has been extensively documented (Haas and D  fago, 2005).

b. *Bacillus* spp.: Species of *Bacillus* produce resistant endospores and possess excellent shelf stability, making them suitable for commercial formulations. *Bacillus subtilis* and *Bacillus amyloliquefaciens* produce lipopeptides and antimicrobial compounds effective against numerous pathogens.

c. *Streptomyces* spp.: Actinomycetes belonging to *Streptomyces* produce diverse antibiotics and bioactive metabolites. They suppress fungal and bacterial pathogens in soil environments.

Biological Control in Different Plant Diseases

Biological control agents have been used successfully against various plant diseases across different cropping systems.

1. Soil-Borne Diseases: Soil-borne pathogens such as *Fusarium*, *Rhizoctonia*, *Pythium*, *Sclerotinia*, and *Phytophthora* cause severe losses worldwide. Biological control agents are particularly effective against these pathogens because they colonize the rhizosphere and root zone. Application of *Trichoderma* and *Pseudomonas* species has shown remarkable success in controlling damping-off, root rot, wilt, and collar rot diseases.

2. Foliar Diseases: Foliar pathogens causing powdery mildew, downy mildew, leaf spots, and blights can also be managed biologically. Microbial antagonists applied as foliar sprays inhibit pathogen establishment and infection.

3. Post-Harvest Diseases: Post-harvest losses due to fungal pathogens are a major concern in fruits and vegetables. Yeasts and bacterial antagonists have been used successfully to suppress storage rots and maintain produce quality.

4. Nematode Diseases: Certain fungi and bacteria suppress plant-parasitic nematodes through parasitism, toxin production, and competition. Biological nematicides are increasingly being integrated into sustainable crop management systems.

Formulation and Commercialization of Biocontrol Agents

Commercial success of biological control depends largely on formulation quality and shelf stability. Formulations must maintain viability and effectiveness of microbial agents during storage and field application. Common formulation types include wettable powders, granules, pellets, liquid suspensions, emulsifiable concentrates, and encapsulated formulations. Carrier materials such as talc, peat, lignite, vermiculite, and alginate are widely used.

Commercialization requires mass production technologies, quality control standards, regulatory approval, and farmer acceptance. Despite increasing market demand, commercialization remains challenging because microbial products are sensitive to environmental conditions and storage limitations.

Opportunities in Biological Control

- 1. Eco-Friendly Disease Management:** Biological control offers environmentally safe disease management without harmful pesticide residues. It contributes significantly to ecological sustainability and biodiversity conservation.
- 2. Reduced Chemical Dependence:** Biocontrol agents reduce reliance on synthetic fungicides and help minimize environmental pollution and pesticide resistance development.
- 3. Compatibility with Organic Farming:** Biological control is a key component of organic agriculture and residue-free crop production systems.
- 4. Enhancement of Soil Health:** Beneficial microorganisms improve soil fertility, microbial diversity, nutrient cycling, and soil structure.
- 5. Plant Growth Promotion:** Many biocontrol microorganisms also function as plant growth-promoting rhizobacteria, enhancing crop productivity and stress tolerance.
- 6. Integration with Integrated Disease Management:** Biological control agents can be integrated with cultural, mechanical, botanical, and limited chemical methods for sustainable disease management.
- 7. Advances in Biotechnology:** Modern molecular tools, genomics, transcriptomics, and metabolomics are improving understanding of microbial interactions and facilitating development of more efficient biocontrol agents.
- 8. Nanotechnology and Microbial Formulations:** Nanotechnology-based formulations improve stability, delivery, and efficacy of microbial biocontrol agents under field conditions.

Challenges in Biological Control

- 1. Inconsistent Field Performance:** One of the major limitations of biological control is variability in field performance due to environmental fluctuations, soil conditions, and microbial competition.
- 2. Limited Shelf Life:** Many microbial formulations have short shelf lives and reduced viability during storage.
- 3. Environmental Sensitivity:** Temperature, humidity, soil pH, moisture, and ultraviolet radiation strongly influence survival and activity of biological control agents.
- 4. Slow Action:** Biological control agents generally act more slowly than chemical pesticides, which may discourage farmers seeking immediate disease suppression.
- 5. Regulatory Constraints:** Registration and commercialization of microbial products involve complex regulatory procedures and quality standards.
- 6. Limited Farmer Awareness:** Lack of technical knowledge and awareness among farmers limits adoption of biological control technologies.
- 7. Host Specificity:** Some biocontrol agents exhibit narrow host ranges and limited effectiveness against multiple pathogens.
- 8. Interaction with Native Microflora:** Introduced microbial agents may fail to establish in the presence of native microbial communities.
- 9. Mass Production Challenges:** Large-scale production of high-quality microbial inoculants remains technologically demanding and costly.
- 10. Economic and Market Constraints:** Limited market infrastructure, inconsistent product quality, and inadequate extension services hinder commercialization.

Integration of Biological Control with Modern Agriculture

Modern agriculture increasingly emphasizes integrated and sustainable disease management strategies. Biological control agents are now combined with resistant cultivars, organic amendments, biofertilizers, precision agriculture, and climate-smart agricultural practices. Integration of microbial consortia containing multiple beneficial microorganisms has shown improved disease suppression compared to single-strain applications. Seed treatment, soil application, root dipping, foliar sprays, and drip irrigation delivery systems are being optimized for enhanced efficacy. Precision agriculture technologies, remote sensing, artificial intelligence, and digital disease forecasting systems may further improve timing and effectiveness of biocontrol applications.

Future Prospects

The future of biological control appears highly promising due to growing environmental concerns and increasing restrictions on chemical pesticides. Advances in microbial ecology, genomics, synthetic biology, and bioinformatics are opening new avenues for identification and engineering of superior biocontrol agents. Metagenomic studies are improving understanding of complex soil microbial communities and disease-suppressive soils. Genome editing technologies may facilitate development of highly efficient microbial strains with enhanced stress tolerance and disease suppression abilities. Development of stable formulations, microbial consortia, nano-biopesticides, and smart delivery systems will likely improve commercialization and field performance. Integration of biological control into climate-resilient agriculture and sustainable food production systems will become increasingly important in the coming decades. Continued research, farmer education, policy support, and public-private partnerships are essential for large-scale adoption of biological control technologies worldwide.

Conclusion

Biological control of plant diseases represents a sustainable, environmentally safe, and economically viable alternative to chemical disease management. Beneficial microorganisms suppress plant pathogens through diverse mechanisms including antibiosis, competition, mycoparasitism, induced resistance, and enzyme production. Numerous fungal and bacterial antagonists have demonstrated remarkable potential against major plant diseases in agricultural systems. The increasing demand for residue-free food, sustainable agriculture, and environmental protection has accelerated interest in microbial disease management technologies. Biological control not only suppresses pathogens but also enhances soil health, plant growth, and ecosystem stability. Despite considerable progress, challenges related to field consistency, formulation stability, environmental sensitivity, commercialization, and farmer adoption continue to limit widespread use. Advances in biotechnology, microbial genomics, nanotechnology, and precision agriculture provide significant opportunities for overcoming these limitations. Future agricultural systems will likely depend heavily on integrated disease management strategies in which biological control will play a central role. Strengthening research, policy support, quality control, and extension services will be essential for realizing the full potential of biological control in sustainable crop protection.

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Impact of Climate Change on Plant Disease Epidemiology

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Dr. Jasmee R. Patel¹, Dr. Dinesh H. Chaudhary², Dr. Mulji D. Jehani³, Dr. Janaki Movalia⁴, Dr. Neethu T. M.⁵

¹Assistant Professor (Plant Pathology), KKIARS, Ganpat University, Kherva, Mahesana, Gujarat.

²Assistant Professor (Plant Pathology), Office of the Director of Research, Navsari Agricultural University, Navsari, Gujarat.

³Scientist (Plant Protection), Krushi Vigyan Kendra, SDAU, Deesa, Gujarat.

⁴Assistant Professor (Soil Science and Agricultural), KKIARS, Ganpat University, Kherva, Mahesana, Gujarat.

⁵Assistant Professor (Soil Science and Agricultural Chemistry), N. M. College of Agriculture, NAU, Navsari, Gujarat.

Abstract

Climate change has emerged as one of the most critical challenges affecting global agriculture and food security. Alterations in temperature, precipitation patterns, atmospheric carbon dioxide concentration, humidity, and the frequency of extreme weather events are significantly influencing plant disease epidemiology across diverse agroecosystems. Plant pathogens, including fungi, bacteria, viruses, nematodes, phytoplasmas, and oomycetes, are highly sensitive to environmental conditions, and even minor climatic fluctuations can alter their survival, reproduction, dispersal, virulence, and host interactions. Climate change also affects host plant physiology, resistance mechanisms, vector populations, and microbial communities, thereby reshaping disease dynamics at local, regional, and global scales. Emerging diseases, expansion of pathogen geographic ranges, increased overwintering survival, accelerated disease cycles, and breakdown of host resistance are becoming increasingly common under changing climatic conditions. The epidemiological triangle involving host, pathogen, and environment is therefore being continuously modified by climate variability. This review comprehensively discusses the influence of climate change on plant disease epidemiology, including the effects of elevated temperature, changing rainfall patterns, humidity fluctuations, carbon dioxide enrichment, and extreme climatic events on major plant pathogens. The review further explores pathogen evolution, vector ecology, disease forecasting, implications for food security, and sustainable disease management strategies under climate change scenarios. Emphasis is also placed on integrated disease management, climate-smart agriculture, resistant cultivars, biological control, and advanced forecasting technologies to mitigate future disease risks. Understanding the intricate relationships between climate change and plant disease epidemiology is essential for developing resilient agricultural systems and ensuring sustainable crop production in the future.

Introduction

Climate change represents a long-term alteration in climatic parameters such as temperature, precipitation, humidity, atmospheric carbon dioxide concentration, and frequency of extreme weather events. Over the last century, anthropogenic activities including industrialization, fossil fuel combustion, deforestation, urbanization, and intensive agricultural practices have significantly increased greenhouse gas emissions, resulting in global warming and climatic instability. Agriculture is one of the most climate-sensitive sectors, and plant health is increasingly threatened by changing environmental conditions. Plant diseases are among the most important constraints limiting agricultural productivity worldwide. Plant disease epidemiology refers to the study of the temporal and spatial development of diseases in plant populations and the factors influencing disease outbreaks. The occurrence and severity of plant diseases are strongly governed by the classical disease triangle consisting of susceptible host, virulent pathogen, and favourable environment. Climate change directly modifies the environmental component of this triangle and indirectly affects host susceptibility and pathogen aggressiveness.

Recent decades have witnessed substantial changes in disease incidence, distribution, and severity due to altered climatic conditions. Rising temperatures have enabled pathogens and vectors to expand into previously unsuitable geographic regions. Changes in rainfall patterns and humidity have increased the prevalence of foliar, soil-borne, and post-harvest diseases. Elevated atmospheric CO₂ levels influence plant physiology and pathogen-host interactions, while extreme weather events such as floods, droughts, storms, and heatwaves create favourable conditions for disease emergence and epidemics.

Climate change not only affects existing diseases but also contributes to the emergence of new diseases and pathogen races. The rapid adaptation and evolution of pathogens under changing environmental conditions present serious challenges for crop protection strategies. Major crops including wheat, rice, maize, soybean, potato, fruits, vegetables, and plantation crops are increasingly vulnerable to climate-driven disease outbreaks. Consequently, understanding the epidemiological implications of climate change is essential for ensuring food security, sustainable agriculture, and global economic stability.

Concept of Plant Disease Epidemiology

Plant disease epidemiology involves the study of disease development within plant populations over time and space. Epidemiology examines factors responsible for disease initiation, spread, severity, and persistence. Disease epidemics depend on interactions among host plants, pathogens, environmental conditions, vectors, and human agricultural activities.

Environmental factors such as temperature, moisture, humidity, wind, solar radiation, and soil conditions profoundly influence pathogen survival, sporulation, infection efficiency, dispersal, and disease progression. Climate change modifies these environmental determinants, thereby altering epidemiological processes. Disease epidemics generally involve several stages including inoculum production, dispersal, infection, colonization, reproduction, and survival. Any climatic alteration affecting one or more stages can significantly influence epidemic development. Consequently, climate change has become a major driver of evolving plant disease epidemiology worldwide.

Climate Change and its Major Components Affecting Plant Diseases

1. Rising Temperature: Temperature is one of the most influential environmental variables affecting plant pathogens and disease development. Global warming has significantly altered disease dynamics by affecting pathogen growth rates, reproduction, virulence, survival, and geographic distribution. Many fungal pathogens exhibit enhanced sporulation and infection efficiency under warmer conditions. Increased temperatures can shorten latent periods, accelerate pathogen life cycles, and increase the number of infection cycles during a cropping season. Diseases such as wheat rusts, powdery mildew, Fusarium head blight, rice blast, and late blight are highly sensitive to temperature changes.

Higher temperatures also influence pathogen overwintering survival. Mild winters allow survival of pathogens and vectors that would otherwise be eliminated under colder conditions. As a result, inoculum pressure during subsequent growing seasons increases substantially. Temperature changes can additionally alter host physiology and resistance mechanisms. Heat stress weakens plant defence systems, making plants more susceptible to pathogen invasion. In some cases, resistance genes become ineffective at elevated temperatures, resulting in resistance breakdown. Garrett et al. (2006) reported that climate warming can increase the risk of plant disease outbreaks by accelerating pathogen development and enhancing survival under previously unfavourable conditions.

2. Changes in Rainfall Patterns: Rainfall plays a critical role in plant disease epidemiology by influencing leaf wetness duration, humidity, soil moisture, and pathogen dispersal. Climate change has caused substantial alterations in precipitation patterns, including increased rainfall intensity, irregular rainfall distribution, and prolonged droughts.

Excessive rainfall and prolonged humidity favour foliar diseases caused by fungi and bacteria. Pathogens such as *Phytophthora*, *Pythium*, *Alternaria*, *Colletotrichum*, and *Xanthomonas* thrive under wet conditions. Water splash during rainfall facilitates dispersal of spores and bacterial cells between plants. Flooding conditions promote soil-borne diseases by creating anaerobic environments that weaken plant roots and enhance pathogen activity. Waterlogged soils favour pathogens such as *Phytophthora* spp., *Pythium* spp., and *Fusarium* spp. Conversely, drought stress can predispose plants to opportunistic pathogens by impairing physiological defence mechanisms. Drought conditions also favour certain diseases such as charcoal rot caused by *Macrophomina phaseolina*. Irregular rainfall patterns create unpredictable disease outbreaks, making disease forecasting increasingly difficult. The synchronization between crop growth stages and favourable environmental conditions for pathogens is becoming more variable under climate change.

3. Elevated Atmospheric Carbon Dioxide: Atmospheric carbon dioxide concentration has increased substantially due to human activities. Elevated CO₂ affects both host plants and pathogens, thereby influencing disease epidemiology. Increased CO₂ levels can enhance photosynthesis and biomass production in plants, leading to denser canopies and altered microclimates favourable for disease development. Dense canopies increase humidity and leaf wetness duration, promoting foliar pathogen infection.

Elevated CO₂ also alters plant tissue composition, including carbon-to-nitrogen ratios, lignin content, and secondary metabolites. These physiological changes may either increase or decrease host susceptibility depending on the pathogen involved. Some studies have shown that elevated CO₂ increases susceptibility to necrotrophic pathogens while reducing severity of certain biotrophic pathogens. Changes in stomatal conductance under elevated CO₂ can also affect pathogen entry into plant tissues. Chakraborty and Newton (2011) emphasized that elevated atmospheric CO₂ significantly modifies host-pathogen interactions and disease epidemiology under future climate scenarios.

4. Relative Humidity and Leaf Wetness: Humidity and leaf wetness are essential factors for infection by many plant pathogens. Increased atmospheric moisture associated with climate change enhances the survival and germination of fungal spores and bacterial propagules. High humidity favours diseases such as downy mildew, rusts, anthracnose, bacterial blight, and gray mold. Extended leaf wetness duration allows successful spore germination and penetration into host tissues. Changing humidity patterns may also alter the temporal occurrence of diseases. Some diseases that were previously confined to humid tropical regions are now appearing in temperate areas due to increasing moisture levels.

5. Extreme Weather Events: Climate change has increased the frequency and intensity of extreme weather events including storms, cyclones, floods, droughts, heatwaves, and hailstorms. These events directly and indirectly influence plant disease epidemiology. Storms and cyclones facilitate long-distance dispersal of pathogen spores and vectors across continents. Floods disseminate soil-borne pathogens through irrigation systems and agricultural fields. Heatwaves weaken plant immunity and increase susceptibility to infection. Extreme climatic disturbances also disrupt ecological balances, allowing invasive pathogens and vectors to establish in new regions. Post-disaster conditions often create highly favourable environments for disease epidemics.

Impact of Climate Change on Major Groups of Plant Pathogens

1. Fungal Pathogens: Fungi constitute the largest group of plant pathogens influenced by climate change. Temperature and moisture strongly regulate fungal growth, sporulation, and dispersal. Climate warming has facilitated expansion of rust pathogens into higher altitudes and latitudes. Wheat stem rust caused by *Puccinia graminis* and stripe rust caused by *Puccinia striiformis* have shown changing epidemiological patterns under warming conditions. Late blight of potato caused by *Phytophthora infestans* has become increasingly severe due to changing temperature and humidity conditions. Similarly, Fusarium head blight in cereals is strongly associated with warm and humid weather. Increased CO₂ and temperature may accelerate fungal mutation rates and emergence of aggressive races capable of overcoming host resistance genes.

2. Bacterial Pathogens: Bacterial diseases are highly dependent on moisture and temperature. Warm and humid conditions enhance bacterial multiplication and infection processes. Diseases such as bacterial blight, bacterial wilt, citrus canker, fire blight, and bacterial leaf spot are increasingly favoured under changing climatic conditions. Heavy rainfall events promote bacterial dissemination through water splash and contaminated irrigation systems. Warmer winters enhance survival of bacterial inoculum, resulting in early disease outbreaks during subsequent seasons.

3. Viral Diseases: Plant viruses are indirectly influenced by climate change through their insect vectors. Temperature changes affect vector biology, migration, feeding behavior, reproduction, and survival. Warmer conditions enhance populations of aphids, whiteflies, thrips, leafhoppers, and other vectors responsible for transmission of viral diseases. Consequently, diseases such as tomato yellow leaf curl virus, rice tungro virus, and cassava mosaic virus are becoming increasingly problematic. Climate-induced shifts in vector distribution are introducing viral diseases into previously unaffected regions.

4. Nematode Diseases: Plant-parasitic nematodes are highly sensitive to soil temperature and moisture. Climate warming accelerates nematode reproduction and increases the number of generations per season. Root-knot nematodes (*Meloidogyne* spp.), cyst nematodes, and lesion nematodes are expected to expand into temperate regions under future warming scenarios. Drought stress often increases plant susceptibility to nematode infection, while changes in soil moisture influence nematode movement and survival.

Climate Change and Host Plant Resistance

Host plant resistance forms the cornerstone of sustainable disease management. However, climate change threatens the durability and effectiveness of resistance genes. High temperatures can suppress expression of resistance-related genes and weaken hypersensitive responses. Certain resistance genes function effectively only within specific temperature ranges. Under elevated temperatures, resistant cultivars may become susceptible. Climate change also accelerates pathogen evolution and emergence of new virulent races capable of overcoming resistance genes. Rapid pathogen adaptation poses significant challenges for breeding durable resistant varieties. Juroszek and von Tiedemann (2013) highlighted that climate change may destabilize host resistance and complicate future disease management strategies.

Emerging and Re-Emerging Plant Diseases

Climate change contributes to the emergence and re-emergence of plant diseases through ecological disturbances, altered vector dynamics, and increased international trade. Previously minor pathogens are emerging as major threats due to favourable climatic conditions. Changes in cropping systems, monoculture expansion, and global movement of planting materials further exacerbate disease emergence. New pathogen-host combinations are becoming increasingly common under changing environments. Climate-induced stress also predisposes plants to opportunistic pathogens. Emerging diseases threaten biodiversity, ecosystem stability, and agricultural productivity worldwide.

Geographic Expansion of Plant Diseases

Rising global temperatures are shifting the geographic distribution of plant pathogens toward higher latitudes and altitudes. Pathogens previously restricted to tropical regions are now appearing in temperate zones. Mountain ecosystems and cooler regions are becoming increasingly vulnerable to diseases historically absent from those areas. Expansion of disease ranges threatens new agricultural areas lacking resistant cultivars and effective management practices. Global trade and climate change together facilitate transboundary movement of pathogens and vectors, increasing the risk of pandemics in agriculture.

Impact on Disease Forecasting and Epidemiological Models

Traditional disease forecasting models are becoming less reliable under rapidly changing climatic conditions. Unpredictable weather patterns complicate disease prediction and management timing. Advanced epidemiological models integrating climate data, remote sensing, machine learning, artificial intelligence, and geographic information systems are increasingly important for predicting future disease outbreaks. Dynamic forecasting systems capable of incorporating real-time climatic variability are essential for effective disease surveillance and early warning systems. Bebbler et al. (2013) reported that many crop pests and pathogens are already shifting their geographic ranges poleward due to global climate warming.

Climate Change and Soil Microbial Ecology

Climate change significantly affects soil microbial communities involved in disease suppression and nutrient cycling. Altered temperature and moisture conditions influence beneficial microorganisms such as rhizobacteria, mycorrhizae, and antagonistic fungi. Disruption of beneficial microbial communities may reduce natural biological control of pathogens. Soil health deterioration under climate stress can increase susceptibility to soil-borne diseases. Understanding the interactions among climate, soil microbiota, and pathogens is crucial for sustainable disease management.

Implications for Food Security

Climate-driven plant disease epidemics threaten global food security by reducing crop yield, quality, and marketability. Increased disease incidence leads to economic losses, reduced farmer income, and instability in food supply chains. Developing countries are particularly vulnerable due to limited infrastructure, inadequate forecasting systems, and restricted access to resistant cultivars and fungicides. Staple crops such as rice, wheat, maize, and potato are increasingly threatened by climate-sensitive diseases. Ensuring future food security requires integrated approaches combining disease management, climate adaptation, and sustainable agriculture.

Management Strategies Under Climate Change

- 1. Development of Climate-Resilient Resistant Varieties:** Breeding climate-resilient and disease-resistant cultivars is essential for sustainable crop protection. Modern breeding approaches including marker-assisted selection, genomic selection, gene editing, and transgenic technologies can accelerate development of resistant varieties. Breeders must focus on durable, broad-spectrum resistance effective across variable climatic conditions.
- 2. Integrated Disease Management:** Integrated disease management combines cultural, biological, chemical, and genetic approaches to reduce disease pressure sustainably. Crop rotation, sanitation, resistant cultivars, balanced fertilization, proper irrigation management, and timely fungicide application remain important strategies under changing climates. Adaptive disease management practices tailored to local climatic conditions are increasingly necessary.
- 3. Biological Control:** Biological control using antagonistic microorganisms offers environmentally sustainable disease management under climate change. Beneficial microbes such as *Trichoderma*, *Pseudomonas*, *Bacillus*, and mycorrhizal fungi can enhance plant resilience against pathogens and abiotic stress. Climate-resilient bio-control agents capable of functioning under variable environmental conditions are receiving growing attention.
- 4. Disease Surveillance and Forecasting:** Advanced surveillance systems using remote sensing, drones, climate models, artificial intelligence, and digital agriculture technologies can improve disease monitoring and early warning systems. Real-time forecasting helps farmers implement timely interventions and minimize disease losses.
- 5. Climate-Smart Agriculture:** Climate-smart agricultural practices including conservation agriculture, agroforestry, precision farming, water conservation, and diversification improve resilience against climate-induced disease risks. Sustainable farming systems help maintain ecosystem balance and reduce pathogen pressure.

Future Research Priorities

Future research should focus on understanding complex interactions among climate variables, pathogens, hosts, vectors, and microbial communities. Long-term epidemiological studies are needed to predict future disease scenarios accurately. Research priorities include development of climate-resilient crops, advanced forecasting models, pathogen genomics, microbial ecology, and integrated management systems. International collaboration and interdisciplinary research are essential for addressing global plant disease challenges under climate change.

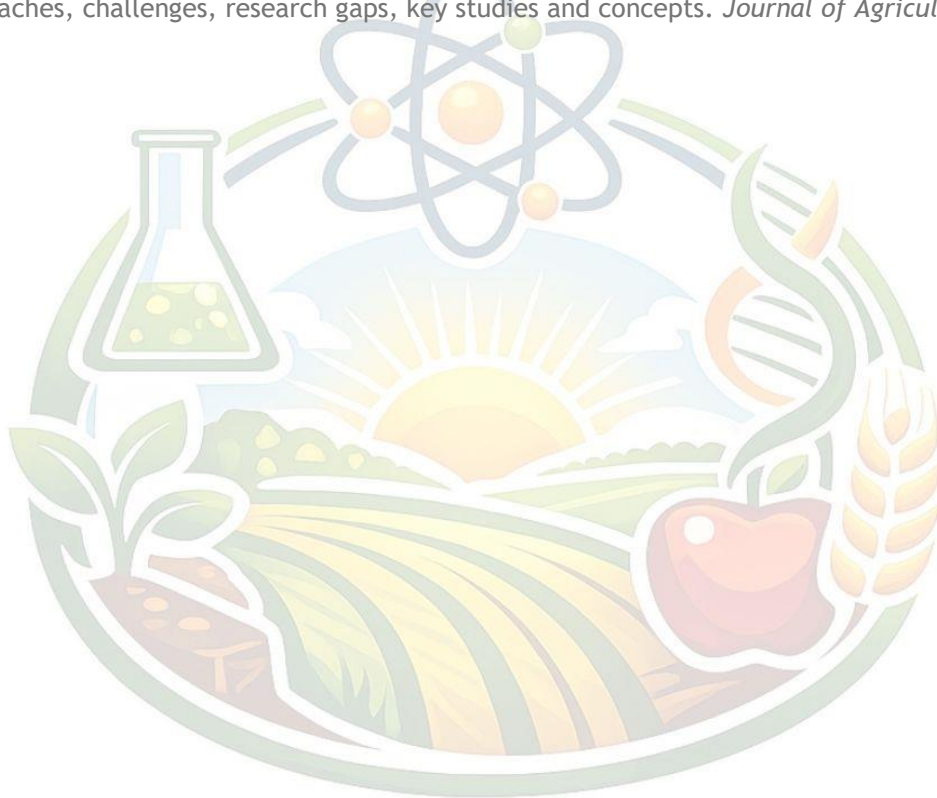
Conclusion

Climate change is profoundly transforming plant disease epidemiology by influencing pathogen biology, host susceptibility, vector ecology, and environmental conditions. Rising temperatures, altered precipitation patterns, elevated atmospheric CO₂, humidity fluctuations, and extreme weather events are reshaping disease dynamics worldwide. Emerging diseases, expansion of pathogen geographic ranges, accelerated pathogen evolution, and breakdown of host resistance are increasingly threatening global agriculture and food security. The epidemiological

triangle involving host, pathogen, and environment is becoming increasingly complex under changing climatic conditions. Traditional disease management strategies may become less effective as pathogens adapt rapidly to new environmental conditions. Therefore, sustainable and adaptive approaches integrating resistant cultivars, biological control, climate-smart agriculture, advanced forecasting systems, and integrated disease management are essential for future crop protection. Comprehensive understanding of climate-driven disease epidemiology will be critical for ensuring agricultural sustainability, environmental protection, and global food security in the coming decades.

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RNA Interference (RNAi) Technology for Plant Disease Management

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Dr. Jasmee R. Patel¹, Dr. Dinesh H. Chaudhary², Dr. Mulji D. Jehani³, Dr. Apurv Kumar M. Patel⁴, Dr. Piyush V. Limbachiya⁵

¹Assistant Professor (Plant Pathology), KKIARS, Ganpat University, Kherva, Mahesana, Gujarat.

²Assistant Professor (Plant Pathology), Office of the Director of Research, Navsari Agricultural University, Navsari, Gujarat.

³Scientist (Plant Protection), Krushi Vigyan Kendra, SDAU, Deesa, Gujarat.

⁴Assistant Professor (Plant Pathology), KKIARS, Ganpat University, Kherva, Mahesana, Gujarat.

⁵Assistant Professor (Fruit Science), Office of the Director of Research, Navsari Agricultural University, Navsari, Gujarat.

Abstract

Plant diseases caused by fungi, bacteria, viruses, nematodes, and other phytopathogens are major constraints to global agricultural productivity and food security. Conventional disease management strategies, including chemical pesticides and resistant cultivars, often face limitations such as environmental pollution, pathogen resistance, residue accumulation, and reduced long-term sustainability. RNA interference (RNAi) technology has emerged as a revolutionary, sequence-specific, environmentally friendly, and highly targeted strategy for plant disease management. RNAi is a natural gene-silencing mechanism that regulates gene expression through small RNA molecules, particularly small interfering RNAs (siRNAs) and microRNAs (miRNAs). In agriculture, RNAi technology has been extensively explored to suppress essential genes in pathogens and pests, thereby reducing disease severity and enhancing crop protection. Various RNAi-based approaches, including Host-Induced Gene Silencing (HIGS), Spray-Induced Gene Silencing (SIGS), Virus-Induced Gene Silencing (VIGS), and exogenous dsRNA application, have shown promising results against fungal, viral, bacterial, and nematode pathogens. Recent advances in nanotechnology, RNA delivery systems, and trans-kingdom RNA interference have further improved the efficiency and applicability of RNAi-mediated disease management. Despite remarkable progress, several challenges such as RNA stability, efficient delivery, off-target effects, biosafety concerns, regulatory issues, and commercialization barriers remain to be addressed. This review comprehensively discusses the mechanism of RNAi, various RNAi-based technologies, their applications in plant disease management, advantages, limitations, recent developments, and future prospects for sustainable agriculture.

Introduction

Agricultural crops are continuously threatened by a wide range of plant pathogens including fungi, bacteria, viruses, viroids, phytoplasmas, oomycetes, and nematodes. Plant diseases significantly reduce crop yield, quality, and economic profitability worldwide. The increasing global population, climate change, environmental degradation, and rising pathogen adaptability have intensified the demand for innovative and sustainable plant disease management strategies. Conventional methods such as chemical fungicides, bactericides, and pesticides have contributed substantially to crop protection; however, excessive dependence on these chemicals has led to environmental contamination, pathogen resistance, destruction of beneficial microorganisms, and concerns regarding human health.

In recent years, molecular biotechnology has provided new opportunities for crop protection. Among these emerging technologies, RNA interference (RNAi) has attracted enormous scientific attention due to its specificity, efficiency, and eco-friendly nature. RNAi is a conserved biological mechanism in eukaryotes that regulates gene expression through sequence-specific degradation or suppression of messenger RNA (mRNA). The discovery of RNAi revolutionized molecular biology and opened new possibilities for disease management in plants and animals.

RNAi-mediated plant protection involves silencing critical genes associated with pathogen virulence, pathogenicity, survival, development, or reproduction. Unlike traditional pesticides that broadly affect organisms, RNAi specifically targets selected genes, thereby minimizing adverse impacts on non-target organisms and the environment. The technology has shown enormous potential in controlling viral diseases, fungal infections, insect pests, and nematode infestations in various crops.

The application of RNAi in agriculture includes transgenic and non-transgenic approaches. Host-Induced Gene Silencing (HIGS) involves the expression of double-stranded RNA (dsRNA) within the plant to silence genes in invading pathogens. Spray-Induced Gene Silencing (SIGS) represents a non-transgenic approach in which dsRNA molecules are externally applied onto plant surfaces. These approaches have demonstrated significant success against several economically important plant diseases.

RNAi technology has become increasingly important in modern agriculture because of its compatibility with sustainable farming practices, precision agriculture, and integrated disease management systems. The integration of RNAi with nanotechnology, bioinformatics, and genomic tools is further expanding its practical applications in crop protection.

Historical Background and Discovery of RNAi

The phenomenon of gene silencing was initially observed in plants during experiments involving transgene expression. Researchers found that introduction of additional pigment-producing genes unexpectedly suppressed pigmentation instead of enhancing it. This phenomenon, known as co-suppression, later became recognized as RNA-mediated gene silencing.

The modern concept of RNA interference was established following the pioneering work of Fire and Mello in 1998, who demonstrated that double-stranded RNA could specifically silence genes in *Caenorhabditis elegans*. Their discovery revealed that dsRNA molecules trigger degradation of homologous mRNA, thereby suppressing gene expression. Subsequently, RNAi mechanisms were identified in plants, fungi, insects, and mammals.

Plant researchers soon recognized that RNA silencing functions as a natural antiviral defence system. Plants produce small RNA molecules that target viral genomes and suppress virus replication. Further investigations revealed that RNAi also regulates endogenous genes involved in development, stress responses, and immunity. The rapid advancement of genomics, transcriptomics, and RNA biology accelerated the development of RNAi-based crop protection technologies. Today, RNAi is considered one of the most promising molecular tools for sustainable agriculture and plant disease management.

Mechanism of RNA Interference

RNA interference is a sequence-specific post-transcriptional gene silencing mechanism mediated primarily by dsRNA molecules. The RNAi pathway involves several important molecular components and sequential biochemical processes. The process begins with the introduction or formation of dsRNA molecules inside the cell. These dsRNAs may originate from viruses, transgenes, endogenous transcripts, or externally applied RNA molecules. The dsRNA is recognized and cleaved by a ribonuclease III enzyme known as Dicer into short fragments called small interfering RNAs (siRNAs), usually 21-24 nucleotides in length. The generated siRNAs are incorporated into the RNA-Induced Silencing Complex (RISC). Within this complex, one strand of the siRNA, known as the guide strand, remains associated with Argonaute proteins, while the passenger strand is degraded. The guide strand directs the RISC complex toward complementary target mRNA molecules.

Upon binding to the target mRNA, Argonaute proteins cleave the mRNA, leading to its degradation and suppression of gene expression. This sequence-specific silencing mechanism enables highly targeted regulation of genes associated with pathogen virulence, toxin production, or essential metabolic pathways. In plants, RNAi signaling can spread systemically through plasmodesmata and vascular tissues, allowing silencing signals to move throughout the plant. This systemic property enhances the effectiveness of RNAi-mediated defense responses against pathogens. RNAi mechanisms also involve microRNAs (miRNAs), trans-acting siRNAs (ta-siRNAs), and secondary siRNAs that regulate various biological functions. The amplification of silencing signals through RNA-dependent RNA polymerases further strengthens the RNAi response.

Types of RNAi Approaches in Plant Disease Management

1. Host-Induced Gene Silencing (HIGS): Host-Induced Gene Silencing is a transgenic RNAi strategy in which plants are genetically engineered to produce dsRNA molecules targeting essential genes in pathogens or pests. During pathogen infection, these RNA molecules are transferred from the host plant into the pathogen, where they trigger gene silencing. HIGS has been successfully used against fungal pathogens such as *Fusarium graminearum*, *Blumeria graminis*, and *Puccinia triticina*. Silencing of fungal pathogenicity genes significantly reduces disease severity and pathogen colonization. Similarly, HIGS has shown promising results against nematodes and insect pests.

One major advantage of HIGS is continuous protection because the plant continuously produces dsRNA molecules. However, the approach requires transgenic crop development, which may face regulatory and public acceptance challenges.

2. Spray-Induced Gene Silencing (SIGS): Spray-Induced Gene Silencing is a non-transgenic approach involving external application of dsRNA or siRNA molecules onto plant surfaces. The applied RNA molecules are absorbed by plants or pathogens and subsequently trigger gene silencing. SIGS has emerged as a highly promising technology because it avoids genetic modification of crops. It offers flexibility, rapid deployment, and compatibility with existing agricultural practices. Studies have demonstrated effective control of fungal pathogens such as *Botrytis cinerea*, *Fusarium asiaticum*, and *Sclerotinia sclerotiorum* using SIGS. The major challenge associated with SIGS is the instability of RNA molecules under field conditions due to degradation by UV radiation, nucleases, and environmental factors. To overcome this limitation, researchers are developing nanoparticle-based delivery systems and protective formulations.

3. Virus-Induced Gene Silencing (VIGS): Virus-Induced Gene Silencing utilizes modified viral vectors to deliver gene fragments into plants and induce RNA silencing. VIGS is mainly used as a research tool for functional genomics and gene characterization but also has applications in disease resistance studies. The method is rapid, efficient, and suitable for transient gene silencing. However, VIGS may cause variable silencing efficiency and unintended viral symptoms.

4. Exogenous dsRNA Application: Exogenous application of dsRNA molecules directly onto plants represents another promising RNAi strategy. dsRNA can be delivered through foliar sprays, trunk injection, root soaking, seed treatment, or nanoparticles. This approach provides flexibility and avoids transgenic modifications. It has shown effectiveness against viruses, fungi, insects, and nematodes. The use of nanocarriers enhances dsRNA stability and uptake efficiency.

Climate Change and Host Plant Resistance

Host plant resistance forms the cornerstone of sustainable disease management. However, climate change threatens the durability and effectiveness of resistance genes. High temperatures can suppress expression of resistance-related genes and weaken hypersensitive responses. Certain resistance genes function effectively only within specific temperature ranges. Under elevated temperatures, resistant cultivars may become susceptible. Climate change also accelerates pathogen evolution and emergence of new virulent races capable of overcoming resistance genes. Rapid pathogen adaptation poses significant challenges for breeding durable resistant varieties. Juroszek and von Tiedemann (2013) highlighted that climate change may destabilize host resistance and complicate future disease management strategies.

RNAi Against Viral Diseases

Plant viruses are among the most devastating pathogens affecting global agriculture. RNAi naturally functions as an antiviral defence mechanism in plants, making RNAi technology highly suitable for controlling viral diseases. RNAi-mediated viral resistance involves targeting viral coat proteins, replicases, movement proteins, or suppressors of RNA silencing. Transgenic plants expressing virus-specific dsRNA molecules exhibit strong resistance against viral infections.

Several successful examples include resistance against Papaya ringspot virus, Tomato spotted wilt virus, Potato virus Y, Cucumber mosaic virus, and Tobacco mosaic virus. RNAi-mediated virus resistance has significantly improved crop productivity and reduced dependence on chemical controls. Topical application of dsRNA has also shown promising antiviral effects. Exogenous RNA molecules can trigger antiviral immunity without altering the plant genome. Such approaches are gaining importance in sustainable agriculture and organic farming systems.

RNAi Against Fungal Diseases

Fungal pathogens cause severe economic losses in agriculture and are often difficult to control due to fungicide resistance and environmental concerns. RNAi technology offers highly specific control of fungal pathogens by targeting genes involved in virulence, cell wall synthesis, metabolism, and toxin production. Research has demonstrated successful silencing of genes in *Botrytis cinerea*, *Fusarium graminearum*, *Sclerotinia sclerotiorum*, *Magnaporthe oryzae*, and *Aspergillus flavus*. Suppression of fungal pathogenicity genes significantly reduces disease development and mycotoxin accumulation.

Trans-kingdom RNAi plays a critical role in plant-fungal interactions. Plants can transfer small RNAs into fungal pathogens, where they silence fungal genes. Similarly, pathogens may deliver small RNAs into plants to suppress host immunity. Understanding these interactions has opened new opportunities for RNAi-based disease management. SIGS has become particularly important for fungal disease management because many fungi can absorb external dsRNA molecules. Researchers are now developing dsRNA sprays as next-generation biofungicides.

RNAi Against Bacterial Diseases

Compared to fungi and viruses, RNAi-based management of bacterial diseases is relatively challenging because bacteria generally lack canonical RNAi machinery. However, RNAi technology can still indirectly improve resistance against bacterial pathogens by targeting host susceptibility genes or regulatory pathways associated with infection. RNAi-mediated silencing of plant genes required for bacterial colonization can reduce disease severity. Furthermore, small RNAs may regulate plant immune responses against bacterial pathogens. Emerging studies indicate that RNA-based approaches may contribute to the management of bacterial wilt, citrus greening, and other bacterial diseases through modulation of host-pathogen interactions.

RNAi Against Nematodes

Plant-parasitic nematodes are major agricultural pests responsible for extensive crop losses worldwide. RNAi technology has shown considerable promise against root-knot nematodes, cyst nematodes, and lesion nematodes. HIGS-mediated silencing of essential nematode genes involved in feeding, development, reproduction, and parasitism significantly reduces nematode infection and reproduction. Several crops expressing nematode-targeted dsRNA molecules have demonstrated enhanced resistance. RNAi approaches targeting genes involved in nematode sensory perception, cuticle formation, and digestive functions have also produced promising results.

Trans-Kingdom RNAi

Trans-kingdom RNAi refers to the movement of small RNA molecules between interacting organisms such as plants and pathogens. This phenomenon has transformed the understanding of plant-pathogen interactions. Plants can export small RNAs into fungal pathogens through extracellular vesicles. These RNAs target fungal virulence genes and suppress infection. Conversely, pathogens can deliver small RNAs into plants to suppress host defence mechanisms. The discovery of trans-kingdom RNAi has provided a strong scientific foundation for HIGS and SIGS technologies. It also offers new opportunities for designing highly specific RNAi-based disease management strategies.

Nanotechnology and RNAi Delivery Systems

Efficient delivery of RNA molecules remains one of the most critical challenges in RNAi technology. Naked dsRNA molecules are highly susceptible to degradation by nucleases, UV radiation, temperature fluctuations, and environmental factors. Nanotechnology has emerged as a powerful solution for enhancing RNA stability and delivery efficiency. Nanocarriers protect dsRNA molecules from degradation and facilitate their uptake into plant tissues and pathogens. Several nanomaterials including layered double hydroxides, carbon nanotubes, liposomes, silica nanoparticles, and chitosan nanoparticles have been explored for RNA delivery. Clay nanosheets have demonstrated remarkable ability to prolong dsRNA stability on plant surfaces. Nanoparticle-mediated RNA delivery improves persistence, targeted delivery, controlled release, and field applicability of RNAi-based products.

Advantages of RNAi Technology in Plant Disease Management

RNAi technology offers numerous advantages over conventional disease management methods. One of the most important advantages is its high specificity. RNAi targets only selected genes, thereby minimizing effects on beneficial organisms and reducing ecological disturbances.

The technology is environmentally friendly because RNA molecules are biodegradable and do not accumulate as toxic residues in soil or water. RNAi also reduces dependence on chemical pesticides and supports sustainable agriculture. Another major advantage is flexibility. RNA sequences can be rapidly designed against emerging pathogens or newly evolved virulence genes. RNAi technology is also compatible with integrated pest and disease management programs. RNAi-based approaches can target multiple genes simultaneously, thereby reducing the likelihood of resistance development. Moreover, non-transgenic approaches such as SIGS may achieve greater public acceptance compared to genetically modified crops.

Limitations and Challenges

Despite significant progress, several challenges hinder the large-scale adoption of RNAi technology in agriculture. RNA instability under field conditions remains a major limitation. Environmental degradation reduces the persistence and effectiveness of dsRNA molecules. Efficient delivery into pathogens and plant tissues is another significant challenge. Off-target effects may occur if RNA sequences unintentionally match non-target genes. Such effects could potentially impact beneficial organisms or plant metabolic processes.

Production costs of large-scale dsRNA synthesis remain relatively high, although advances in biotechnology are gradually reducing costs. Regulatory frameworks for RNAi-based products are still evolving in many countries. Public perception and biosafety concerns regarding RNA-based technologies may also influence commercialization. Furthermore, variable RNA uptake efficiency among pathogens affects the success of RNAi-mediated disease control. Pathogens may eventually develop resistance mechanisms such as reduced dsRNA uptake, enhanced RNA degradation, or mutations in target genes. Therefore, continuous monitoring and integrated management strategies are necessary.

Commercialization and Regulatory Aspects

Several RNAi-based products are currently under development or commercialization for agricultural applications. Regulatory agencies are evaluating RNAi products based on environmental safety, specificity, persistence, and non-target effects. Compared to chemical pesticides, RNAi products generally exhibit lower toxicity and environmental risk. However, standardized protocols for risk assessment, biosafety evaluation, and environmental monitoring are still needed.

The commercialization of SIGS-based bio-fungicides and RNA sprays represents a major milestone in sustainable crop protection. Advances in large-scale dsRNA production and formulation technologies are accelerating market development.

Future Prospects

RNAi technology is expected to play a transformative role in future agriculture. Advances in genomics, bioinformatics, synthetic biology, and nanotechnology will enhance the efficiency, precision, and affordability of RNAi-based disease management. Artificial intelligence and computational biology may facilitate the identification of optimal RNA targets and minimize off-target effects. Improved delivery systems will increase field stability and commercial feasibility.

Integration of RNAi with CRISPR-based genome editing, microbiome engineering, and precision agriculture may revolutionize crop protection strategies. RNAi-based biopesticides could significantly reduce chemical pesticide usage and contribute to climate-resilient agriculture. The future success of RNAi technology will depend on interdisciplinary research, regulatory harmonization, public awareness, and cost-effective commercialization strategies.

Conclusion

RNA interference technology has emerged as one of the most promising and innovative approaches for sustainable plant disease management. By enabling sequence-specific silencing of pathogen-related genes, RNAi provides precise, environmentally friendly, and highly effective crop protection. Various RNAi approaches including HIGS, SIGS, VIGS, and exogenous dsRNA application have demonstrated remarkable success against viruses, fungi, nematodes, and insect pests. Recent developments in trans-kingdom RNAi, nanoparticle-mediated delivery systems, and RNA-based bio-fungicides have significantly expanded the practical applicability of RNAi technology in agriculture. Although several challenges such as RNA stability, delivery efficiency, regulatory concerns, and production costs remain, continuous scientific advancements are steadily overcoming these barriers. RNAi-based disease management has immense potential to reduce dependence on conventional chemical pesticides and support sustainable agricultural systems. With further research, technological refinement, and global collaboration, RNAi technology is likely to become an integral component of next-generation crop protection strategies.

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Natural Farming: Scope and Importance

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Dr. H. B. Sodavadiya¹, Dr. M. P. Chaudhari¹, Dr. V. Y. Patel¹, Dr. P. M. Sankhla¹

¹Sardarkrushinagar Dantiwada Agricultural University, SKNagar- 385506.

Introduction

In recent decades, humanity has greatly benefited from economic growth and advancements in agricultural science. The adoption of modern, intensive farming practices has led to remarkable increases in crop yields—such as 109% in rice, 208% in wheat, 157% in maize, 78% in potatoes, and 36% in cassava—thereby supporting the needs of a rapidly expanding global population and reducing food shortages (Wiebe *et al.*, 2021).

Despite these achievements, such progress has come at a significant environmental cost. Conventional agricultural systems depend heavily on synthetic fertilizers, pesticides, and fossil fuel-based energy. The overuse of these inputs has resulted in soil degradation, environmental pollution, reduced food quality, and potential risks to both human and animal health.

Data from FAI (2020) indicate that fertilizer consumption in India has increased nearly thirteenfold between 1970 and 2020. This excessive use has disturbed soil nutrient balance and reduced the efficiency of crop responses. The optimal ratio of essential nutrients—nitrogen, phosphorus, and potassium (4:2:1)—has been altered, leading to long-term soil fertility issues. Furthermore, such practices contribute to higher greenhouse gas emissions and create unstable and unsustainable farming systems.

At the same time, the rising cost of agricultural inputs, coupled with low returns from farm produce, has placed considerable financial strain on farmers, often leading to increased indebtedness. These challenges have intensified the need for sustainable and environmentally friendly farming alternatives.

Concept of Natural Farming

Natural farming, particularly in the Indian context, represents a sustainable and low-cost agricultural approach that avoids the use of synthetic chemical inputs. Instead, it relies on locally available resources such as cow dung, cow urine, jaggery, pulse flour, and organic residues to maintain soil fertility and promote plant growth.

This approach focuses on strengthening soil health by enhancing microbial activity, increasing organic matter, and encouraging biodiversity within the farming ecosystem. It supports crop diversification and efficient recycling of farm biomass, creating a balanced and self-sustaining agricultural system.

Natural farming incorporates several ecological practices, including mulching, composting, green manuring, crop rotation, intercropping, agroforestry, and integration of livestock. These practices collectively aim to improve productivity while preserving environmental health.

Core Principles of Natural Farming

The framework of natural farming is built upon a set of guiding principles:

1. Adoption of **diverse cropping systems**, including integration of trees with annual and perennial crops.
2. Complete avoidance of **chemical fertilizers, pesticides, and herbicides**.
3. Ensuring **continuous soil cover** using mulch or cover crops to conserve moisture and improve soil structure.
4. Preference for **indigenous seed varieties**, which are cost-effective and more adaptable to local conditions.
5. Use of **bio-inputs and plant-based extracts** to stimulate soil biology and manage pests naturally.
6. Practice of **reduced or minimal tillage** to protect soil structure and organisms.
7. **Integration of livestock** to enhance nutrient cycling and provide additional economic benefits.

Status and Promotion in India

Natural farming is gaining momentum across several Indian states. Andhra Pradesh, Himachal Pradesh, and Gujarat are among the leading adopters, while states such as Uttar Pradesh, Madhya Pradesh, Odisha, Chhattisgarh, Jharkhand, and Tamil Nadu are also expanding its practice.

To support this transition, the Government of India introduced the Bharatiya Prakritik Krishi Paddhati (BPKP) during 2020-21 under the Paramparagat Krishi Vikas Yojana (PKVY). This initiative has already covered around 6.1 lakh hectares, supported by a financial allocation of ₹49.8 crore.

Given India's diverse agro-climatic zones and the wealth of traditional farming knowledge among its farmers, the country holds strong potential for scaling up natural farming practices in the future (Kumar *et al.*, 2019).

Natural Farming - A Timely Necessity

A report by NITI Aayog highlights that natural farming has become increasingly important in the current agricultural scenario. The rising cost of food grain production—driven by expensive inputs such as chemical fertilizers, pesticides, fungicides, and herbicides—has made conventional farming economically challenging for farmers.

Natural farming offers a sustainable alternative by helping restore degraded soils, improve soil health, conserve water resources, and significantly reduce dependence on chemical inputs. In addition, it contributes to better nutritional quality of crops and strengthens local food systems, making it a holistic solution for present-day agricultural concerns.

Key Features of Natural Farming

- 1. Nutrient sourcing from nature:** Natural farming is based on the idea that plants derive about 98% of their nutrients from air, water, and sunlight. The remaining 2% is supplied by healthy soil enriched with beneficial microorganisms, similar to natural forest ecosystems.
- 2. Permanent soil cover:** The soil is kept covered for most of the year using organic mulch. This practice promotes humus formation, retains moisture, and supports microbial growth.
- 3. Use of bio-cultures:** Farm-prepared formulations such as *Beejamrit* (for seed treatment), *Jeevamrit* (for foliar application), and *Ghanjeevamrit* (for soil enrichment) are used instead of chemical fertilizers. These inputs are made from small quantities of cow dung and urine, especially from indigenous (desi) cow breeds known for their rich microbial content.
- 4. Improved farmer livelihoods:** Natural farming has the potential to increase farmers' income by lowering input costs while simultaneously restoring soil fertility, improving environmental conditions, and reducing greenhouse gas emissions.
- 5. No external fertilizers:** Neither chemical nor commercial organic fertilizers are applied. Instead, nutrient availability is enhanced through natural decomposition processes driven by soil organisms like microbes and earthworms.
- 6. Minimal soil disturbance:** The system mimics natural ecosystems with limited tillage. Weeds are not completely removed; rather, they are utilized as live or dead mulch to support soil health.
- 7. Natural pest management:** Eco-friendly, farm-made pesticides such as *Neem Astra* are used to manage pests and diseases without harming the environment.
- 8. Promotion of crop diversity:** Multi-cropping systems are preferred over monocropping, ensuring better resource use, resilience, and ecological balance.

The following Figure presents a comparison between natural farming and organic farming based on their underlying principles, techniques, and practices.

NATURAL FARMING vs ORGANIC FARMING

S. No.	NATURAL FARMING 3	ORGANIC FARMING 4
	1. Definition Relies on natural processes without using any external inputs	Avoids synthetic chemicals, relying on natural inputs, crop rotation, and biodiversity
	2. Use of Inputs No external inputs; relies purely on nature's cycle	Uses natural and organic inputs, like organic composts and natural pesticides
	3. Soil Fertility Soil fertility is maintained through natural processes like mulching and microbial activity	Soil fertility is enhanced using organic composts, manures, and green manuring
	4. Pest Management Pest management through beneficial insects and natural predators	Uses organic, non-synthetic pesticides and encourages beneficial insects for managing pests
	5. Weed Management Depends on natural processes and manual methods for weed control	Weed control through manual weeding, mulching, and sometimes natural herbicides
	6. Seed Treatment Seeds are typically untreated or fermented with natural solutions	Seeds can be soaked in organic solutions or used as-is if non-GMO
	7. Cost of Cultivation Low cultivation cost, as known for being low-cost, especially in "zero budget" approaches	Might involve some costs for organic inputs, certification, and labour
	8. Certification No standardized certification process worldwide	Strict certification processes, often regulated by national/international bodies
	9. Time & Labour Can be less time-intensive due to fewer interventions	Might be more time-consuming due to specific organic practices and rotations
	10. Philosophy Adopts the philosophy of "Work in harmony with nature"	Emphasizes avoiding synthetic chemicals while actively managing farm health

Importance of Natural Farming

Natural farming is gaining importance due to increasing food demand, climate change, and health concerns. It promotes sustainable agriculture by avoiding chemical inputs and working in harmony with nature. It improves soil fertility, enhances biodiversity, conserves water, and reduces environmental pollution. It also ensures safe, chemical-free food and supports farmer income, rural employment, and ecological balance.

Scope of Natural Farming

The scope of natural farming is wide and includes:

1. **Environmental:** Improves soil health, biodiversity, water conservation, and reduces pollution
2. **Economic:** Low cost of cultivation, higher market value, and better resilience
3. **Health:** Produces nutrient-rich and chemical-free food
4. **Social:** Empowers rural communities and preserves traditional knowledge
5. **Innovation:** Encourages research and integration with modern technologies
6. **Global:** Helps in climate change mitigation and supports sustainable development goals

Current Scenario of Natural Farming in India

Natural farming in India is witnessing rapid growth as a sustainable alternative to conventional agriculture. As of 2023, approximately **4.09 lakh hectares** of agricultural land are under natural farming practices across the country. To support this transition, the Government of India has released **₹4587.17 lakh** across eight states, reflecting strong institutional backing.

Among the states, **Andhra Pradesh, Madhya Pradesh, Chhattisgarh, and Kerala** are leading in terms of area under natural farming, largely due to effective implementation under the **Bharatiya Prakritik Krishi Paddhati (BPKP)** scheme. Other participating states include Odisha, Himachal Pradesh, Jharkhand, and Tamil Nadu, though with comparatively smaller areas.

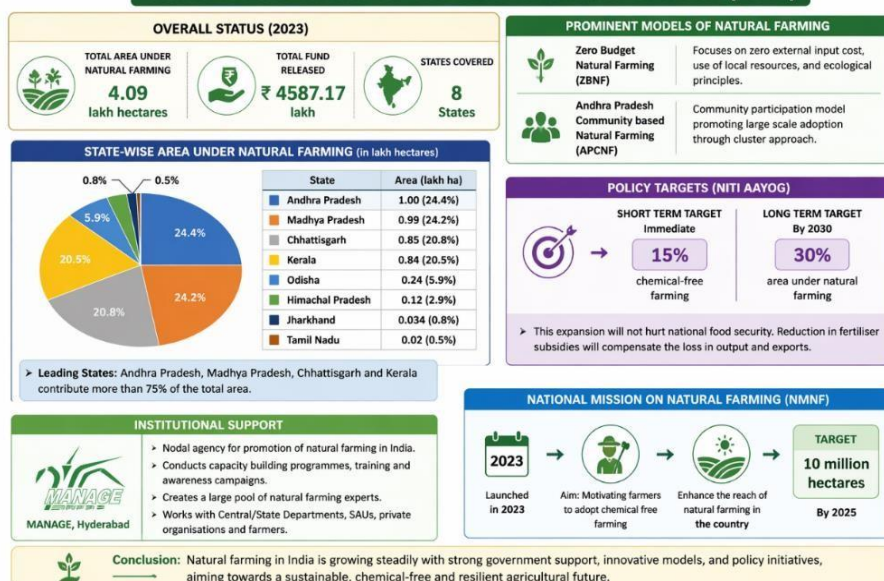
Two prominent models driving natural farming adoption in India are **Zero Budget Natural Farming (ZBNF)** and **Andhra Pradesh Community Natural Farming (APCNF)**. These models emphasize low-cost, chemical-free farming by utilizing locally available resources and community-based approaches.

According to **NITI Aayog**, India has the potential to expand chemical-free farming to **15% of total agricultural land in the short term** and up to **30% by 2030**, without adversely affecting food security. The anticipated reduction in fertilizer subsidies is expected to offset any minor decline in yield or exports.

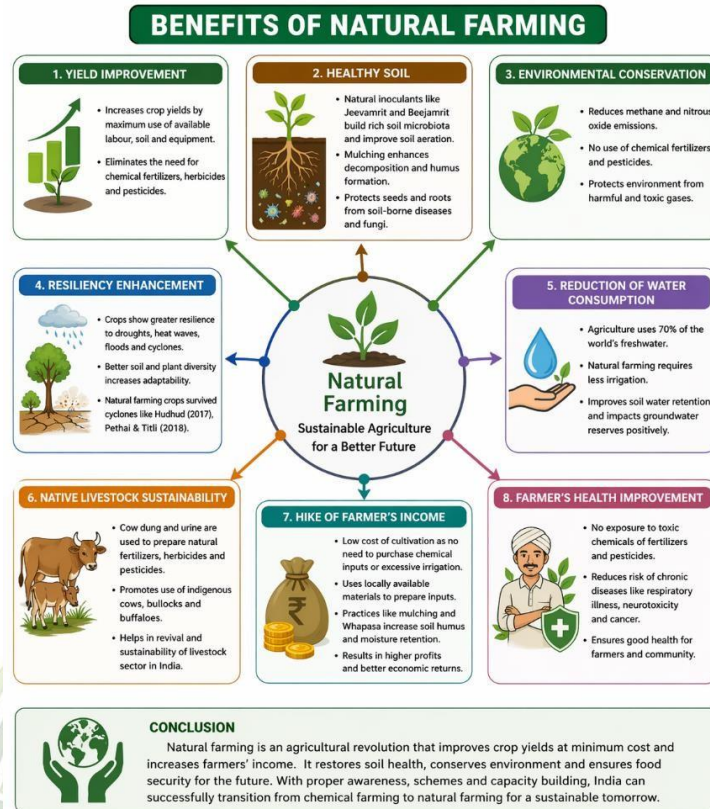
Institutionally, the **National Institute of Agricultural Extension Management (MANAGE), Hyderabad** serves as the nodal agency for promoting natural farming. It conducts training programs, capacity-building initiatives, and awareness campaigns for farmers, extension workers, and stakeholders across the country.

Further strengthening the initiative, the Government of India launched the **National Mission on Natural Farming (NMNF)** in **2023**, with an ambitious target to bring **10 million hectares** under natural farming by **2025**. This mission aims to scale up adoption, enhance farmer awareness, and ensure long-term sustainability of Indian agriculture.

CURRENT SCENARIO OF NATURAL FARMING IN INDIA (2023)



Benefits of Natural Farming



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Best Management Practices to Improve Nitrogen Use Efficiency

Article ID: 73739

D. Leninraja¹, P. Radha², K. Manobharathi³, T. Ragul⁴

¹ Asst. Professor (SS&AC), HC&RI, TNAU, Periyakulam, Theni, Tamil Nadu.

² Asst. Professor (Biochemistry), FC&RI, TNAU, Mettupalayam, Tamil Nadu.

³ Asst. Professor (Agrl. Extension), Mother Teresa College of Agriculture, Pudukkottai, Tamil Nadu.

⁴ Research Scholar (SS&AC), AC&RI, TNAU, Coimbatore, Tamil Nadu.

Nitrogen ranks first among the applied inputs to maximize agricultural production since it is very essential for plant growth and development. The efficiency of N fertilizer applied to crop plants is very low, generally around 30-40%, in some cases even lower. The low N-use efficiency is attributed mainly to ammonia volatilization, denitrification, leaching, and runoff losses leading to environmental pollution and health problems besides reducing crop yield. Though these problems cannot be alleviated completely they can be minimized by certain management practices.

Selection of Suitable Fertilizer

Selection of fertilizers should be done according to the soil reaction (pH) viz., acidic fertilizer for alkaline soils and basic fertilizers for acidic soils. Slow release nitrogen fertilizers coated with nitrification inhibitors and urease inhibitors can be chosen for wet land crops to reduce N losses due to leaching especially in light textured soil.

Split Application of N Fertilizer

Split application of N to meet the immediate crop growth stage specific N needs is recommended for maximum N use efficiency with reduced losses. Splitting the total N into two doses one half as basal and rest as top-dressing especially in heavy soils. In case of light soils, nitrogen should be applied in three equal splits i.e 1/3 after 30 days of sowing and the balance 1/3 at about 50-60 days after sowing. Finally splitting should be crop specific and crop stage specific to match the growth stage specific N demand. The chlorophyll meter (SPAD) and leaf colour chart (LCC) are simple, portable diagnostic tools that can measure the crop stage N demand to determine the timing of topdressing. It is well known that grain yield response diminishes with increasing rates of N application, and yields could further decrease due to lodging and increased incidence of insect pests and diseases at high N levels. It is important to select rice varieties with higher N-use efficiency that are tolerant to lodging and pests and diseases at high N supply.

The SPAD or LCC reading should be measured once in a week starting from 14 DAT for transplanted rice and 21 days after seeding for wet seeded rice. Threshold level for chlorophyll meter (SPAD) reading is 35 for transplanted rice in Dry season and 32 for transplanted rice in wet season. If SPAD / LCC value falls below the critical level, the following quantity of nitrogen can be applied to optimize N content on the foliage especially in rice.

Crop stage	Dry season	Wet season
Transplanted rice		
Early growth stage (14-21 days)	30 kg N / ha	20 kg N / ha
Rapid growth state (21 - 49 days)	45	30
Late growth stage (49 - flowering)	30	20
Wet seeded rice		
Early growth stage (21 - 35 days)	30 kg N / ha	20 kg N / ha
Rapid growth state (35 - 56 days)	45	30
Late growth stage (56 - flowering)	30	20

Method of Application of Fertilizer

The widely practiced method of fertilizer application in India is by surface application through broadcasting. This method is preferred under conditions such as crops with a dense stand and not sown in rows.

1. Band application: Band application of fertilizer is the placing a small quantity of fertilizer at about 3-4 cm by the side or below the seed. The distance and quantity of fertilizer placement is depends on the type and stage of crop. However, this method is commonly practiced under the situations of 1) small quantity of fertilizers is to be supplied b) Soil with high nutrient fixation c) Soil with low fertility d) crops sown or planted in definite rows e) application of fertilizer to shallow rooted crops.

2. Fertigation: Recently the fertigation method of fertilizer application is getting popular. Application of fertilizer along with irrigation water through drip system is termed as fertigation. It increases nutrient use efficiency from 80 to 90 percent besides reducing the nutrient losses. This method is highly beneficial to farmers in timely and site specific

application of nutrient in addition to reducing quantity of fertilizer applied as the nutrients are directly supplied to root zone.

Controlled or Slow-Release Fertilizers

These fertilizers can be classified in two basic groups: compounds of low solubility and coated water-soluble fertilizers. Other products, known as N stabilizers or bio-inhibitors, are not true slow-release products, but reduce N losses by slowing N transformations. Polymer-coated controlled release fertilizers look promising for widespread use in agriculture because they can be designed to release nutrients in a more controlled manner. The polymers are generally durable and exhibit consistent release rates that are predictable when average temperature and moisture conditions can be estimated. Nutrient release rate is altered by manipulating properties of the polymer coating.

1. Slow release N fertilizer: Slow-release fertilizers are of particular importance for special applications and they increase the efficiency of N. These have been developed to better adapt the rate of N release to the N demands of plants, reduce the number of splits required, improve nitrogen-use efficiency and reduce N losses. There are a large number of slow-release fertilizers and their mixtures, with N-release rates extending from short to long periods. Some examples of slow-release fertilizers are crotonylidene urea (CDU), isobutylidene diurea (IBDU), combinations of formaldehyde and urea, and oxamide (diamide of oxalic acid). Polymer-coated urea has been shown to be an effective N source. Different degrees of release can be distinguished by analytical methods with fractions soluble in hot water acting more slowly than those soluble in cold water, and fractions insoluble in hot water acting extremely slow. Soil microbes gradually liberate the N in these slow-release fertilizers with the decomposition rate depending largely on temperature. They are expensive in terms of per unit of N and are, therefore, restricted mainly to commercial and special applications.

2. Bio-inhibitors or urease inhibitors: Urease is produced by many soil microorganisms and plants, and is present in nearly all soils. When applied urea is hydrolyzed by urease, much of the resulting ammonium is held on soil cation exchange sites. During the conversion, the pH temporarily rises and ammonia gas is produced. The loss of ammonia gas is termed as volatilization. Urease inhibitors are used to temporarily reduce the activity of the enzyme and slowdown the rate at which urea is hydrolyzed. There are many compounds that can inhibit urease, but only a few are non-toxic, effective at low concentrations, chemically stable and able to be mixed with or coated with urea-containing fertilizers. The most widely used urease inhibitor is N-(n-Butyl) thiophosphoric triamide (NBPT or NBPT), which converts to active N-(n-Butyl) phosphoric triamide (NBPTO or BNPO). Other widely studied urease inhibitors include phenylphosphorodiamidate (PPD/PPDA) and hydroquinone. Ammonium thiosulfate and some metals can also inhibit urea hydrolysis. There are many other organic compounds, especially structural analogues of urea, capable of inhibiting urease.

Application of Soluble Chloride or Nitrate Salts of Calcium, Magnesium and Potassium

Ammonia (NH_3) volatilization can be reduced by co-application of calcium (Ca^{2+}), magnesium (Mg^{2+}), or potassium (K^+) salts (chloride and nitrate) with urea. When urea is applied to soil, it is converted to ammonium carbonate, which is susceptible to NH_3 volatilization loss. If nitrate or chloride salt of calcium or magnesium is applied with urea, it reduces volatilization loss of nitrogen by forming ammonium chloride or nitrate. Potassium (K^+) reduces NH_3 volatilization loss indirectly by increasing calcium carbonate precipitation by replacing Ca^{2+} from the exchange complex in high Ca^{2+} soil. Addition of KCl or KNO_3 with urea reduces ammonia volatilization loss significantly and consequently increases N use efficiency significantly.

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Soil Moisture Management in Annual Moringa

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D. Leninraja¹, P. Radha², K. Manobharathi³, T. Ragul⁴

¹ Asst. Professor (SS&AC), HC&RI, TNAU, Periyakulam, Theni, Tamil Nadu.

² Asst. Professor (Biochemistry), FC&RI, TNAU, Mettupalayam, Tamil Nadu.

³ Asst. Professor (Agrl. Extension), Mother Teresa College of Agriculture, Pudukkottai, Tamil Nadu.

⁴ Research Scholar (SS&AC), AC&RI, TNAU, Coimbatore, Tamil Nadu.

Moringa (*Moringa oleifera*) is a tropical plant and exhibits certain degree of xerophytic behaviour. Botanically the perennial moringa types are featured with large size water storage cells in limbs and low transpiration rate to tolerate against drought and also have the adaptation of shedding all its leaves to reduce transpiration loss. Moreover the developing fruits are autotrophic since they also contain high chlorophyll content and also draw water from the storage cells for photosynthesis. This mechanism was helpful in the retention and development of fruit. Basic understanding of the growth and development physiology of moringa is very much important before to chalk out the soil moisture management for flowering.

Moringa can be successfully grown in soils with good drainage viz., red loam, red sandy loam, clay loam and sandy loam soils. Moringa roots are highly sensitive to water logging. Annual moringa types raised through seeds requires frequent and regular irrigation compare to perennial or country types. In annual moringa types the roots are highly succulent and fast spreading and draw more water from the subsoil region hence it needs frequent and regular irrigation with an interval of 7-10 days whereas the perennial moringa types are hardy and can be irrigated with an interval of 10-15 days interval based on the soil type during its vegetative growth respectively. Shorter period of 10-15 days water stress immediately after the pinching is very much useful for the development of more number of laterals in annual moringa. Soil moisture stress for the period of 20 - 30 days depending upon the soil types will be beneficial in flower induction of moringa.

Soil moisture stress for limited period of time has the positive role on flower bud development by suppressing the excessive vegetative growth in moringa. However the water stress is not advisable for during the peak flowering and fruit setting stage. Moisture stress during this stage would be highly detrimental for moringa crop and results in flower drop, pollen dryness, immature fruit drop and desiccation of immature fruits from tip to downwards. Hence regular and frequent irrigation with 7-10 days interval depending upon the soil type is necessary to improve the fruit set and fruit development of moringa. Excess watering and water stagnation has to be completely avoided during this stage since that also leads to flower drop and immature fruit drop. During peak fruit development and maturation stage requires moderate irrigation otherwise the fruits are highly succulent, less palatability and poor post-harvest life. Complete stoppage of irrigation is recommended during the fruit maturation and fruit colour changes into straw yellow for seed production purpose.

During the severe drought and in hot summer period, the moringa tree can be sprayed with anti - transpirants like green miracle, PMA, kaolin etc., to safeguard against the trees from drought and also to check the flower drop or fruit drop.

The base of the moringa trunk should always well protected by earthing up or mounding the soil around the tree base and also against termite and bark borer incidence. Since the roots are highly succulent and fragile in nature and heavy wind will pull out the whole plant and limbs and roots are tends to easily breaks down. If conventional irrigation systems in beds and channel method are followed care should be taken to avoid the water contact directly on the trunk surface or base. Since this will weaken the plant against wind. Whereas if the drip irrigation is followed the laterals and emitters should be placed 1 to 1.5 feet away from the main trunk or base of the moringa tree.

Agronomic practices viz., summer ploughing, broad bed and furrow system, adoption of drip irrigation system, mulching with crop residues, use of organic manures and humic substances can be integrated for successful soil moisture management of moringa for high flowering and fruit yield.

Use of Artificial Intelligence in Agriculture Advisory

Article ID: 73741

 Divyanshu Saharan¹, Dr. Geeta Mohan²
¹Student, B.Sc. (Hons.), Faculty of Agriculture, Jagannath University, Jaipur (Raj.) 303901.

²Professor, Faculty of Agriculture, Jagannath University, Jaipur (Raj.) 303901.

Abstract

Artificial Intelligence (AI) is transforming agricultural advisory services by improving decision-making, increasing productivity, and supporting sustainable farming practices. AI technologies such as machine learning, predictive analytics, computer vision, robotics, and natural language processing are helping farmers receive accurate and timely information related to crop management, pest control, irrigation, weather forecasting, and market trends. Traditional agricultural extension systems often face challenges such as shortage of experts, delayed communication, and limited reach. AI-based advisory systems overcome these limitations by providing real-time recommendations through mobile applications, chatbots, drones, and smart sensors. These technologies help farmers reduce production costs, optimize resource utilization, and improve crop yields. AI also plays an important role in climate-smart agriculture by predicting weather changes and suggesting adaptive farming practices. In developing countries, AI-driven advisory platforms are enhancing farmers' access to scientific knowledge and digital services. However, issues such as lack of digital literacy, poor internet connectivity, high implementation costs, and data privacy concerns remain major challenges. Proper government support, infrastructure development, and farmer training are essential for successful adoption of AI in agriculture.

Keywords: Artificial Intelligence, Agriculture Advisory, Smart Farming, Precision Agriculture, Machine Learning, Digital Extension, Crop Management, Agricultural Technology.

Introduction

Agriculture is the backbone of many developing economies and plays a vital role in ensuring food security and rural livelihoods. Farmers continuously face challenges such as climate change, pest attacks, soil degradation, water scarcity, and fluctuating market prices. To address these issues, agricultural advisory services provide technical guidance and information to farmers. Traditionally, agricultural extension officers have been responsible for delivering recommendations related to crop production, disease management, and farm practices.

In recent years, Artificial Intelligence (AI) has emerged as a revolutionary technology in the agricultural sector. AI refers to computer systems that can perform tasks requiring human intelligence, such as learning, reasoning, problem-solving, and decision-making. By combining AI with digital agriculture, farmers can receive accurate, timely, and location-specific advisory services.

AI-based agricultural advisory systems use data collected from satellites, drones, sensors, weather stations, and mobile devices to generate practical recommendations. These systems assist farmers in selecting suitable crops, predicting weather conditions, detecting pests and diseases, managing irrigation, and improving market access. The integration of AI into agriculture is contributing to higher productivity, efficient resource utilization, and sustainable farming.

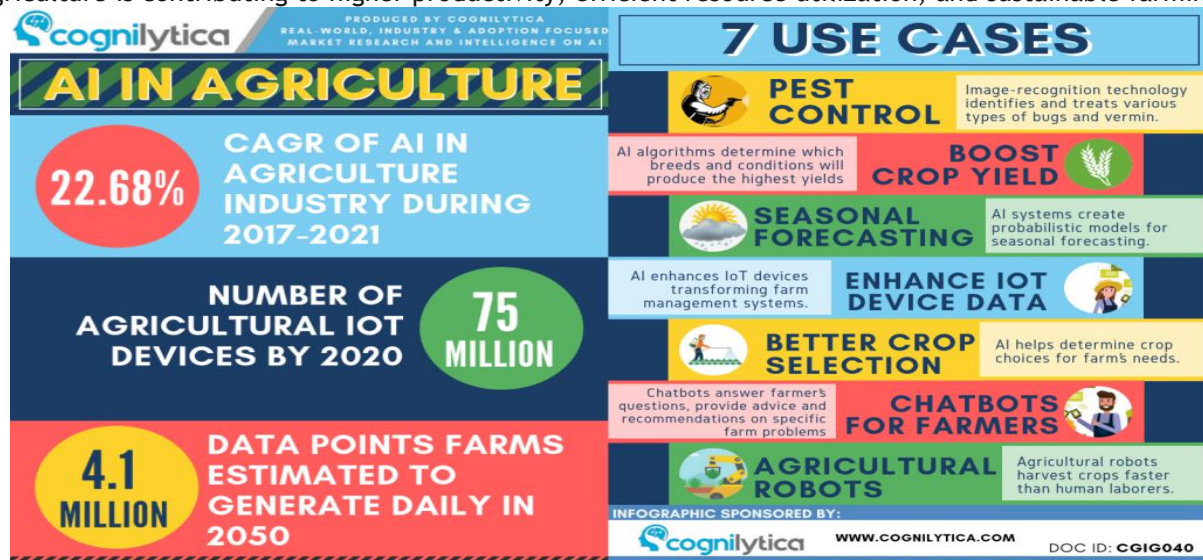


Figure 1- AI in Agriculture

Concept of Artificial Intelligence in Agriculture Advisory

Artificial Intelligence in agriculture advisory refers to the use of intelligent computer systems and algorithms to support farmers with scientific recommendations and farm management decisions. AI systems analyze large amounts of agricultural data and provide customized solutions based on crop conditions, soil health, weather patterns, and pest occurrence.

The major AI technologies used in agricultural advisory include:

- a. Machine Learning
- b. Deep Learning
- c. Computer Vision
- d. Robotics
- e. Internet of Things (IoT)
- f. Natural Language Processing (NLP)
- g. Predictive Analytics

These technologies enable smart farming practices and help improve agricultural efficiency.

Applications of AI in Agriculture Advisory

1. Weather Forecasting and Climate Advisory: AI-powered systems analyze weather data and provide accurate forecasts related to rainfall, temperature, humidity, and storms. Farmers can use this information for crop planning, irrigation scheduling, and disaster preparedness.

AI Systems

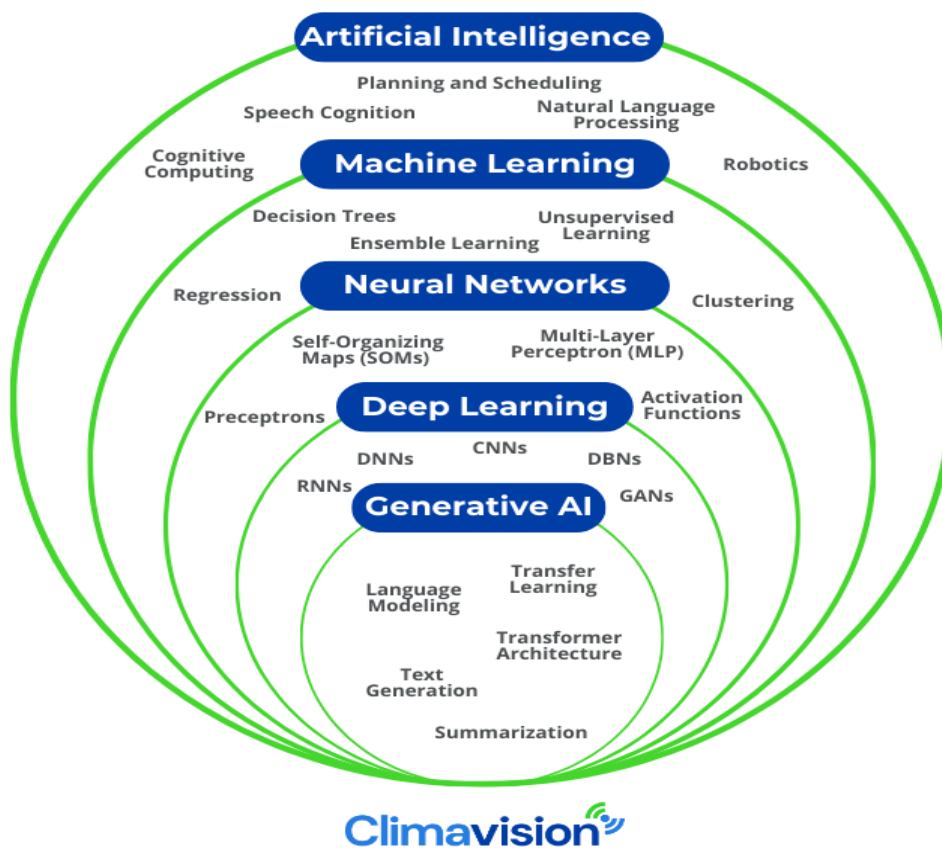


Figure 2: AI-Based Weather Advisory System

Benefits:

- a. Reduces climate-related risks
- b. Supports timely sowing and harvesting
- c. Improves crop management

2. Pest and Disease Detection: AI technologies use image recognition and machine learning algorithms to identify pests and crop diseases at an early stage. Farmers can upload images of infected plants through mobile applications, and AI systems provide diagnostic recommendations.

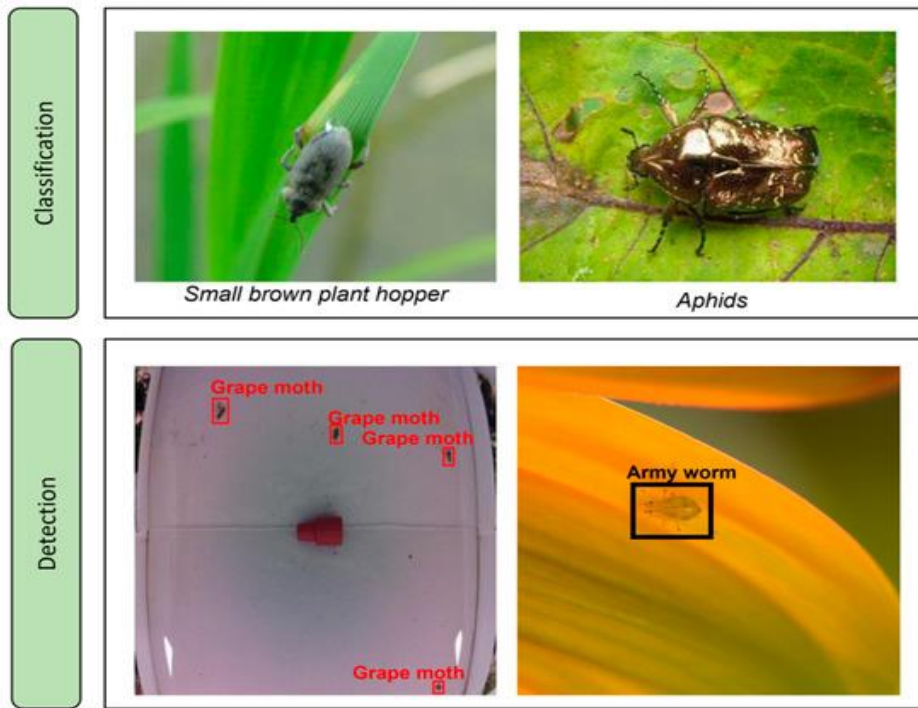


Figure 3 : AI Pest Detection Process

Advantages:

- Early disease diagnosis
- Reduced pesticide use
- Improved crop protection

3. Precision Farming: Precision agriculture involves the use of AI, GPS, drones, and sensors to manage farm operations accurately. AI helps farmers apply fertilizers, pesticides, and water only where needed.

Benefits:

- Efficient resource utilization
- Reduced production costs
- Increased crop productivity

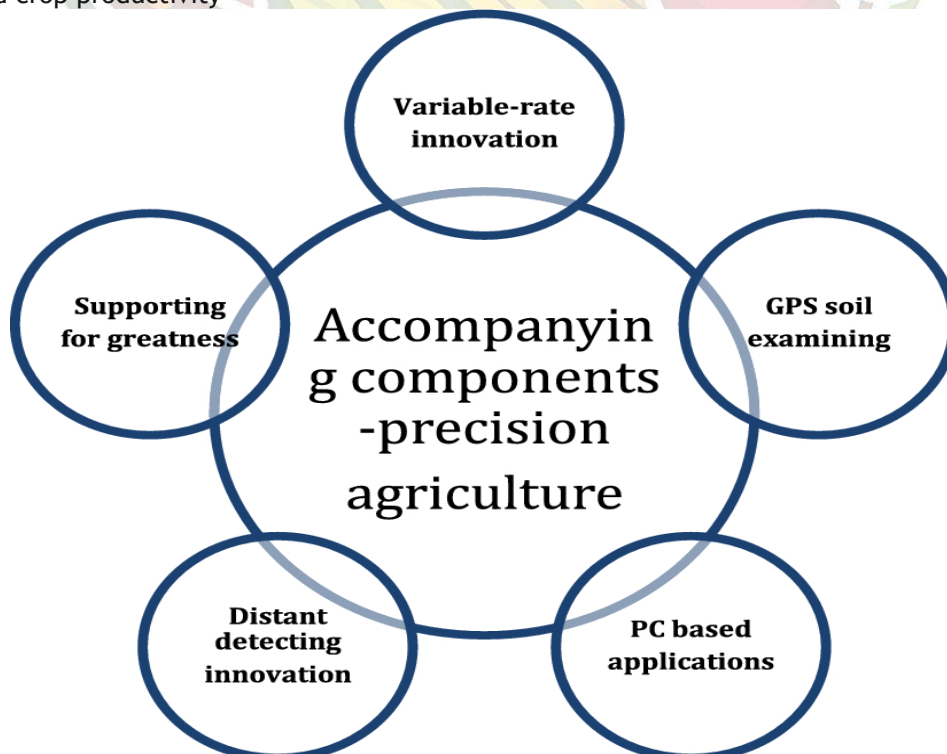


Figure 4: Components of Precision Agriculture

4. Irrigation Management: AI-based irrigation systems monitor soil moisture and weather conditions to determine the exact water requirements of crops. Smart irrigation reduces water wastage and enhances water-use efficiency.

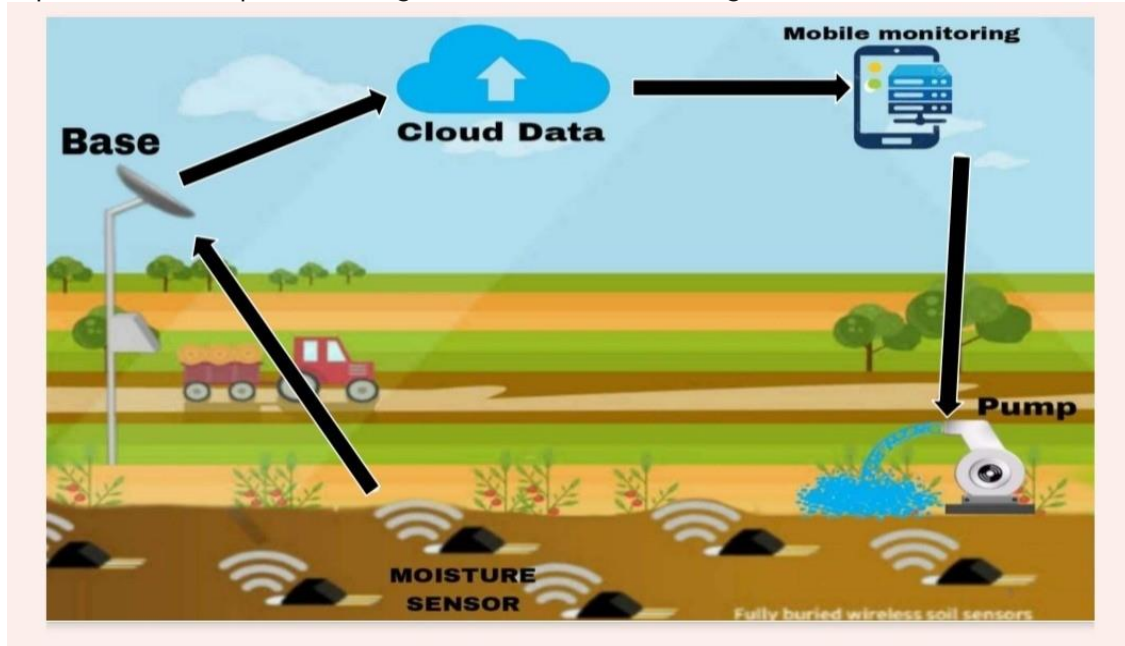


Figure 5: Smart Irrigation System

Advantages:

- a. Conserves water resources
- b. Prevents over-irrigation
- c. Improves crop growth

5. Market Information and Price Prediction: AI tools analyze market trends and provide farmers with information about crop prices, demand, and marketing opportunities. Farmers can make better selling decisions and avoid financial losses.

Benefits:

- a. Better market planning
- b. Increased farmer income
- c. Reduced exploitation by middlemen

6. Agricultural Chat bots and Virtual Assistants: AI-powered chat bots provide farmers with instant answers to agricultural queries through mobile phones and online platforms. These systems support multiple languages and are available 24/7.

Examples of services provided:

- a. Crop recommendations
- b. Fertilizer application guidance
- c. Weather updates
- d. Pest management advice.

Benefits of AI in Agriculture Advisor

Improved Decision-Making: AI systems provide accurate recommendations based on scientific data analysis, helping farmers make informed decisions.

Increased Productivity: AI technologies optimize farming operations and improve crop yields through precise management practices.

Resource Efficiency: AI reduces unnecessary use of water, fertilizers, and pesticides, resulting in sustainable agriculture.

Time and Labor Saving: Automation and smart technologies reduce manual labor and improve farm efficiency.

Better Risk Management: AI helps farmers predict weather changes, disease outbreaks, and market fluctuations, minimizing risks.

Enhanced Accessibility: Digital advisory platforms provide information to farmers even in remote rural areas.

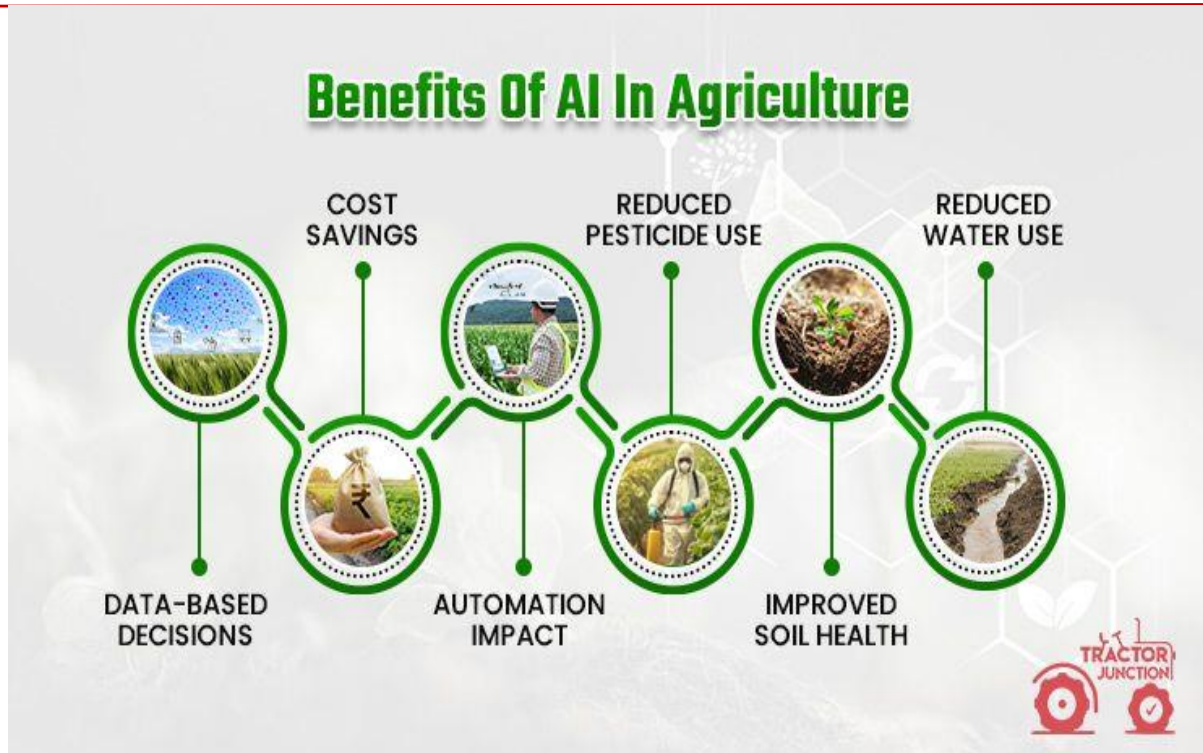


Figure 6 Benefits of AI in Agriculture

Challenges in Implementing AI in Agriculture Advisory

High Initial Investment: AI technologies such as drones, sensors, and smart equipment are expensive for small and marginal farmers.

Lack of Digital Literacy: Many farmers have limited knowledge of smart phones, internet services, and digital tools.

Poor Internet Connectivity: Rural areas often suffer from weak internet infrastructure, limiting access to AI-based services.

Data Privacy and Security: Agricultural data collected through digital platforms may face privacy and cybersecurity risks.

Limited Technical Expertise: There is a shortage of trained personnel to develop and manage AI systems in agriculture.

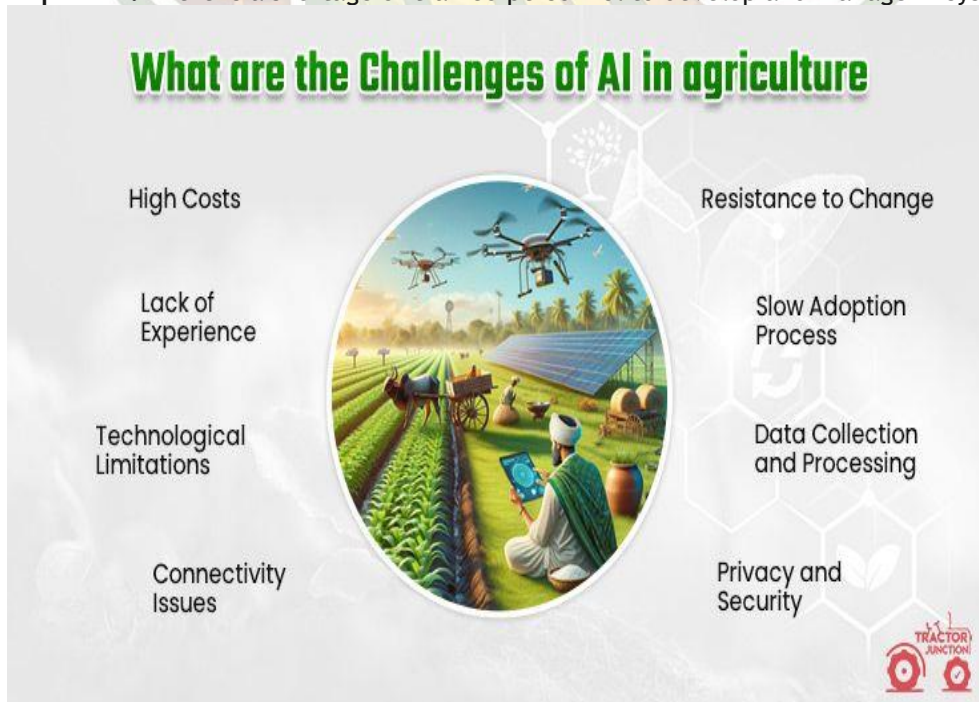


Figure 7 Challenges in Implementing AI in Agriculture

Future Prospects of AI in Agriculture Advisory

The future of AI in agriculture advisory is highly promising. Governments, research institutions, and private organizations are increasingly investing in digital agriculture technologies. AI will continue to improve precision farming, climate-smart agriculture, and automated farm management.

Future developments may include:

- a. AI-powered autonomous tractors
- b. Advanced robotic harvesting systems
- c. Real-time satellite monitoring
- d. Voice-based advisory systems in local languages
- e. Integration of AI with block chain and big data analytics

These innovations will strengthen sustainable agriculture and improve farmers' livelihoods globally.

Conclusion

Artificial Intelligence is revolutionizing agricultural advisory services by making farming more efficient, precise, and sustainable. AI technologies provide farmers with timely and reliable information related to weather forecasting, pest management, irrigation scheduling, and market intelligence. These systems improve productivity, reduce input costs, and support better decision-making. Although challenges such as high costs, digital illiteracy, and infrastructure limitations exist, continuous technological advancements and supportive government policies can promote wider adoption of AI in agriculture. Training and awareness programs are essential to help farmers effectively utilize AI-based advisory services. In the coming years, AI is expected to play a significant role in achieving food security, environmental sustainability, and rural development.

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Smart Hydroponics

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Manjeet Kaur¹, Nandana KC², Niyanza KP², Neha Yadav², Nishita Sharma², Netansh Bishnoi², Neha Kumari², Ojasv Singh²

¹Assistant professor, Faculty of Agriculture, Jagannath University, Jaipur (Raj.) 303901.

²Student, B.Sc. (Hons.), Agriculture, Faculty of Agriculture, Jagannath University, Jaipur (Raj.) 303901.

Abstract

Smart hydroponics is an advanced agricultural system that combines hydroponic farming with modern technologies such as Artificial Intelligence (AI), Internet of Things (IoT), automation, sensors, and data analytics. The system enables soil-less crop cultivation through precise monitoring and automated control of environmental conditions, nutrient supply, and water management. Smart hydroponic systems improve crop productivity, reduce water consumption, minimize pesticide usage, and support year-round cultivation. This article discusses the concept, working mechanism, technologies, applications, benefits, challenges, and future scope of smart hydroponics. The study highlights the role of AI and IoT in enhancing operational efficiency, resource management, and sustainable agricultural practices. Despite challenges such as high installation costs and technical complexity, smart hydroponics offers significant potential for urban farming and future food security. The integration of intelligent technologies in hydroponics can contribute to sustainable agriculture and efficient food production systems worldwide.

Introduction

The increasing demand for food production, rapid urbanization, shrinking agricultural land, and the adverse effects of climate change have encouraged the development of innovative and sustainable farming practices. Among these emerging technologies, hydroponics has gained significant attention as an efficient soil-less cultivation system capable of producing high-quality crops with minimal resource utilization. Hydroponics involves growing plants in nutrient-rich water solutions instead of traditional soil, allowing precise control over plant nutrition, water supply, and environmental conditions. In recent years, the integration of advanced digital technologies such as Artificial Intelligence (AI), the Internet of Things (IoT), sensors, automation, and data analytics has transformed conventional hydroponics into “Smart Hydroponics,” a modern approach to controlled environment agriculture.

Smart hydroponic systems utilize real-time monitoring and automated decision-making to optimize plant growth and resource management. Various sensors are employed to monitor critical parameters such as pH level, temperature, humidity, electrical conductivity, light intensity, and nutrient concentration. These data are analyzed using intelligent algorithms that can automatically regulate irrigation, nutrient dosing, ventilation, and lighting systems. Such automation reduces human intervention, enhances crop productivity, minimizes water wastage, and improves overall operational efficiency. Furthermore, smart hydroponics supports year-round cultivation and enables food production in urban areas, rooftops, greenhouses, and regions with infertile soil.



The adoption of smart hydroponic technology is also aligned with the goals of sustainable agriculture and food security. Compared to conventional farming, hydroponic systems consume significantly less water and reduce the dependency on chemical pesticides and fertilizers. Additionally, the integration of AI-driven predictive analytics helps farmers detect diseases, nutrient deficiencies, and environmental stress at early stages, thereby reducing crop losses and improving yield quality.

Therefore, smart hydroponics represents a promising solution for future agriculture by combining technological innovation with sustainable farming practices. Its growing importance in modern agriculture highlights the need for comprehensive research on its applications, benefits, challenges, and future prospects.

Concept and Working of Smart Hydroponics

Smart hydroponics is an advanced form of hydroponic farming that combines soil-less cultivation techniques with modern digital technologies such as Artificial Intelligence (AI), Internet of Things (IoT), automation, sensors, and data analytics. Unlike conventional farming, hydroponics does not require soil for plant growth. Instead, plants are cultivated in a nutrient-rich water solution that directly supplies essential minerals to the roots. The integration of smart technologies into hydroponic systems enables real-time monitoring, automated control, and efficient resource management, thereby improving crop productivity and sustainability.

The primary concept of smart hydroponics is based on precision agriculture, where environmental conditions and plant requirements are continuously monitored and adjusted automatically. The system uses interconnected sensors and smart devices to collect data related to temperature, humidity, pH level, electrical conductivity (EC), water level, nutrient concentration, and light intensity. These parameters are essential for maintaining optimal plant growth conditions. The collected information is transmitted through IoT-enabled networks to a central control unit or cloud-based platform where the data are analyzed using intelligent algorithms.

Based on the analysis, automated actions are performed to maintain the desired environmental balance. For example, if the nutrient concentration decreases, the system automatically injects the required nutrients into the water reservoir. Similarly, if the temperature or humidity exceeds the optimum range, ventilation systems or cooling mechanisms are activated. Automated LED grow lights can also regulate light exposure according to crop requirements. This intelligent control mechanism minimizes human intervention and ensures efficient utilization of water, nutrients, and energy.

The working process of smart hydroponics generally begins with the preparation of a nutrient solution containing essential macro and micronutrients. Plants are placed in specially designed channels, pipes, or containers where their roots remain partially or fully submerged in the circulating nutrient solution. Water pumps continuously circulate the solution throughout the system, ensuring adequate oxygen and nutrient supply to the roots. Sensors installed in different sections continuously monitor system performance and environmental conditions.

In advanced smart hydroponic systems, Artificial Intelligence and Machine Learning algorithms analyze historical and real-time data to predict plant growth patterns, nutrient deficiencies, diseases, and water requirements. This predictive capability enhances decision-making and reduces the risk of crop failure. Furthermore, mobile applications and cloud platforms allow farmers to monitor and control the hydroponic system remotely, making the technology more efficient and user-friendly.

Different hydroponic techniques such as Nutrient Film Technique (NFT), Deep Water Culture (DWC), Drip Systems, Wick Systems, and Aeroponics can also be integrated with smart technologies. Among these, NFT and DWC are commonly used in commercial smart farming due to their efficiency and ease of automation.

Therefore, smart hydroponics represents a technologically advanced agricultural system that combines automation, data-driven decision-making, and sustainable farming practices. Its ability to maximize crop production while minimizing resource consumption makes it an important innovation in modern agriculture and future food production systems.

Technologies Used in Smart Hydroponics

Smart hydroponics integrates modern digital technologies with hydroponic cultivation systems to improve agricultural productivity, resource efficiency, and crop management. These technologies enable automation, real-time monitoring, and intelligent decision-making, making hydroponic farming more sustainable and efficient than traditional agricultural methods. The major technologies used in smart hydroponics include Artificial Intelligence (AI), Internet of Things (IoT), Machine Learning (ML), sensors, automation systems, cloud computing, and data analytics.

Artificial Intelligence (AI): Artificial Intelligence plays a significant role in enhancing the efficiency and productivity of smart hydroponic systems. AI-based algorithms analyze environmental and crop-related data to make intelligent decisions regarding nutrient supply, irrigation scheduling, lighting control, and climate management. AI systems can identify abnormalities in plant growth, detect diseases at an early stage, and recommend corrective actions. Predictive analysis using AI helps farmers estimate crop yield, optimize resource utilization, and reduce operational costs. The technology also supports automated decision-making, minimizing human intervention in farm management activities.

Internet of Things (IoT): The Internet of Things is one of the core technologies used in smart hydroponics. IoT refers to the interconnection of sensors, devices, and control systems through the internet for data collection and communication. In hydroponic farming, IoT-enabled devices continuously monitor important parameters such as water level, temperature, humidity, pH value, nutrient concentration, and light intensity. The collected data are transmitted to cloud-based platforms or mobile applications where farmers can monitor system performance remotely. IoT technology enables real-time management and quick response to environmental changes, improving crop health and productivity.

Machine Learning (ML): Machine Learning is a branch of AI that allows systems to learn from historical and real-time data. In smart hydroponics, ML models analyze crop growth patterns, environmental conditions, and nutrient requirements to improve farming efficiency. Machine learning algorithms can predict water consumption, identify nutrient deficiencies, and detect disease symptoms before visible damage occurs. These predictive capabilities help farmers take preventive measures and optimize cultivation practices. Over time, the system becomes more accurate and efficient as it continuously learns from data.

Smart Sensors: Sensors are essential components of smart hydroponic systems because they provide accurate real-time information about environmental and nutrient conditions. Different types of sensors are used to measure pH level, electrical conductivity (EC), dissolved oxygen, temperature, humidity, carbon dioxide concentration, and light intensity. These sensors ensure that plants receive optimal growing conditions throughout the cultivation cycle. Sensor-based monitoring reduces manual errors and supports automated control mechanisms for efficient crop management.

Automation and Robotics: Automation technology is widely used in smart hydroponics to control irrigation, nutrient delivery, lighting, and ventilation systems. Automated pumps and valves regulate the flow of nutrient-rich water to plant roots according to crop requirements. Timers and programmable controllers help maintain precise environmental conditions inside greenhouses or indoor farming units. In advanced systems, robotic technologies are used for seed planting, harvesting, and crop monitoring. Automation reduces labor requirements, increases operational efficiency, and ensures consistency in crop production.



Cloud Computing and Data Analytics: Cloud computing enables the storage and management of large amounts of agricultural data collected from sensors and IoT devices. Farmers can access this information through smartphones, computers, or tablets from any location. Cloud-based systems facilitate remote monitoring and control of hydroponic farms. Data analytics tools process the collected information to identify trends, improve decision-making, and optimize farming operations. By analyzing historical and real-time data, farmers can improve productivity, reduce wastage, and maintain system efficiency.

LED Grow Light Technology: Smart hydroponic systems often use energy-efficient LED grow lights to support plant growth in indoor environments. These lights provide specific wavelengths required for photosynthesis and plant development. Automated lighting systems can adjust light intensity and duration based on crop growth stages and environmental conditions. LED technology reduces energy consumption while ensuring healthy plant growth and higher yields.

Wireless Communication Systems: Wireless communication technologies such as Wi-Fi, Bluetooth, Zigbee, and GSM are used to connect sensors and smart devices within hydroponic systems. These communication networks allow seamless data transfer between monitoring devices and central control systems. Wireless connectivity enhances remote accessibility, real-time monitoring, and automated control functions.

Application of Smart Hydroponics

Smart hydroponics is widely used in modern agriculture due to its ability to improve crop production and resource efficiency. The technology is increasingly adopted in urban farming, greenhouse cultivation, indoor farming, and vertical farming systems. Some of the applications are as follows:

- 1. Urban Farming:** Smart hydroponics is widely used in urban areas for cultivating crops on rooftops, balconies, and indoor spaces where agricultural land is limited.
- 2. Vertical Farming:** The technology supports vertical farming systems in which crops are grown in multiple stacked layers to maximize space utilization.
- 3. Greenhouse Cultivation:** Smart hydroponic systems are integrated with greenhouses to maintain controlled environmental conditions for year-round crop production.
- 4. Commercial Crop Production:** Large-scale farms use smart hydroponics for producing vegetables, herbs, and fruits with higher yield and improved quality.
- 5. Indoor Farming Systems:** Artificial lighting and automated climate control enable crop cultivation inside buildings and controlled environments.

Challenges and Limitations of Smart Hydroponics

High Initial Investment: Smart hydroponic systems require significant investment for setting up sensors, automation devices, LED lights, pumps, climate control systems, and monitoring equipment. This makes the technology expensive for small-scale farmers.

Technical Complexity: The operation of smart hydroponic systems requires technical knowledge related to automation, nutrient management, IoT devices, and data analysis. Lack of technical expertise may affect system efficiency and crop production.

Dependence on Electricity: Hydroponic systems rely heavily on electricity for water circulation, lighting, ventilation, and automated monitoring. Power failures can disrupt plant growth and may lead to crop damage.

Maintenance Requirements: Regular maintenance of pumps, sensors, nutrient reservoirs, and pipelines is essential for proper system functioning. Poor maintenance can result in equipment failure and reduced productivity.

Risk of Water-Borne Diseases: Since plants share the same nutrient solution, diseases and pathogens can spread rapidly throughout the system if contamination occurs.

Nutrient Management Challenges: Maintaining the correct balance of nutrients, pH, and electrical conductivity requires continuous monitoring. Any imbalance can negatively affect plant growth and yield quality.

Future Scope and Trends

The future of smart hydroponics is promising due to the growing need for sustainable and efficient food production systems. The integration of Artificial Intelligence (AI), Internet of Things (IoT), automation, and Machine Learning (ML) is expected to improve crop monitoring, nutrient management, and disease prediction. Advanced sensors and cloud-based technologies will enable real-time monitoring and remote control of hydroponic farms.

The adoption of vertical farming and indoor agriculture is also expected to increase, especially in urban areas with limited agricultural land. Renewable energy sources such as solar power may further improve the sustainability and cost-efficiency of hydroponic systems. In the future, fully automated hydroponic farms using robotics and smart technologies may reduce labor requirements and increase productivity. Therefore, smart hydroponics has strong potential to support sustainable agriculture, resource conservation, and global food security in the coming years.

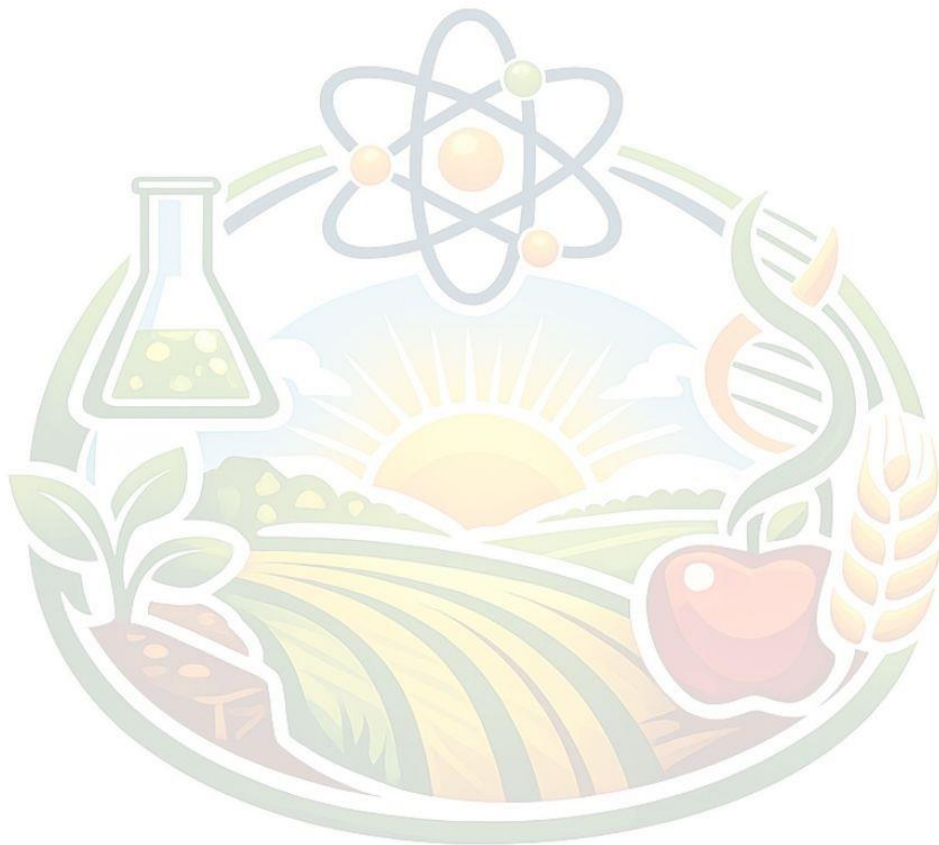
Conclusion

Smart hydroponics represents an innovative and sustainable approach to modern agriculture by integrating hydroponic farming with advanced technologies such as Artificial Intelligence, IoT, automation, and smart sensors. The system improves crop productivity, resource efficiency, and year-round cultivation while reducing water consumption and dependence on soil. Despite challenges such as high initial costs and technical complexity, smart hydroponics offers significant potential for urban farming and sustainable food production. With continuous advancements in digital technologies and automation, smart hydroponics is expected to play a crucial role in ensuring future food security, environmental sustainability, and efficient agricultural development worldwide.

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Smart Irrigation Systems Using Artificial Intelligence: A Comprehensive Study

Article ID: 73743

Neha Yadav¹, Manjeet Kaur²

¹Student, B.Sc. (Hons.) Agriculture, Faculty of Agriculture, Jagannath University, Jaipur (Raj.) 303901.

²Assistant Professor, Faculty of Jagannath University, Jaipur (Raj.) 303901.

Abstract

Water scarcity and inefficient agricultural practices pose significant challenges to global food security. Smart irrigation systems powered by Artificial Intelligence (AI) offer a promising solution by optimizing water usage while maintaining or improving crop yields. This article explores the integration of AI technologies—such as machine learning, predictive analytics, and IoT-based sensors—into modern irrigation systems. These systems analyse real-time data including soil moisture levels, weather conditions, crop type, and evapotranspiration rates to make precise irrigation decisions. By automating water delivery and reducing human intervention, AI-driven irrigation minimizes water wastage, enhances resource efficiency, and supports sustainable agriculture. The article also discusses implementation challenges; including cost, data availability, and scalability, while highlighting future opportunities for innovation in precision farming. Overall, smart irrigation with AI represents a transformative approach toward resilient and environmentally sustainable agricultural practices.

Introduction

Agriculture has always been the backbone of human civilization, yet it faces increasing pressure due to climate change, population growth, and water scarcity. Traditional irrigation practices, which often rely on fixed schedules or manual observation, are no longer sufficient to meet modern agricultural demands. This has led to the emergence of smart irrigation systems powered by Artificial Intelligence (AI), which aim to optimize water usage while improving crop productivity.

A smart irrigation system integrates sensors, data analytics, and intelligent algorithms to make informed decisions about when and how much to irrigate. Unlike conventional systems, it adapts dynamically to environmental conditions, making it a crucial component of sustainable agriculture.

Evolution of Irrigation Practices

Irrigation has evolved significantly over time. Early methods included manual watering and basic canal systems. Later, technologies such as sprinkler and drip irrigation improved efficiency by distributing water more evenly. However, these systems still depended heavily on human control.

The integration of digital technologies marked a turning point. With the introduction of the Internet of Things, irrigation systems became capable of collecting real-time data. AI further enhanced these systems by enabling predictive and automated decision-making, transforming irrigation from a manual task into an intelligent process.

Theoretical Foundations of Smart Irrigation

1. Soil-Water-Plant Relationship: The effectiveness of any irrigation system depends on understanding the relationship between soil, water, and plant growth. Soil properties determine how water is stored and made available to plants. Two key parameters are field capacity and permanent wilting point, which define the optimal moisture range for plant growth.

AI systems continuously monitor soil moisture using sensors and ensure that irrigation occurs within this optimal range. This prevents both water stress and waterlogging, leading to healthier crops.

2. Evapotranspiration and Water Requirement: One of the most important theoretical concepts in irrigation science is **Evapotranspiration**. It represents the total water loss from soil and plants to the atmosphere.

To estimate evapotranspiration accurately, models such as the **Penman-Monteith Equation** are used. AI systems incorporate these models along with real-time weather data to calculate precise water requirements for crops.

2. Machine Learning and Decision-Making: AI-driven irrigation systems rely on machine learning algorithms to analyze data and make decisions. These algorithms can identify patterns in environmental conditions and crop responses.

- Supervised learning models predict irrigation needs based on historical data
- Unsupervised learning detects hidden patterns in soil and climate data
- Reinforcement learning optimizes irrigation strategies over time
- As more data is collected, the system improves its accuracy, making it highly adaptive.
- Control Systems and Automation**

Smart irrigation systems are based on control system theory. Traditional irrigation often follows an open-loop system, where water is applied without feedback. In contrast, AI-based systems operate as closed-loop systems, using real-time sensor data to adjust irrigation.

This feedback mechanism ensures that water is applied only when necessary, significantly improving efficiency.

Components of AI-Based Smart Irrigation Systems

A smart irrigation system consists of several interconnected components:

1. **Sensors:** Measure soil moisture, temperature, humidity, and light intensity
2. **Communication Network:** Transfers data using IoT technologies
3. **AI Processing Unit:** Analyses data and generates irrigation decisions
4. **Actuators:** Control valves, pumps, and sprinklers
5. **User Interface:** Allows farmers to monitor and control the system

These components work together to create an intelligent and automated irrigation process.

Role of Data and Predictive Analytics

Modern irrigation systems rely heavily on data. AI uses historical and real-time data to predict future conditions such as rainfall, temperature changes, and crop water needs.

Technologies like Cloud Computing enable large-scale data storage and analysis. Predictive models use this data to optimize irrigation schedules, reducing water wastage.

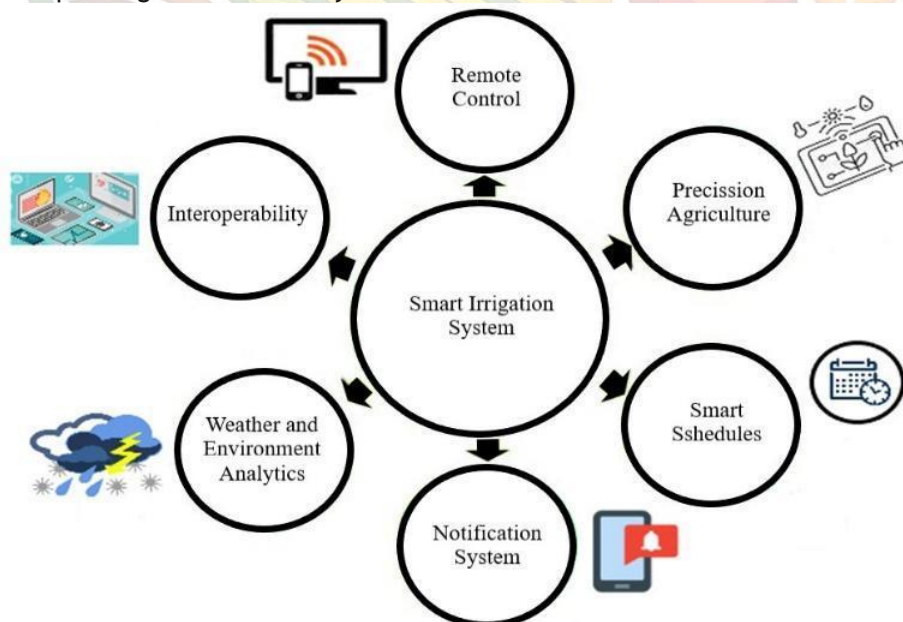
Integration with Precision Agriculture

Smart irrigation is a key part of Precision Agriculture, which focuses on optimizing agricultural inputs. By delivering the right amount of water at the right time, AI-based systems improve resource efficiency and crop yield.

Remote sensing technologies, such as drones and satellite imagery, further enhance precision. Tools like the Normalized Difference Vegetation Index help monitor crop conditions and guide irrigation decisions.

Some Ways of Smart Irrigation System

1. **Sensor-Based Irrigation:** This method uses soil moisture sensors to measure how much water is present in the soil. Irrigation is triggered only when moisture drops below a certain level. Sensors send real-time data to a controller, which decides whether irrigation is needed. A wheat farm installs moisture sensors in different parts of the field. When soil moisture falls below 20%, the system automatically turns on drip irrigation until optimal levels are restored. It prevents overwatering and ensures plants get water exactly when needed.



2. **Weather-Based Irrigation:** This approach uses weather data like temperature, humidity, and rainfall forecasts to plan irrigation schedules. It often relies on the concept of Evapotranspiration to estimate how much water crops lose daily. A farmer uses a weather-based controller that skips irrigation if rain is predicted the next day, saving both water and energy. It adapts irrigation to environmental conditions instead of following a fixed schedule.

3. Drip Irrigation with Automation: Drip irrigation delivers water directly to plant roots through pipes and emitters. When combined with automation, it becomes a smart system. Automated valves control water flow based on sensor data or programmed logic. In a vegetable farm, automated drip system waters plants every morning for a precise duration, adjusted daily based on soil moisture readings. Minimizes water loss due to evaporation and improves efficiency.

4. AI-Based Predictive Irrigation: This is a more advanced method where Artificial Intelligence predicts future irrigation needs using historical and real-time data. It often integrates technologies like the Internet of Things to collect data from multiple sources. A smart farming platform analyses past crop data, weather patterns, and soil conditions to predict that a corn field will need irrigation in two days. The system schedules watering in advance. It goes beyond reacting to current conditions and anticipates future needs.

5. Time-Based Smart Irrigation (Improved Scheduling): Unlike traditional timers, smart time-based systems adjust schedules based on data inputs. Irrigation times are modified automatically using seasonal and environmental data. A garden irrigation system runs longer in summer and shorter in winter based on temperature trends. More flexible than fixed timers and reduces unnecessary watering.

6. Remote-Controlled Irrigation: Farmers can monitor and control irrigation systems using smartphones or computers. A farmer uses a mobile app to turn on irrigation while away from the farm after checking soil moisture data. Provides convenience and real-time control from anywhere.

7. Drone and Satellite-Based Irrigation: Advanced systems use aerial data to assess crop health and water needs. Tools like the Normalized Difference Vegetation Index help identify dry or stressed areas. A drone survey shows that one section of a field is drier than others. The irrigation system targets only that area. Enables precision irrigation at a large scale.

Benefits of Smart Irrigation Systems

1. Water Conservation: AI-based systems minimize water wastage by applying only the required amount of water. This is particularly important in regions facing water scarcity.

2. Improved Crop Yield: Maintaining optimal soil moisture levels leads to healthier plants and higher productivity.

3. Cost Efficiency: Reduced water and energy usage lower operational costs for farmers.

4. Labor Reduction: Automation reduces the need for manual monitoring and intervention.

5. Environmental Sustainability: Efficient water use prevents soil erosion, nutrient leaching, and environmental degradation.

Challenges and Limitations

1. Data Dependency and Quality Issues: AI-driven smart irrigation systems rely heavily on large volumes of accurate and real-time data, including soil moisture levels, weather conditions, crop type, and evapotranspiration rates. In many agricultural regions, especially in developing countries, the lack of reliable sensors and inconsistent data collection practices can lead to incomplete or noisy datasets. This compromises the accuracy of AI predictions and irrigation scheduling.

2. High Initial Investment and Operational Costs: The deployment of smart irrigation systems involves significant capital investment in hardware such as soil moisture sensors, weather stations, automated valves, IoT devices, and communication infrastructure. Additionally, costs associated with software, maintenance, and system upgrades can be substantial, making adoption difficult for small and marginal farmers.

3. Technical Complexity and Skill Requirements: AI-based irrigation systems require a certain level of technical expertise for installation, calibration, operation, and data interpretation. Farmers and field operators may lack the necessary digital literacy or training to effectively use these systems, limiting their practical applicability and long-term sustainability.

4. Dependence on Connectivity and Power Supply: Most AI-enabled irrigation systems depend on cloud computing, real-time data transmission, and remote monitoring. In rural areas, unreliable internet connectivity and inconsistent power supply can disrupt system functionality, leading to inefficiencies or system failure during critical irrigation periods.

5. Limited Adaptability to Local Conditions: AI models are often developed using region-specific datasets and may not perform well when applied to different agro-climatic zones, soil types, or cropping systems. Without proper localization and calibration, irrigation recommendations may not accurately reflect field conditions, reducing system effectiveness.

6. Sensor Reliability and Maintenance Issues: The performance of smart irrigation systems depends on the proper functioning of sensors and hardware components. Sensors are prone to damage due to environmental factors such as dust, moisture, temperature fluctuations, and physical wear. Regular maintenance and calibration are required, which can increase operational complexity and costs.

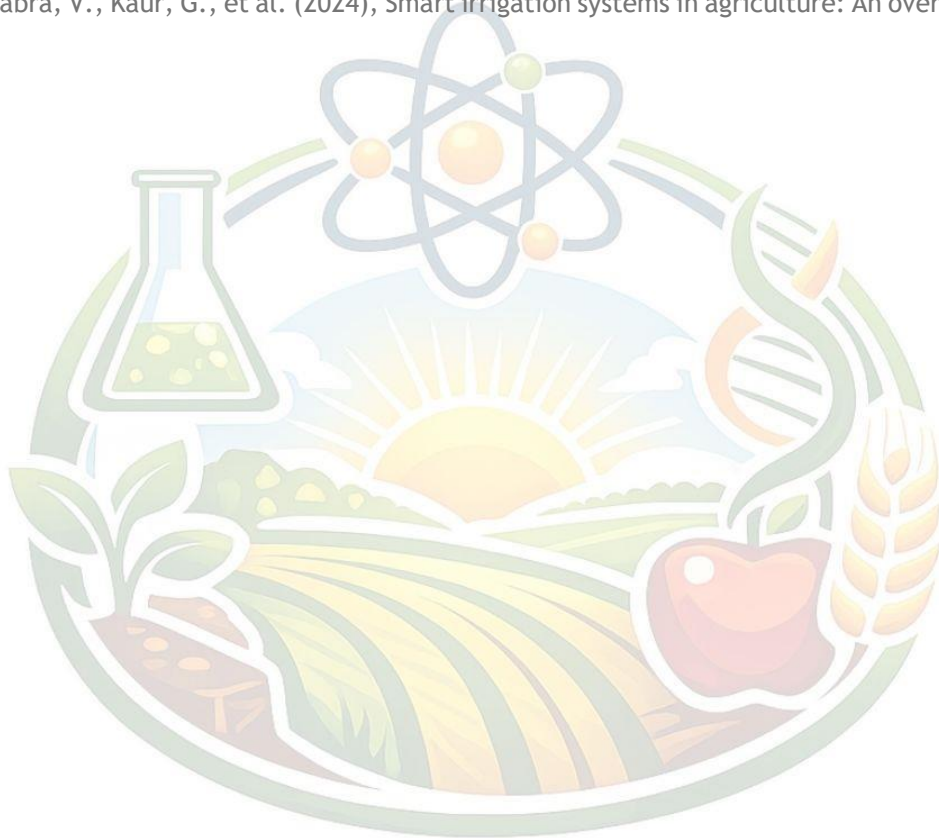
Conclusion

Smart irrigation systems powered by Artificial Intelligence represent a significant advancement in modern agriculture. By combining scientific principles with advanced technologies, these systems optimize water usage, improve crop yields, and promote sustainability.

As global water resources become increasingly limited, the adoption of intelligent irrigation systems will be essential. With continued innovation and investment, AI-based irrigation has the potential to transform agriculture and ensure food security for future generations.

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Beekeeping and Honey Production: A Low-Investment Enterprise with High Export Potential

Article ID: 73744

Sanjiv Kumar¹, Manvi Choudhary²

¹Faculty of Agriculture, Jagannath University, Jaipur-303901, Rajasthan, 303901.

²Student, B.Sc. (Hons.), Agriculture, Faculty of Agriculture, Jagannath University, Jaipur, Rajasthan, 303901.

Abstract

Beekeeping, also known as apiculture, is an important low-investment agricultural enterprise that contributes significantly to rural income generation, employment creation, and sustainable agricultural development. The present article examines the process of honey production, scientific management practices, economic importance, and export potential of beekeeping in India. Honeybees play a vital role in pollination, thereby improving crop productivity, biodiversity conservation, and ecological balance. The article discusses the selection of suitable bee species, apiary management, honey extraction, processing, and value addition techniques essential for quality honey production. It also highlights the increasing global demand for natural and organic honey and the growing opportunities for honey exports from India. Despite challenges such as climate change, pesticide exposure, and disease incidence, scientific beekeeping practices and institutional support can enhance productivity and profitability. Beekeeping therefore represents a sustainable and export-oriented enterprise with considerable potential for rural economic development.

Introduction

Beekeeping also known as apiculture, is the scientific management of honeybee colonies for the production of honey and other useful products. It is one of the most profitable and environmentally friendly rural enterprises because it requires low investment and provides good economic returns. In India, where agriculture is the main source of livelihood for a large population, beekeeping has become an important supplementary occupation for farmers, rural youth, and women. Honeybees are valuable not only for honey production but also for pollination. They help increase the yield and quality of many agricultural crops such as mustard, sunflower, fruits, and vegetables. Therefore, beekeeping contributes to agricultural productivity, biodiversity conservation, and rural development.

Honey Production Process and Management Practices

The selection of suitable bee species is one of the most important factors influencing honey production. Different species vary in their adaptability, honey collection capacity, resistance to diseases, and climatic suitability. In India, commonly reared species include *Apis mellifera* and *Apis cerana indica*.

Apis mellifera, also known as the European honeybee, is widely preferred for commercial beekeeping because of its high honey-producing capacity and efficient colony management characteristics. On the other hand, *Apis cerana indica* is better adapted to local climatic conditions and requires relatively lower management costs. The choice of species depends on factors such as climate, floral availability, and the scale of operation.



Site Selection for Beekeeping

A suitable location plays a significant role in successful honey production. Bee colonies should be placed in areas rich in flowering plants, as nectar and pollen are the primary food sources for bees. Agricultural fields, orchards, forests, and gardens with abundant floral resources are considered ideal for apiaries.

The selected site should have:

- a. Adequate sunlight and ventilation

- b. Access to clean water sources
- c. Protection from strong winds and excessive rainfall
- d. Minimal exposure to pesticides and industrial pollution

A pollution-free environment helps maintain the purity and quality of honey. Beekeepers often relocate colonies seasonally to areas with better flowering crops, a practice known as migratory beekeeping, which increases honey yield and pollination efficiency.

Essential Equipment Used in Beekeeping

Scientific beekeeping requires certain basic equipment for the safe handling and management of colonies. Proper equipment reduces colony disturbance and improves operational efficiency. Commonly used tools include:

1. **Beehives or bee boxes:** Wooden structures that provide shelter and space for colony development.
2. **Protective clothing:** Includes gloves, masks, and bee suits to protect beekeepers from stings.
3. **Smoker:** Produces smoke to calm bees during hive inspection.
4. **Hive tool:** Used for opening hive parts and cleaning wax deposits.
5. **Honey extractor:** A mechanical device used for extracting honey from combs without damaging them.

The use of hygienic and well-maintained equipment is essential for maintaining honey quality and preventing disease transmission among colonies.

- a. **Colony Management Practices:** Proper colony management is necessary for healthy bee populations and higher honey production. Beekeepers must regularly inspect hives to monitor colony strength, food availability, queen health, and signs of diseases or pests.



- b. **Feeding and Nutrition:** During periods of low flowering, bees may face food shortages. Supplementary feeding with sugar syrup or pollen substitutes helps maintain colony strength and prevents starvation.
- c. **Seasonal Management:** Bee colonies require different management practices during different seasons. During winter, colonies need protection from cold temperatures, whereas in summer they require adequate ventilation and water availability. Seasonal migration to flowering regions also improves nectar collection.
- d. **Queen Management:** The queen bee is the reproductive center of the colony. A healthy queen ensures proper egg-laying and colony growth. Replacing old or weak queens periodically helps maintain productivity and colony stability.
- e. **Disease and Pest Control:** Bee colonies are vulnerable to diseases, fungal infections, mites, and predators such as wax moths and ants. Scientific monitoring and timely treatment are essential to minimize colony losses. Excessive use of chemicals should be avoided, as it can contaminate honey and affect export quality standards.
- f. **Honey Extraction and Processing:** Honey extraction is performed when honeycombs are fully sealed with wax, indicating that the honey has matured and moisture content is suitable for storage. The extraction process generally involves the following steps:
 - i. Removal of honey-filled combs from the hive
 - ii. Uncapping of wax seals using a heated knife or uncapping tool
 - iii. Extraction of honey using centrifugal honey extractors
 - iv. Filtration to remove wax particles and impurities
 - v. Storage in clean and airtight containers.



Proper hygiene during extraction and processing is extremely important to maintain the purity, taste, and nutritional value of honey. Moisture control is also essential because excess moisture may lead to fermentation during storage.

g. Packaging and Value Addition: Packaging plays an important role in the marketing and export of honey products. Processed honey is packed in glass jars, food-grade plastic containers, or bulk storage units depending on market requirements. Attractive labeling and branding increase consumer appeal and market value. In recent years, value-added honey products have gained popularity due to rising health awareness among consumers. These include:

- i. Organic honey
- ii. Herbal honey
- iii. Flavored honey
- iv. Medicinal honey products
- v. Beeswax-based products

Value addition not only increases profitability but also creates opportunities for rural entrepreneurship and export-oriented businesses.

Importance of Scientific Management

Scientific management practices improve both the quantity and quality of honey production. Proper colony care, disease management, hygienic extraction, and quality control help beekeepers meet national and international standards. Efficient management also supports sustainable agriculture by enhancing pollination, biodiversity conservation, and ecological balance. Thus, honey production and beekeeping management represent a sustainable agricultural enterprise that combines economic benefits with environmental conservation. With appropriate training, modern technology, and institutional support, beekeeping can become a reliable source of income and rural development.

Economic Importance of Beekeeping

Low Investment and High Profitability: Beekeeping is considered a low-investment enterprise because it requires only basic equipment such as bee boxes, smokers, protective clothing, and honey extractors. Unlike other agricultural businesses, there is no need for large areas of land or expensive infrastructure. Farmers can easily practice beekeeping along with crop cultivation. The maintenance cost of bee colonies is also low because honeybees collect nectar and pollen from nearby flowering plants. Within a short period, beekeepers can earn income through the sale of honey and other bee products.

Employment Generation: Beekeeping provides self-employment opportunities in rural areas. It is especially suitable for small and marginal farmers, landless laborers, and women. Many self-help groups and rural entrepreneurs have adopted beekeeping as a source of additional income.

Pollination Benefits: Honeybees play a major role in pollination. While collecting nectar from flowers, they transfer pollen from one flower to another, helping in fertilization. This process improves the quantity and quality of agricultural produce. Studies have shown that bee pollination can increase crop yields by 20-40 percent in many crops.

Environmental Importance: Beekeeping is an eco-friendly activity that helps maintain ecological balance. Honeybees support biodiversity by pollinating flowering plants and preserving natural ecosystems.

Types of Honeybees

Several species of honeybees are found in India. The important ones are:

1. ***Apis mellifera* (Italian Bee):** This is the most commonly used species in commercial beekeeping because of its high honey production capacity and gentle behavior.
2. ***Apis cerana indica* (Indian Bee):** This indigenous species is well adapted to Indian climatic conditions and is resistant to local diseases.
3. ***Apis dorsata* (Rock Bee):** These are wild bees found mainly in forests and tall trees. Although they produce large quantities of honey, they are difficult to domesticate.

Bee Products and their Uses

Besides honey, beekeeping provides several useful products:

Product	Uses
Honey	Food, medicine, natural sweetener
Beeswax	Candles, cosmetics, polish
Royal Jelly	Health supplements
Bee Pollen	Nutritional products
Propolis	Herbal medicine

These products have good market value and increase the profitability of beekeeping.

Scope and Export Potential in India

India has excellent potential for honey production because of its diverse climate and rich floral resources. Major honey-producing states include Punjab, Haryana, Rajasthan, Uttar Pradesh, Bihar, and Himachal Pradesh.

The global demand for natural and organic honey is increasing rapidly due to rising health awareness among consumers. India exports honey to countries such as the United States, Saudi Arabia, UAE, Canada, and Bangladesh. Indian honey is appreciated for its natural quality, medicinal value, and different floral varieties.

India has several advantages in the international honey market:

- a. Rich biodiversity and floral resources
- b. Low production cost
- c. Availability of skilled labor
- d. Production of different honey varieties
- e. Increasing organic honey production

Special varieties such as mustard honey, eucalyptus honey, and forest honey have high export demand. With proper quality control and modern packaging, India can further expand its honey export market.

Challenges in Beekeeping

Despite its benefits, beekeeping faces some challenges:

1. Diseases and pests affecting bee colonies
2. Excessive use of pesticides in agriculture
3. Climate change and irregular flowering
4. Lack of scientific knowledge among rural beekeepers
5. Marketing and pricing problems

Proper training, scientific management, and government support are necessary to overcome these challenges.

Conclusion

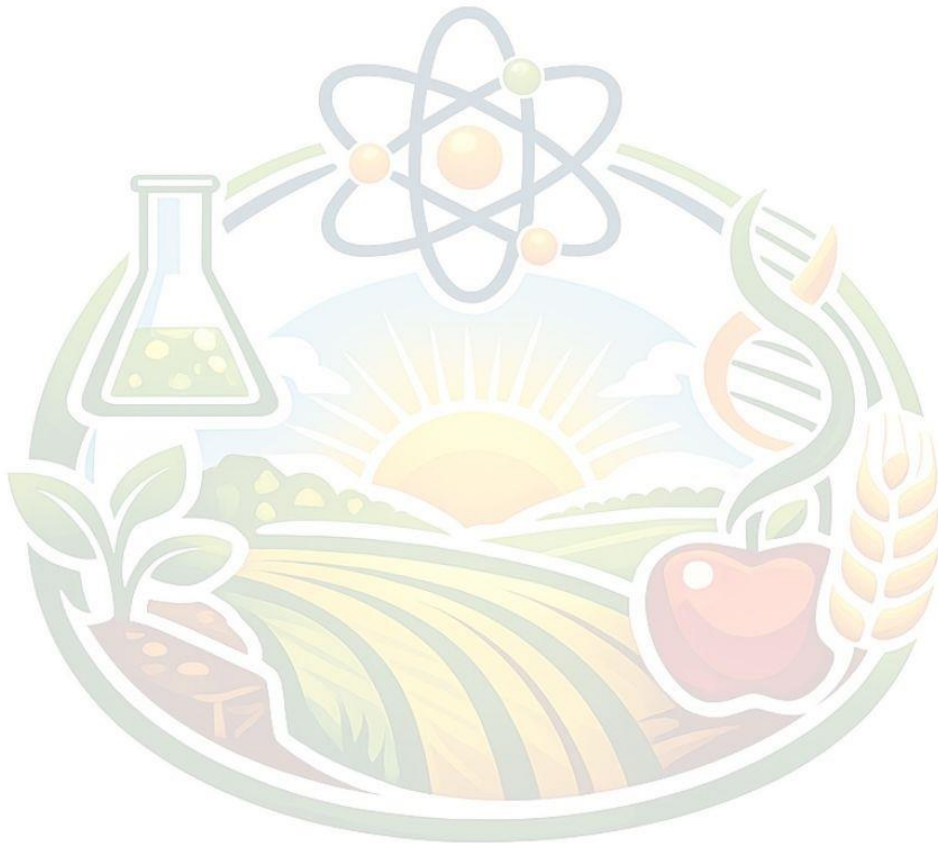
Beekeeping and honey production have become important low-investment enterprises with high income and export potential. The enterprise not only provides honey and other valuable products but also improves agricultural productivity through pollination. It offers employment opportunities to farmers, women, and rural youth while supporting environmental conservation.

India has favorable climatic conditions and rich floral diversity for large-scale honey production. With increasing global demand for natural and organic honey, the future of beekeeping in India is very promising. Scientific beekeeping practices, better marketing, and government support can help India become a leading producer and exporter of honey in the world.

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Valorization of Luffa as a Natural Eco-Friendly Biomaterial

Article ID: 73745

S. Reddy Veera Nagaveni¹, B. P. Bisen²
^{1&2}Department of Horticulture, Jawaharlal Nehru Krishi Vishwa Vidyalaya, Jabalpur (Madhya Pradesh)-482004.

Introduction

Luffa (Loofah) is a natural sponge obtained from the fully matured fruits of Sponge gourd (*Luffa cylindrica* / *Luffa aegyptiaca*). It is widely used as a bath sponge, kitchen scrubber, exfoliator, eco-friendly cleaning tool, and even in handicrafts (Yawalkar., 2004). The sponge is made from the fibrous vascular network inside the fruit, which becomes hard and net-like when fully dried.

Natural Preparation of Luffa from Sponge Gourd

Luffa is prepared naturally from the sponge gourd plant by allowing the fruits to grow fully on the vine until they reach complete maturity. Instead of harvesting them when green and tender, the fruits are left on the plant until they naturally dry out, turning brown, hard, and lightweight. During this stage, the outer skin becomes brittle while the inner fibrous network fully develops into the sponge. Once the fruits are completely dried on the plant, they are harvested and kept for a little more sun-drying to ensure the shell becomes easy to remove. The dry outer skin is then peeled away by hand, revealing the natural luffa sponge inside. After removing the seeds and washing the fiber to clear any dust or pulp, the sponge is again sun-dried until it becomes clean, firm, and ready for use. This simple, natural process produces a clean, eco-friendly luffa without any chemicals or artificial processing (Thamburaj and Singh 2015).

HOW TO PREPARE A LOOFAH

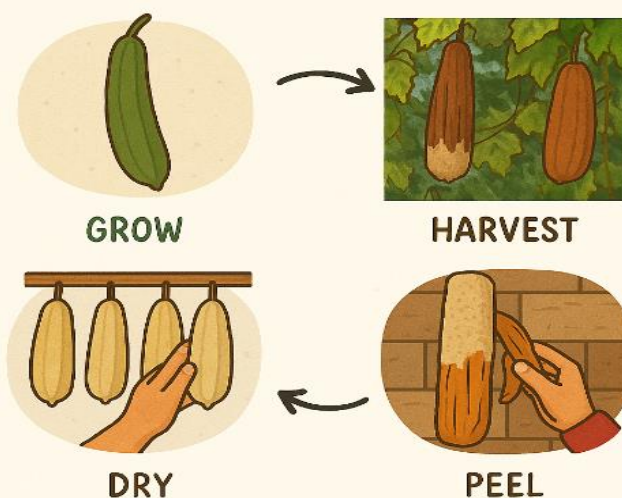


Fig 1. Natural Preparation Process of Luffa from Sponge Gourd

Multifunctional Uses of Luffa

Luffa is a highly versatile natural product, and its uses extend far beyond the bathroom. In personal care and beauty routines, luffa is most commonly used as a bathing sponge that helps exfoliate the skin, remove dead cells, and improve blood circulation. Thin slices of luffa are also used as gentle facial scrub pads, while thicker pieces work well for deep body exfoliation and foot scrubbing. Many people also use luffa during massages, as its natural texture helps stimulate lymphatic movement and refresh the skin. (Mansour and El-Gendy 2018).

Beyond personal care, luffa has a wide range of applications in the home. In the kitchen, it serves as an excellent natural dishwashing scrubber, cleaning utensils without scratching them. It can also be used to wash vegetables, especially root crops like potatoes and carrots. Around the house, luffa functions as a reusable cleaner for sinks, tiles, bathroom surfaces, and kitchen platforms, providing effective scrubbing while remaining gentle. Thin strips of luffa are particularly useful for cleaning bottles and jars, reaching places that hands cannot.

In gardening and agriculture, luffa is valued for its biodegradable, water-absorbent, and soil-friendly nature. Gardeners often use small luffa rings as seed starters, helping seedlings germinate with good moisture retention. Shredded luffa

can be mixed into soil to improve aeration and drainage. Old or worn-out luffa pieces break down easily and can be added to compost, enriching the soil. Even dried fibers can be used as natural plant ties, soft enough not to harm delicate stems.

Luffa in Crafts, DIY and Commercial Industries

Luffa is also popular in the world of crafts and DIY. Artists and hobbyists use it to create handmade exfoliating soaps, embedding a slice inside soap bars. Its natural texture makes it perfect for decorative crafts, wall hangings, and textured art pieces. Shredded luffa is also used as eco-friendly stuffing for handmade toys or as a pet toy material, thanks to its lightweight and fibrous structure.



Fig 2. Natural and Eco-friendly Commercial Products Developed from Luffa

Commercial and industrial sectors have also embraced luffa. It is used in creating eco-friendly cleaning tools, biodegradable brushes, and durable natural sponges. Some automobile detailers prefer luffa for gentle polishing. Industries also use shredded luffa as a biodegradable packaging filler, replacing plastic. In small-scale filtration systems, luffa fibers can even act as a natural filtration medium.

Overall, luffa supports an eco-friendly, zero-waste lifestyle since it is natural, reusable, and fully compostable. It replaces synthetic scrubbers in many parts of daily life and serves as one of the most multi-purpose, sustainable materials available

Economic Benefits for Farmers

A farmer can benefit economically from selling luffa because it is a low-cost, high-value product that requires minimal inputs and uses the natural drying process on the plant itself. Once the sponge gourd fruits mature and dry on the vine, the farmer can harvest, peel, and clean them with almost no additional investment, turning each dried fruit into a ready-to-sell natural sponge (Singh and Kaur., 2018). Since luffa is in high demand for uses in bathing, kitchen cleaning, beauty products, gardening, crafts, and eco-friendly markets, farmers can earn more by selling it in different forms such as whole luffa, cut pieces, face pads, dish scrubbers, and value-added products like luffa-embedded soaps. The product has a long shelf life, low risk of spoilage, and strong appeal in urban organic stores, online platforms, and local markets, allowing farmers to generate steady income with high profit margins while tapping into the growing eco-friendly and zero-waste consumer trend.

Conclusion

Overall, luffa stands out as a naturally abundant, eco-friendly product with wide-ranging uses and strong market potential. From personal care and household cleaning to gardening, crafts, and commercial applications, its versatility makes it a valuable everyday material. With rising consumer demand for sustainable, biodegradable alternatives, luffa has emerged as an easily marketable, high-profit commodity. In every way, it supports both environmental sustainability and rural economic empowerment, making it a promising crop for cultivation and small-scale enterprise.

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Bio-Packaging from Horticultural Residues

Article ID: 73746

Aasima Rafiq¹, Mansha Farooq¹

¹AICRP on PHET, Division of Food Science and Technology, Sher-e-Kashmir University of Agricultural Sciences and Technology.

Abstract

The growing environmental concerns associated with synthetic plastic packaging have intensified the search for sustainable and biodegradable alternatives derived from renewable resources. Horticultural residues such as fruit peels, vegetable pomace, seed husks, stalks, leaves, and agro-industrial by-products possess significant potential for the development of eco-friendly bio-packaging materials due to their rich composition of cellulose, hemicellulose, starch, pectin, lignin, and bioactive compounds. Recent advances in biopolymer extraction, nanotechnology, and composite fabrication have enabled the production of biodegradable films, edible coatings, trays, and active packaging systems with improved mechanical and barrier properties. Bio-packaging derived from horticultural waste not only reduces plastic pollution but also promotes waste valorization and circular bioeconomy practices. However, limitations related to moisture sensitivity, thermal instability, and high production costs still restrict large-scale commercialization. This review discusses the sources, composition, processing technologies, properties, applications, advantages, limitations, and future prospects of bio-packaging materials produced from horticultural residues.

Keywords: Bio-packaging; Horticultural residues; Biodegradable films; Agro-waste valorization; Sustainable packaging

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Introduction

Conventional petroleum-based plastic packaging materials are extensively used in food and agricultural industries because of their excellent mechanical strength, flexibility, and barrier properties. However, their non-biodegradable nature has led to severe environmental pollution, landfill accumulation, and microplastic contamination in terrestrial and aquatic ecosystems. Global plastic production continues to increase annually, with packaging accounting for a major share of total plastic consumption (Kossalbayev et al., 2025). The poor recycling efficiency of plastic waste has created an urgent need for sustainable packaging alternatives.

Horticultural processing industries generate large quantities of residues such as fruit peels, pomace, seeds, stalks, leaves, and pulp during processing operations including juice extraction, canning, drying, and minimal processing. Traditionally, these residues are discarded as waste or used as low-value animal feed, resulting in environmental disposal problems. However, these by-products are rich sources of natural biopolymers including cellulose, starch, lignin, pectin, proteins, and phenolic compounds that can be utilized for biodegradable packaging development (Gómez Human et al., 2025).

The utilization of horticultural residues for packaging production supports the principles of circular economy and sustainable waste management. Bio-packaging materials derived from agro-residues are biodegradable, renewable, compostable, and capable of reducing dependence on petroleum-derived plastics. Furthermore, the incorporation of natural antioxidants and antimicrobial compounds from fruit and vegetable wastes enhances food preservation and shelf life (Ayhan et al., 2026).

Background of Bio-Packaging

Bio-packaging refers to packaging materials produced from renewable biological resources that are biodegradable or compostable under natural conditions. These materials may be derived from plant-based polymers, microbial polymers, or agro-industrial residues. Increasing environmental awareness, strict government regulations regarding single-use plastics, and growing consumer demand for sustainable products have significantly accelerated research in biodegradable packaging systems.

Horticultural residues are particularly attractive for packaging applications because they are inexpensive, abundant, and rich in valuable biopolymers. Fruit and vegetable wastes contain cellulose fibers that improve tensile strength, pectin that forms edible films, starch that contributes to film-forming ability, and phenolic compounds that provide antioxidant and antimicrobial activities (Ali et al., 2023). Examples include banana pseudostem fibers for biodegradable trays, citrus

peel pectin for edible coatings, tomato pomace for antioxidant films, and potato peel starch for biodegradable bioplastics.

Recent innovations in biodegradable packaging include nanocellulose reinforcement, antimicrobial coatings, active packaging systems, and mycelium-based composites developed from agricultural residues. These technologies have improved the mechanical performance, barrier properties, and functional characteristics of biodegradable packaging materials.

Sources of Horticultural Residues for Bio-Packaging

1. Fruit Processing Residues: Fruit processing industries generate substantial quantities of peels, seeds, pomace, and pulp residues. Mango peels, citrus peels, banana peels, apple pomace, grape pomace, and pomegranate rind are rich in pectin, cellulose, and antioxidants suitable for film and coating development. Citrus peel pectin has been extensively utilized in edible coating applications because of its excellent film-forming properties (Ayhan et al., 2026).

2. Vegetable Processing Residues: Vegetable processing wastes such as potato peels, tomato pomace, carrot pulp, onion skins, cabbage leaves, and beetroot residues contain starch, cellulose, and bioactive compounds useful for biodegradable packaging production. Potato peel starch is widely used in bioplastic formulations because of its biodegradability and low cost. Tomato pomace contains lycopene and phenolic compounds that enhance antioxidant properties in active packaging systems (Ali et al., 2023).

3. Fiber-Rich Agricultural Residues: Banana pseudostem, coconut coir, rice husk, wheat straw, corn stalks, and sugarcane bagasse are important lignocellulosic residues used as reinforcement materials in bio-composite packaging. These fibers improve mechanical strength, thermal stability, and barrier properties of biodegradable films and trays.

Composition of Horticultural Residues

The suitability of horticultural residues for bio-packaging depends on their biochemical composition and structural properties.

- 1. Cellulose:** Provides structural integrity and mechanical strength.
- 2. Hemicellulose:** Enhances flexibility and biodegradability.
- 3. Lignin:** Improves rigidity and moisture resistance.
- 4. Pectin:** Acts as a natural film-forming agent.
- 5. Starch:** Contributes to thermoplastic behavior and biodegradability.
- 6. Phenolic compounds:** Provide antioxidant and antimicrobial activities.

These components are generally extracted using alkaline treatment, enzymatic hydrolysis, steam explosion, or solvent extraction methods before film or composite preparation.

Processing Technologies for Bio-Packaging



Fig 1: Processing Technologies for Bio-Packaging

- 1. Solvent Casting:** Solvent casting is one of the most widely used techniques for producing biodegradable films from starch, pectin, and cellulose extracts. In this method, biopolymers are dissolved in suitable solvents, cast into molds, and dried into thin films.
- 2. Extrusion:** Extrusion technology is commonly employed for large-scale commercial production of biodegradable thermoplastic packaging materials. Plasticizers such as glycerol and sorbitol are added to improve flexibility and processability.
- 3. Compression Molding:** Compression molding is used for manufacturing biodegradable trays, containers, plates, and packaging boards from lignocellulosic fibers and starch-based composites.
- 4. Nanotechnology-Based Approaches:** Nanotechnology has significantly improved the performance of biodegradable packaging materials. Incorporation of nanocellulose, nano-clay, and nanoparticles enhances tensile strength, barrier properties, and thermal stability.

Properties of Bio-Packaging Materials

- 1. Mechanical Properties:** Biodegradable packaging materials should possess adequate tensile strength, flexibility, and durability to withstand handling, transportation, and storage conditions. Fiber reinforcement improves the mechanical performance of biopolymer-based materials.
- 2. Barrier Properties:** Water vapor permeability and oxygen transmission rates are important quality parameters in food packaging. Addition of lipids, waxes, and nanofillers helps improve moisture barrier properties.
- 3. Biodegradability:** Bio-packaging materials decompose naturally through microbial activity, thereby reducing environmental pollution and landfill accumulation.



Fig 2: Biodegradability process of packaging films

- 5. Antioxidant and Antimicrobial Properties:** Incorporation of phenolic-rich extracts from horticultural wastes enhances antimicrobial and antioxidant activities, which contribute to improved food preservation and shelf life.



Fig 3: Bio-packaging from Horticultural Residues



Fig 4: From Horticultural Residues to Bio-packaging

Applications of Bio-Packaging

Bio-packaging materials derived from horticultural residues are increasingly used in various industrial applications, including:

1. Edible films and coatings for fruits and vegetables
2. Biodegradable trays and food containers
3. Active and antimicrobial packaging systems
4. Compostable shopping bags and wrappers
5. Cushioning and foam packaging materials
6. Fresh produce packaging
7. Pharmaceutical and cosmetic packaging

These applications contribute significantly to sustainable packaging systems and environmental protection.

Advantages of Bio-Packaging from Horticultural Residues

1. Reduction of plastic pollution and landfill accumulation
2. Utilization and valorization of agro-industrial waste
3. Renewable, biodegradable, and compostable nature
4. Reduction in greenhouse gas emissions
5. Improved food safety and shelf life
6. Promotion of circular economy and sustainability
7. Value addition to horticultural by-products.

Limitations and Challenges

Despite their advantages, biodegradable packaging materials face several challenges:

1. Poor moisture resistance
2. Lower mechanical strength compared to synthetic plastics
3. High production and processing costs
4. Limited industrial scalability
5. Short storage stability
6. Lack of standardized regulations and composting infrastructure

Further technological advancements and policy support are necessary for successful commercialization

Future Prospects

Future research should focus on improving the barrier properties, thermal stability, and economic feasibility of biodegradable packaging materials. Emerging technologies such as nanotechnology, active packaging, intelligent packaging, and mycelium-based composites offer promising opportunities for commercial applications. Integration of artificial intelligence and machine learning in material optimization and packaging design may further accelerate innovation in sustainable packaging systems. Increased industrial collaboration, supportive government policies, and consumer awareness are expected to drive the growth of biodegradable packaging industries in the coming years.

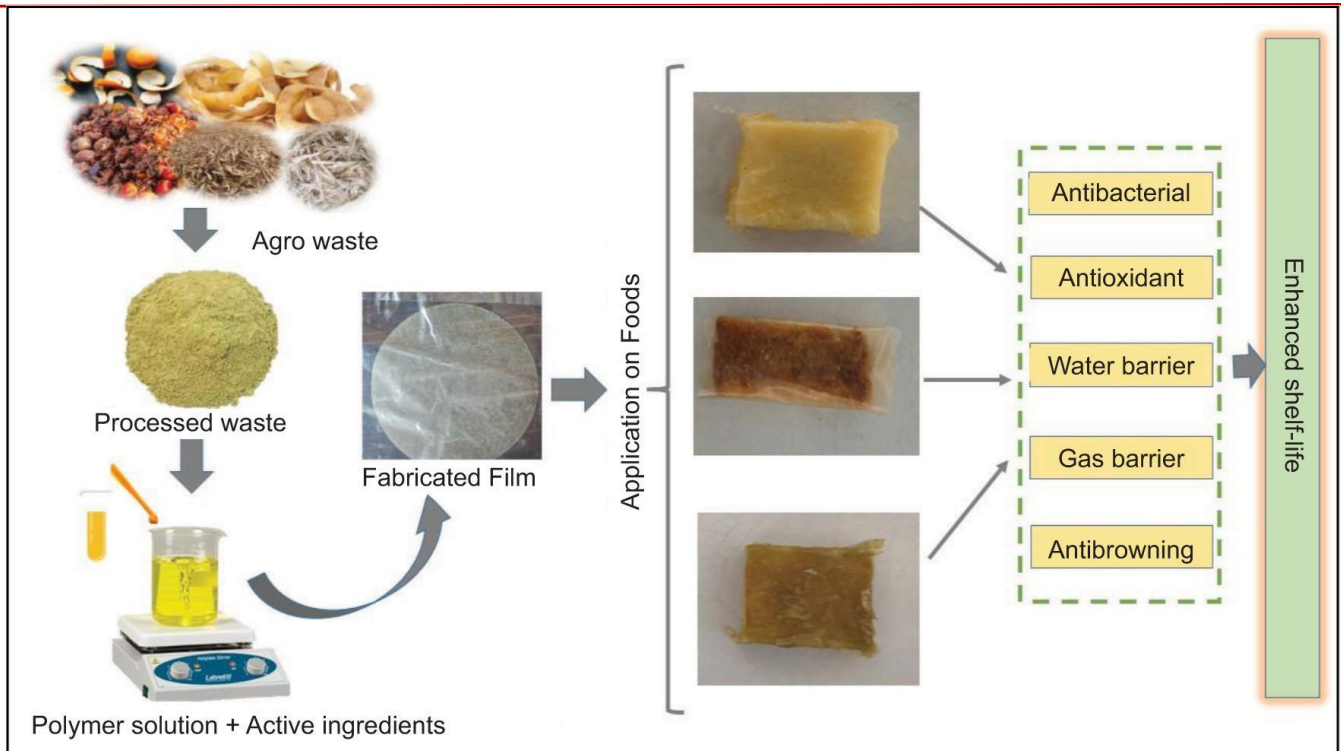
Conclusion

Bio-packaging from horticultural residues represents a sustainable and environmentally friendly alternative to conventional petroleum-based plastics. Fruit and vegetable processing wastes are rich in valuable biopolymers and bioactive compounds that can be effectively utilized for developing biodegradable films, coatings, trays, and active packaging systems. These materials not only help reduce environmental pollution and plastic waste but also promote waste valorization and circular economy practices. Although several technological and economic challenges remain, advancements in material science, nanotechnology, and biopolymer processing are expected to improve the commercial feasibility of bio-packaging systems. Therefore, the utilization of horticultural residues for packaging applications holds great promise for sustainable food processing and environmental conservation.

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Eco-Friendly Aquaculture Through Wastewater Utilization

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Abhishek M S.¹, Dr. T. J. Ramesha², Alla Bhumika Reddy¹

¹College of Fisheries, Mangalore,

²Senior Scientist and Head ICAR-Krishi Vigyan Kendra (KVK), DakshinaKannada,
Karnataka Veterinary, Animal and Fisheries Sciences University, Bidar, Karnataka (575002), India.

Abstract

Wastewater-fed aquaculture is an eco-friendly and sustainable method of fish farming that uses treated or partially treated wastewater for the culture of aquatic organisms such as fish, prawns, and shellfish. The wastewater contains nutrients like nitrogen and phosphorus, which support the growth of aquatic species and reduce the need for artificial fertilizers. Different treatment methods such as sedimentation, biofiltration, wetlands, and disinfection are used to improve water quality before use in aquaculture. Species like tilapia, carp, catfish, mussels, and freshwater prawns are commonly cultured because of their adaptability to nutrient-rich conditions. This system helps conserve freshwater resources, reduces environmental pollution, and lowers production costs. However, proper management and monitoring are essential to avoid risks related to pathogens, heavy metals, and water contamination. Overall, wastewater-fed aquaculture offers a promising approach for sustainable fish production and efficient wastewater utilization.

Introduction

Waste water fed aquaculture is a sustainable practice that involves using treated or partially treated wastewater to cultivate aquatic organisms such as fish, shellfish, and plants. This method takes advantage of the nutrients present in the wastewater, which can promote the growth of these organisms, while simultaneously treating the water through natural biological processes.

Keywords: Wastewater, aquaculture, fish, water treatment.

Water Treatment Methods

These methods typically include:

1. **Pre-Treatment:** Pre-treatment involves the removal of large debris and sediments that can harm aquatic life or interfere with subsequent treatment processes. Common pre-treatment methods include:
 - a. **Screening:** Using screens or sieves to remove large particles and debris.
 - b. **Sedimentation:** Allowing suspended solids to settle at the bottom of a sedimentation tank.
2. **Primary Treatment:** Primary treatment aims to reduce organic matter and suspended solids in the wastewater.
 - a. **Settling Tanks or Clarifiers:** These structures allow solids to settle out of the water column.
 - b. **Flotation:** Dissolved air flotation (DAF) can be used to remove suspended solids and grease by floating them to the surface for removal.
3. **Secondary Treatment:** Secondary treatment focuses on biological processes to break down organic matter and nutrients.
 - a. **Activated Sludge:** This process involves aerating the wastewater to support the growth of microorganisms that consume organic matter.
 - b. **Biofilters:** Utilizing media such as rocks or plastic that support microbial growth, biofilters help in breaking down organic pollutants.
 - c. **Constructed Wetlands:** Man-made wetlands that mimic natural processes to treat wastewater through plant uptake and microbial action.
4. **Tertiary Treatment:** Tertiary treatment provides additional purification to meet higher water quality standards.
 - a. **Filtration:** Using sand filters, membrane filters, or other filtration systems to remove remaining fine particles.
 - b. **Disinfection:** Methods such as chlorination, ultraviolet (UV) radiation, or ozonation to kill pathogenic microorganisms.
 - c. **Nutrient Removal:** Advanced processes such as biological nutrient removal (BNR), chemical precipitation, or ion exchange to reduce nitrogen and phosphorus levels.
5. **Polishing:** Polishing treatments ensure the final effluent quality is high and safe for aquaculture.
 - a. **Polishing Ponds:** Additional ponds or lagoons that provide further settling and biological treatment.
 - b. **Advanced Oxidation Processes (AOPs):** Techniques like ozonation combined with UV or hydrogen peroxide to degrade remaining organic pollutants and micropollutants.

6. Monitoring and Control: Continuous monitoring of water quality parameters (e.g., dissolved oxygen, pH, temperature, ammonia, nitrates, and phosphates) is essential to ensure optimal conditions for aquaculture.

Species Selection for Wastewater Aquaculture

Selecting species for wastewater-fed aquaculture involves considering several factors, such as the species' tolerance to varying water quality, their ability to utilize available nutrients, and their economic value. Here are some suitable species categories and examples:

1. Tilapia (*Oreochromis spp.*): Highly adaptable, fast-growing, and able to tolerate a range of water conditions, tilapia are one of the most popular choices.

2. Common Carp (*Cyprinus carpio*): Known for their hardiness and ability to grow in various water conditions, carp can efficiently utilize organic matter in the water.

3. Catfish (*Clarias spp.* and *Ictalurus spp.*): These species are tolerant of low dissolved oxygen levels and high nutrient concentrations, making them ideal for such systems.



4. Mussels (*Mytilus spp.*): Filter feeders that can help improve water quality by removing particulates and microorganisms.

5. Oysters (*Crassostrea spp.*): Also filter feeders, oysters are efficient at removing organic matter and can be an economically valuable product.

6. Freshwater Prawns (*Macrobrachium rosenbergii*): These prawns are adaptable to various water conditions and can grow well in nutrient-rich environments.



Culture Practises

1. The fish-culturing practice is basically a composite system using different species of fish which utilize different ecological niches of pond ecosystem.

2. The polyculture practices followed is three species of Indian major carps with exotic carps and sometimes minor carp.

3. Stocking density varies according to seed availability, time of stocking and culture system.

4. For production of 1 year an initial stocking density of 5000-7000 fingerlings ha⁻¹ is followed.

5. The total stocking density is split into several instalments and distributed throughout the year.

6. The introduction of selected species of fishes to ensure a short food chain is considered to be a profitable proposition.

7. No definite stocking ratio among fishes is followed, but farmers, on recommendations, use greater proportions of more tolerant and bottom grazing fishes like tilapia, common carp and mrigal in preference to other species.

With multiple cropping pattern in both, the culture period is about 1 year. When necessary, the ponds are completely dried up for detoxification.



The bulk of the harvested fish consists of Indian major carps and tilapia.

Pond Management

1. Lime is applied to the ponds at a rate of 400-500 kg ha⁻¹ during the winter months when the ponds dry up.
2. No supplementary feeding or pond fertilization is done during the culture period.
3. No aeration device is installed in fishponds, but regular boating and netting operations are done during late at night, helping to enhance oxygen levels in the water to some extent.



Drying of ponds is undertaken during



Silt is removed at least once in three years

Disease Problems

1. In sewage fed farms, bacterial diseases are not common.
2. Even when there were problems with Epizootic Ulcerative Disease (EUS) in recent years with carps in other areas, carps in these sewage-fed ponds remained uninfected.
3. However, parasitic infections by *Lernaea* (anchor worm) and *Argulus* are common.

Sewage fed fishponds; locally called “Bheries” have a bamboo sluice structure to prevent the entry of wild fishes and escape of the stocked fishes.

Harvesting Methods

1. **Seine Netting:** Using large nets (seines) to encircle and capture fish. This method is common in pond systems.
2. **Draining Ponds:** Partially or fully draining ponds to concentrate fish in a smaller area for easier capture. Use of nets or buckets to collect the concentrated fish.

Advantages

1. Wastewater contains nutrients like nitrogen and phosphorus that are beneficial for the growth of aquatic plants and animals, reducing the need for artificial fertilizers.
2. It provides an effective means of utilizing wastewater, reducing the environmental impact of waste discharge and contributing to waste management solutions.
3. Reduced costs for water and fertilizers can lead to significant savings in aquaculture operations.
4. Enhanced growth rates of aquatic organisms due to nutrient-rich water can increase overall productivity and profitability.
5. By reusing wastewater, this practice conserves freshwater resources, which is critical in areas with limited water availability.
6. It can reduce the discharge of untreated or partially treated wastewater into natural water bodies, thereby minimizing pollution and its negative impacts on ecosystems.
7. Constructed wetlands and ponds used in wastewater-fed aquaculture can create habitats for various wildlife species.

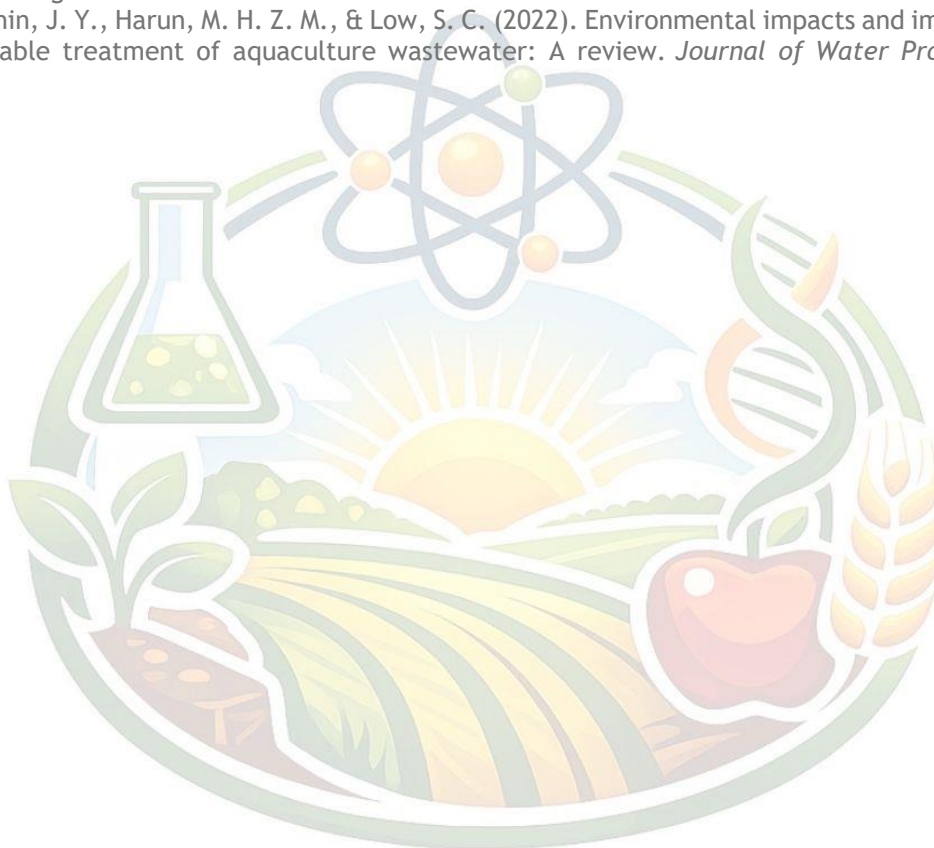
Disadvantages

1. There is a risk of pathogen and toxin contamination in the cultivated organisms if the wastewater is not adequately treated, posing health risks to consumers.
2. Wastewater may contain heavy metals and chemical residues that can accumulate in the organisms, making them unsafe for consumption.
3. The system requires continuous monitoring and maintenance to ensure water quality and the health of the organisms.
4. Effective management often requires technical expertise in both aquaculture and wastewater treatment processes.
5. Adhering to strict regulations and standards for water quality and food safety can be challenging and costly.
6. Obtaining necessary permits and approvals for using wastewater in aquaculture can be a complex and time-consuming process.

7. If not managed properly, the introduction of nutrient-rich water into natural ecosystems can lead to eutrophication, harming local aquatic environments.
8. The spread of non-native species cultivated in wastewater-fed systems to natural water bodies can negatively impact local biodiversity.
9. There may be negative perceptions among consumers regarding the safety and quality of products grown in wastewater, potentially affecting market acceptance and demand.

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Export of Food and Agri Products Registered as GI from Maharashtra

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Sangita J. Kadlag¹

¹Assistant Professor of Agricultural Economics, MVP's K.D.S.P College of Agriculture, Chachadgaon , Nashik-Peth Highway Nashik.

Introduction

GI stands for **Geographical Indication**. It is a certification mark used on agricultural and food products to indicate that they possess specific qualities, reputations, or characteristics largely attributable to their region of origin.

A Geographical Indication acts essentially as an intellectual property right. It serves several key purposes:

- 1. Proof of Origin:** It guarantees consumers that the product was indeed grown, harvested, or processed in a specific, defined geographic area.
- 2. Quality Assurance:** It signifies that the item has unique, authentic qualities derived from local natural factors (like soil and climate) or traditional production methods.
- 3. Legal Protection:** It prevents unauthorized producers outside the designated region from falsely marketing their goods under that famous name.

Why GI Matters for Agri-Food Products?

- 1. Local Identity:** It preserves centuries-old farming techniques, regional recipes, and local knowledge.
- 2. Economic Value:** Products with recognized GI tags often fetch premium prices in the market because of their authenticity and high quality.

Role of GI products in export for India: Geographical Indication (GI) products drive India's export growth by guaranteeing authenticity, securing premium prices, and protecting traditional knowledge from counterfeits. They act as a powerful branding tool, allowing regional producers to bypass middlemen and tap into lucrative international markets.

Key Roles of GI Products in India's Exports

- 1. Premium Pricing & Market Premium:** International consumers associate GI tags with assured origin and quality. Exporters of GI products often command a 20-30% price premium over non-tagged equivalents.
- 2. Legal Protection & Trust:** The GI tag prevents the unauthorized use of regional names (e.g., stopping international companies from selling fake Darjeeling tea or Basmati rice). It eliminates information asymmetry, assuring foreign buyers of the product's true origin.
- 3. Empowering Rural Economies:** By boosting export value, GI tags directly improve the livelihood of rural artisans, weavers, and farmers. It helps preserve regional heritage while transforming local manufacturing into a global business.
- 4. Boosting Niche & Agricultural Exports:** Beyond major commodities, the government actively promotes niche GI-tagged agri-products (like Alphonso mangoes, Nagpur oranges, and Indi Lime) to diverse international destinations such as the UAE, USA, Japan, and the EU.

Government & Institutional Support

To enhance the global reach of these regional treasures, India has rolled out several export facilitation programs:

- 1. APEDA Initiatives:** The Agricultural and Processed Food Products Export Development Authority (APEDA) regularly organizes Virtual Buyer-Seller Meets and international promotional events to connect GI producers with global importers.
- 2. Trade Promotion:** Trade bodies and Export Promotion Councils (EPCs) highlight GI-tagged handicrafts and agricultural goods at international trade fairs to gain visibility.

Registration & Guidance: The Geographical Indications Registry and associated bodies guide local communities on securing international IP protection.

From India there are 123 food and agri products registered as GI products. Out of India's GI products 24 food and Agri products (nearly 20 % products) are from Maharashtra.

These includes Foodgrains (Rice & Jowar), Fruits (12 fruits) Vegetables (3 vegetables) Spices (2 types) and one food products.

List of GI Tag for Agri and Food Products from Maharashtra

Sr no	Type	Geographical Indication	Geographical Area	Class	Journal no
1	Food grains	Ajara Ghansal Rice	Taluka Ajara, District-Kolhapur	30	76
2		Ambemohar Rice	Mulshi TalukaDist- Pune	30	88
3		Mangalwedha Jowar	Taluka Mangalwedha, District: Solapur	30	78
4	Fruits	Nashik Grapes	Maharashtra	31	35
5		Nagpur Orange	Akola , Maharashtra	31	55
6		Sindhudurg and Ratnagiri Kokam	Taluka - Malvan Dist-Sindhudurg	29	76
7		Beed Custard Apple	Tal - Dhanur Dist-Beed	31	79
8		Jalna Sweet Orange	Dist- Jalna	31	79
9		Purandar Fig	Pune	31	80
10		Solapur Pomegranate	Pune	31	80
11		Dahanu Gholvad Chikoo	Tal -Dahanu Dist- Thane	31	88
12		Jalgaon Banana	Tal -Raver Dist- Jalgaon	31	88
13		Marathwada Kesar Mango	Dist- Aurangabad	31	88
14		Alphonso	Tal -Dapoli Dist- Ratnagiri	31	106
15		Mahabaleshwar Strawberry	Tal - Mahabaleshwar Dist- Satara	31	33
16	Vegetable	Waghya Ghevada	Taluka - Koregaon Dist-Satara	31	77
17		Lasalgaon Onion	Taluka - Niphad , Dist- Nashik	31	77
18		Jalgaon Brinjal	Dist-Jalgaon	31	80
19	Spices	Waigaon Turmeric	Tal -Samudrapur Dist - Wardha	30	80
20		Bhivapur Chilli	Tal - Bhivapur Dist - Nagpur	30	88
21		Sangli Turmeric	Dist- Sangli	30	108
22	Food Product	Kolhapur Jaggery	Dist- Kolhapur	31	54
23		Navapur Tur Dal	Tal - Navapur Dist- Nandurbar	31	77
24		Sangli Raisins	Tal - Miraj Dist - Sangli	31	78

What is Mean by Class in GI Products in India

In India, a "class" refers to the specific product category under which a Geographical Indication (GI) is registered. India uses a standardized classification system (similar to the international Nice Classification) with **34 distinct classes**, which determines exactly what type of goods a GI tag protects.

Why Classes Matter?

- 1. Scope of Protection:** A GI tag only protects a product within its assigned class. For example, a registered GI for "Alphonso" under Class 31 (Fruits) stops anyone from falsely labeling unverified mangoes as Alphonso, but it doesn't cover "Alphonso" flavored chocolates or cotton fabric.
- 2. The 34 Categories:** The registry divides all registerable goods into 34 classes ranging from agricultural products, foodstuff, and alcoholic beverages to handicrafts, textiles, and chemicals.

Common GI Classes in India

The majority of India's hundreds of recognized GIs fall into these primary classes:

- 1. Class 23 & 24:** Textiles and Textile Goods (e.g., Banarasi Silk, Kashmir Pashmina, Chanderi Fabric).
- 2. Class 30:** Agricultural and Food Products (e.g., Hyderabad Haleem, Dharwad Pedha).
- 3. Class 31:** Raw Agricultural Products (e.g., Darjeeling Tea, Basmati Rice, Alphonso Mango).
- 4. Class 1 to 22:** Handicrafts and Manufactured Goods (e.g., Jaipur Blue Pottery, Bidriware, Mysore Sandal Soap).

How to Check Product Class

When artisans, farmers, or cooperatives apply for a GI tag, they must specify the exact class of their product. You can view the entire registry and the class assigned to every verified product by checking the official Intellectual Property India (GI Registry) portal.

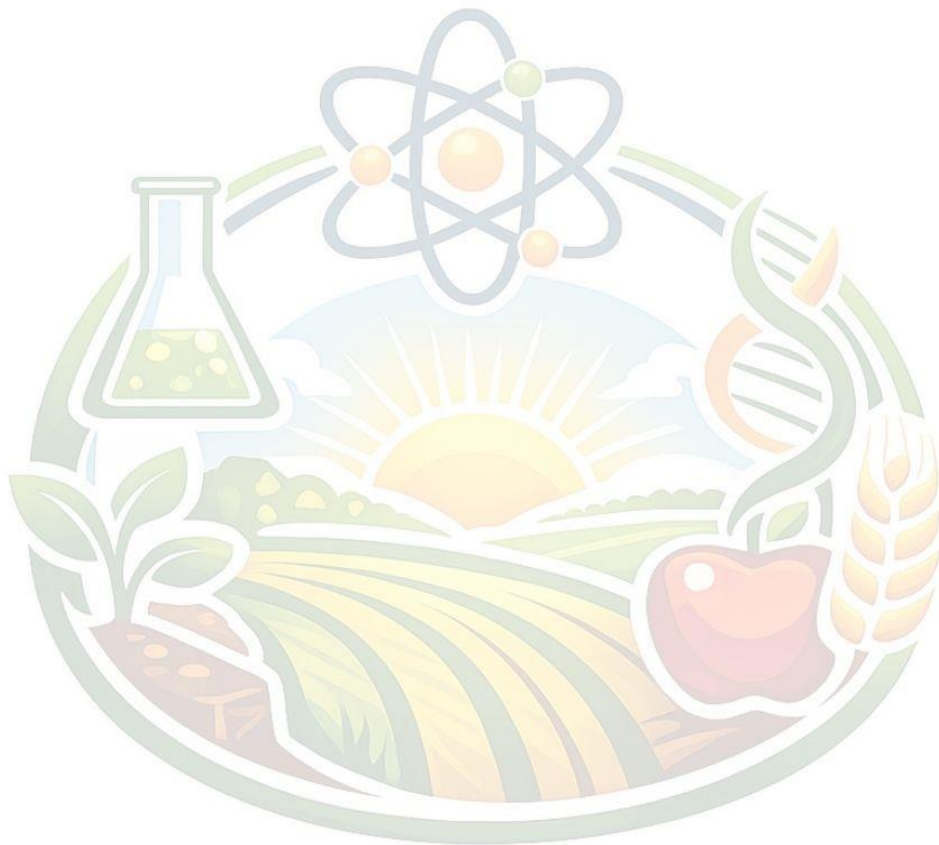
What is Mean by Journal Number in GI Products in India?

In the context of Geographical Indication (GI) products in India, a **Journal Number** refers to the specific edition of the official *Geographical Indications Journal* where a product's GI application was published.

1. The Public Notice: Before a GI tag is officially granted, the GI Registry in India publishes the details of the product (its name, origin, unique qualities, and producers) in its official journal. This journal number tells you exactly *where* to look to find this public notice.

2. Opportunity for Opposition: The publication of an application in a specific journal starts a clock (usually 3 months) during which the public or other interested parties can file an opposition or objection to the GI registration.

3. Journal Reference: Once the tag is registered, the journal number remains on the product's official registration records as a permanent reference point.



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Agri-Export Business: Navigating Global Markets for Spices, Grains, and Processed Foods

Article ID: 73749

Sanjiv Kumar¹, Deen Dayal Bairwa², Manish Kumar³

^{1,2} Faculty of Agriculture, Jagannath University, Jaipur, Rajasthan, 303901.

³ Student, B.Sc. (Hons.), Agriculture, Faculty of Agriculture, Jagannath University, Jaipur, Raj. 303901.

Abstract

The agri-export business has become an important component of global agricultural trade, contributing significantly to economic growth, foreign exchange earnings, and rural development. This article examines the expanding role of agricultural exports with special reference to spices, grains, and processed foods. It highlights the importance of agri-exports in enhancing farmers' income, generating employment opportunities, promoting value addition, and strengthening international trade relations. The study also discusses the growing global demand for high-quality and value-added agricultural products due to changing consumer preferences and increasing health awareness. Major challenges such as stringent quality standards, market competition, inadequate infrastructure, and fluctuating global prices are analyzed in the context of export competitiveness. Furthermore, the article emphasizes the importance of modern agricultural technologies, efficient supply chain management, quality certification, and government support for sustainable export growth. The agri-export sector therefore offers substantial potential for economic development, market expansion, and global competitiveness in the agricultural economy.

Introduction

Agricultural exports have become an important component of global trade and economic development, creating new opportunities for farmers, food processors, and agribusiness enterprises. The growing international demand for agricultural commodities such as spices, grains, and processed foods has encouraged many developing countries to strengthen their export-oriented agricultural sectors. In recent years, globalization, technological advancements, and liberalized trade policies have significantly expanded access to international markets, allowing agricultural producers to participate more actively in global supply chains.

In India, agriculture remains a major source of livelihood for a large section of the population, and the agri-export sector plays a crucial role in generating foreign exchange earnings and rural employment. India possesses diverse agro-climatic conditions, fertile soils, and rich biodiversity, which support the cultivation of a wide variety of agricultural products. The country is internationally recognized for its spices, cereals, pulses, fruits, vegetables, and processed food items. Products such as Basmati rice, turmeric, black pepper, cumin, and ready-to-eat food products have gained considerable acceptance in global markets due to their quality, flavor, and nutritional value.

The increasing preference for natural, organic, and value-added food products among consumers worldwide has further enhanced the export potential of agricultural commodities. Spices are widely used not only for culinary purposes but also for medicinal and nutraceutical applications. Similarly, grains continue to remain essential food commodities in international trade because of rising global population and food security concerns. Processed foods have also witnessed rapid growth due to changing lifestyles, urbanization, and the increasing demand for convenience foods. The agri-export business contributes significantly to economic growth by promoting agricultural diversification, encouraging value addition, and improving farmers' income. Export-oriented agriculture also stimulates the development of infrastructure such as storage facilities, transportation networks, food processing units, and cold-chain systems. In addition, international trade creates employment opportunities in packaging, logistics, quality testing, and marketing sectors. Despite its vast potential, the agri-export sector faces several challenges, including strict international quality standards, fluctuating market prices, trade regulations, and supply chain inefficiencies. Therefore, successful participation in global agricultural markets requires scientific production practices, quality assurance, efficient processing, and effective export management strategies.

Importance of Agri-Export Business

1. Contribution to National Economic Growth: The agri-export business plays a significant role in strengthening the national economy by generating foreign exchange earnings and improving the balance of trade. Export of agricultural commodities such as spices, grains, fruits, vegetables, and processed foods increases national income and supports economic stability. In countries like India, agricultural exports contribute substantially to the growth of the agribusiness sector and enhance the country's participation in international trade markets.

2. Enhancement of Farmers' Income: Agricultural exports provide farmers with access to larger and more profitable international markets. Export-oriented production often offers better prices compared to domestic markets, thereby

increasing farm income and improving rural livelihoods. Cultivation of high-demand export crops such as Basmati rice, turmeric, chili, and organic food products enables farmers to diversify their income sources and achieve greater economic security.

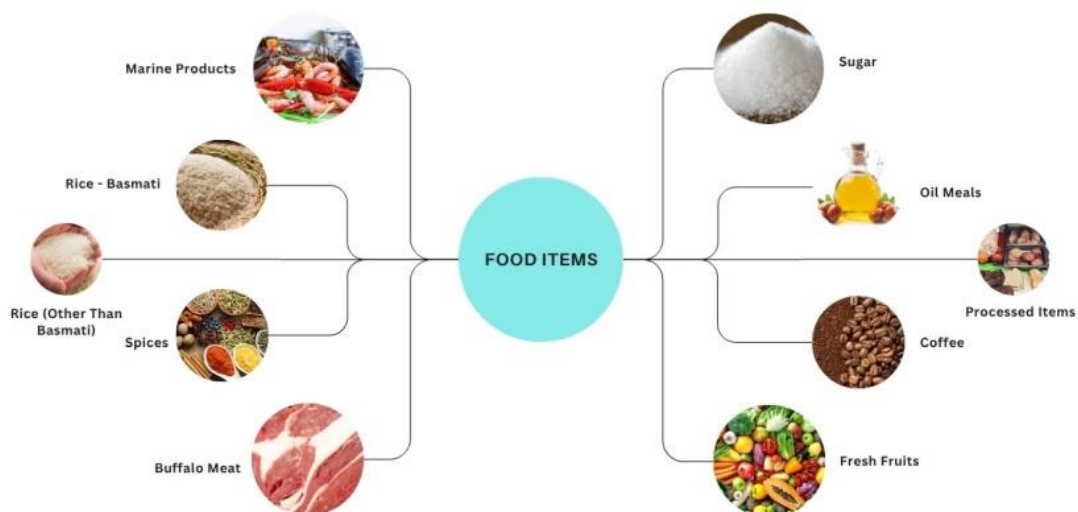


3. Employment Generation and Rural Development: The agri-export sector creates direct and indirect employment opportunities in farming, processing, and packaging, transportation, warehousing, and marketing activities. It promotes rural industrialization and encourages the establishment of food processing units and export enterprises. As a result, agri-export business contributes to poverty reduction, skill development, and overall rural development, particularly in agricultural regions.

4. Promotion of Value Addition and Food Processing: Agri-export business encourages value addition through processing, grading, packaging, branding, and quality improvement of agricultural products. Processed and packaged products generally have higher market value and longer shelf life than raw agricultural commodities. The growing global demand for processed foods, ready-to-eat products, and organic commodities has increased the importance of food processing industries in international trade.

5. Strengthening International Trade and Market Expansion: Agricultural exports help countries establish strong trade relations and expand their presence in global markets. International trade promotes the exchange of agricultural technologies, quality standards, and market information. It also increases the global recognition of indigenous agricultural products such as Indian spices and specialty grains. Through effective export strategies and quality assurance systems, countries can enhance their competitiveness and secure long-term opportunities in international agricultural markets.

Top 10 Food Product Exports from India



Challenges in Agri-Export Business

1. Stringent Quality and Safety Standards: One of the major challenges in the agri-export business is compliance with international quality and food safety standards. Importing countries often impose strict sanitary and phytosanitary regulations to ensure that agricultural products are free from harmful chemicals, pesticide residues, and microbial contamination. Exporters must maintain proper quality control, certification, grading, and packaging systems to meet these standards. Failure to comply with international regulations can lead to rejection of consignments and financial losses.

2. Fluctuations in Global Market Prices: Agricultural export markets are highly influenced by changes in global demand and supply conditions. Prices of spices, grains, and processed foods often fluctuate due to climatic variations, geopolitical issues, trade restrictions, and changing consumer preferences. Such uncertainty creates financial risks for exporters and farmers. Sudden declines in international prices may reduce profitability and affect the sustainability of export-oriented agricultural enterprises.

3. Inadequate Infrastructure and Logistics: Efficient transportation, storage, and supply chain systems are essential for successful agricultural exports. However, many developing countries, including India, face challenges related to inadequate cold storage facilities, poor transportation networks, and insufficient warehousing infrastructure. Perishable agricultural products require proper handling and temperature-controlled logistics to maintain quality during transit. Weak infrastructure often results in post-harvest losses, delayed shipments, and increased transportation costs.

4. Competition in International Markets: The global agri-export sector is highly competitive, with several countries exporting similar agricultural commodities. Countries such as China, Thailand, and Vietnam are strong competitors in the export of spices, rice, and processed foods. Exporters must continuously improve product quality, branding, packaging, and pricing strategies to remain competitive in international markets.

5. Lack of Market Information and Export Awareness: Many small and marginal farmers have limited knowledge regarding international market trends, export procedures, documentation requirements, and foreign consumer preferences. Lack of awareness about export opportunities, quality certifications, and digital marketing platforms restricts their participation in global trade. In addition, complex export documentation and regulatory procedures can discourage new entrepreneurs from entering the agri-export business. Therefore, training, institutional support, and market intelligence are essential for improving export competitiveness and market access.

Strategies for Enhancing Agri-Exports

Adoption of Modern Agricultural Technologies: The adoption of modern agricultural technologies is essential for improving productivity, quality, and competitiveness in international markets. Advanced farming methods such as precision agriculture, drip irrigation, greenhouse cultivation, and digital monitoring systems help farmers produce high-quality crops with better efficiency. The use of traceability systems and digital supply chain management also increases transparency and consumer confidence in export products. Technological advancements enable exporters to meet international quality standards and reduce production losses.

Improvement in Processing, Packaging, and Value Addition: Efficient processing and attractive packaging play a significant role in increasing the market value of agricultural products. Proper cleaning, grading, sorting, and hygienic processing improve product quality and shelf life. International consumers prefer well-packaged and branded products that ensure safety and convenience. Value-added products such as spice powders, ready-to-eat foods, frozen vegetables, and organic food items generate higher profits compared to raw agricultural commodities. Therefore, investment in food processing industries and modern packaging technologies is necessary for export growth.

Strengthening Quality Standards and Certification Systems: Maintaining international quality and food safety standards is one of the most important requirements in agri-export business. Exporters must comply with sanitary and phytosanitary regulations, residue limits, and certification requirements imposed by importing countries. Adoption of Good Agricultural Practices (GAP), organic certification, and quality assurance systems enhances the credibility of export products in global markets. Regular quality testing and scientific post-harvest management help reduce rejection of export consignments and improve international market acceptance.

Development of Infrastructure and Supply Chain Facilities: Strong infrastructure and efficient logistics systems are essential for successful agricultural exports. Development of cold storage facilities, warehouses, refrigerated transportation, and modern ports helps maintain the quality of perishable commodities during storage and transit. Efficient supply chain management reduces post-harvest losses and transportation costs. In India, investment in export-oriented infrastructure can significantly improve the competitiveness of spices, grains, and processed foods in international markets.

Government Support and Market Promotion : Government policies and institutional support play a vital role in promoting agri-export business. Export incentives, financial assistance, training programs, and market development schemes encourage farmers and entrepreneurs to participate in global trade. Organizations such as Agricultural and Processed Food Products Export Development Authority and Spices Board India provide guidance regarding export

standards, quality certification, and international marketing opportunities. Participation in international trade fairs, digital marketing platforms, and export promotion campaigns also helps expand market access and strengthen global trade relationships.

Conclusion

The agri-export business has emerged as an important driver of economic growth, rural development, and international trade. The increasing global demand for spices, grains, and processed foods has created significant opportunities for agricultural producers and agribusiness enterprises. In India, favorable agro-climatic conditions, rich biodiversity, and diverse agricultural production provide strong potential for expanding agricultural exports. Agri-exports not only generate foreign exchange earnings but also enhance farmers' income, promote employment generation, and encourage value addition through food processing and packaging industries. However, challenges such as strict quality standards, market competition, infrastructure limitations, and fluctuating global prices continue to affect export performance. Therefore, the adoption of modern technologies, efficient supply chain systems, quality certification, and supportive government policies is essential for strengthening global competitiveness. With scientific management and sustainable agricultural practices, the agri-export sector can contribute significantly to long-term economic development and global market expansion.

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Women Empowerment in Agribusiness: Driving Innovation in Smallholder Value Chains

Article ID: 73750

Sanjiv Kumar¹, Deen Dayal Bairwa², Mayra Khanna³

^{1,2} Faculty of Agriculture, Jagannath University, Jaipur, Rajasthan, 303901.

³ Student, B.Sc. (Hons.), Agriculture, Faculty of Agriculture, Jagannath University, Jaipur, Rajasthan, 303901.

Introduction

Women play a central role in agriculture and agribusiness across developing countries, particularly in smallholder farming systems. They contribute significantly to crop production, livestock management, food processing, marketing and household nutrition. In India and many parts of Asia and Africa, women are increasingly becoming the backbone of agricultural value chains. According to the Food and Agriculture Organization (FAO), women constitute nearly 40% of the global agricultural workforce and in several developing regions their participation exceeds 50%. Despite their contribution, women often face challenges such as limited land ownership, lack of access to credit, poor market linkages, lower wages, restricted mobility and limited exposure to technology and training. Empowering women in agribusiness has emerged as a powerful strategy for improving agricultural productivity, enhancing rural livelihoods, reducing poverty and promoting inclusive economic growth. Women empowerment in agribusiness is not only a social issue but also an economic necessity. When women gain access to productive resources, education, technology and markets, they contribute to innovation and resilience within smallholder value chains. Their participation strengthens food systems, improves household nutrition and promotes sustainable agriculture.

Role of Women in Smallholder Value Chains

Smallholder value chains include all activities involved in agricultural production, processing, storage, transportation and marketing. Women participate at every stage of these chains. They are actively engaged in seed selection, cultivation, harvesting, grading, packaging, processing and retail marketing. In India, women contribute heavily to sectors such as dairy, poultry, vegetable cultivation, floriculture, fisheries and food processing. The feminization of agriculture has increased due to migration of men toward non-farm employment. Reports indicate that more than 70% of working women in South Asia are employed in agrifood systems. Women-led self-help groups (SHGs), farmer producer organizations (FPOs) and cooperatives have become important institutions in rural agribusiness development. These organizations help women access markets, improve bargaining power and adopt value addition practices. Examples include dairy cooperatives, millet processing units, organic farming groups and rural food enterprises. Women also contribute to innovation by introducing sustainable agricultural practices, traditional knowledge systems, and climate-resilient farming techniques. Their involvement in seed conservation, organic farming and nutrition-sensitive agriculture enhances biodiversity and environmental sustainability.

Challenges Faced by Women in Agribusiness

Although women contribute immensely to agribusiness, they continue to face structural and socio-economic barriers.

- 1. Limited Access to Land and Assets:** Land ownership among women remains very low in many developing countries. In India, only a small proportion of women own agricultural land, which restricts their ability to access institutional credit and government schemes. Lack of ownership reduces decision-making power and economic independence.
- 2. Lack of Access to Finance:** Women entrepreneurs in agribusiness often face difficulties in obtaining loans due to absence of collateral, low financial literacy and gender discrimination. Limited financial inclusion restricts investment in modern technologies and value addition activities.
- 3. Technology and Digital Divide:** Many rural women have limited access to digital technologies, smartphones, mechanization, and extension services. As agriculture becomes more technology-driven, exclusion from digital innovation can widen gender inequality.
- 4. Market Constraints:** Women producers often depend on middlemen due to poor transportation, limited mobility, and lack of market information. This reduces profitability and limits participation in high-value markets.
- 5. Workload and Social Norms:** Women manage both farm work and household responsibilities, resulting in heavy workloads and time poverty. Traditional social norms often limit leadership opportunities and participation in decision-making processes. Research shows that unequal access to resources significantly affects productivity and income generation among women farmers.

Innovation Driven by Women in Agribusiness

Women are increasingly becoming agents of innovation in agribusiness value chains. Their participation has transformed rural economies through entrepreneurship, technology adoption and collective action.

1. Value Addition and Food Processing: Women-led enterprises are contributing to value addition through pickle making, dairy processing, millet products, spice packaging and ready-to-eat foods. These activities increase farm income and reduce post-harvest losses. For example, rural women's self-help groups in India have successfully established micro-enterprises for processing pulses, oilseeds, fruits, and vegetables. Such enterprises generate employment and strengthen local food systems.

2. Digital Agriculture and Agritech: Digital technologies are empowering women farmers through mobile applications, e-commerce platforms, and online advisory services. Agritech innovations provide information related to weather, crop management, pest control and market prices.

Studies on female farmers indicate that mobile-based agricultural services improve productivity and market participation. AI-powered agricultural advisory platforms are also supporting smallholder women farmers by offering localized and timely information. These tools improve decision-making and reduce dependency on traditional extension systems.

3. Climate-Resilient Agriculture: Women are adopting climate-smart practices such as organic farming, water conservation, integrated farming systems and diversified cropping patterns. Their knowledge of local biodiversity contributes to resilience against climate change. Global organizations emphasize that strengthening women's resilience is critical for sustainable agricultural supply chains.

4. Collective Enterprises and Cooperatives: Women-led cooperatives and farmer producer organizations help smallholders access inputs, storage facilities, processing units and organized markets. Collective enterprises improve economies of scale and enhance negotiation power. Successful examples include dairy cooperatives, women-managed seed banks and organic farming collectives that connect rural producers directly with consumers.

Economic and Social Impact of Women Empowerment

Empowering women in agribusiness creates multiple economic and social benefits.

Increased Agricultural Productivity: Studies suggest that equal access to productive resources can significantly increase farm productivity and reduce hunger. Women tend to invest more in family welfare, education and nutrition.

Improved Household Nutrition: Women farmers prioritize food security and nutritional diversity. Their participation in horticulture, livestock, and kitchen gardening improves household diets and child health.

Poverty Reduction: Income generated through women-led agribusiness enterprises contributes directly to rural livelihoods and poverty reduction.

Employment Generation: Women-owned agribusiness ventures create local employment opportunities, particularly for rural youth and marginalized groups.

Strengthening Rural Economies: Inclusive value chains strengthen local economies by promoting entrepreneurship, reducing migration, and increasing community resilience.

According to FAO, gender equality in agrifood systems contributes to sustainable development and resilient food systems.

Strategies for Strengthening Women Empowerment in Agribusiness

To maximize women's contribution in agribusiness value chains, several policy and institutional measures are required:

1. Improve Access to Land Rights: Legal reforms and awareness programs should ensure women's ownership and inheritance rights.

2. Expand Financial Inclusion: Banks and microfinance institutions should provide gender-sensitive credit and insurance services.

3. Promote Digital Literacy: Training programs should improve women's access to smartphones, digital platforms and agritech services.

4. Strengthen Capacity Building: Extension services, entrepreneurship training and leadership development programs should target women farmers.

5. Support Women-Led Enterprises: Governments should encourage women-owned agribusinesses through subsidies, incubation centers and market support.

6. Develop Gender-Inclusive Policies: Agricultural policies must integrate gender perspectives into value chain development and rural development programs.

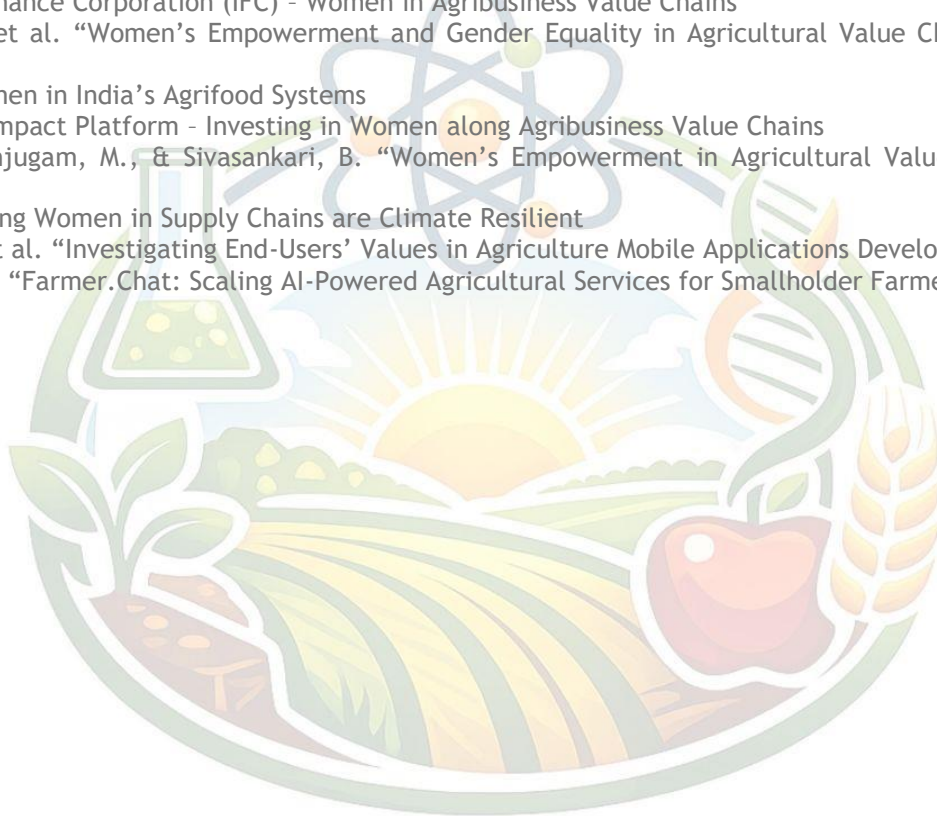
7. Enhance Market Linkages: Better infrastructure, e-commerce access and direct marketing opportunities can improve profitability for women entrepreneurs.

Conclusion

Women empowerment in agribusiness is essential for building sustainable and inclusive smallholder value chains. Women are not only contributors to agricultural production but also innovators, entrepreneurs and leaders driving rural transformation. Their participation improves productivity, strengthens food security, enhances nutrition and promotes economic growth. However, gender inequalities continue to limit their potential. Addressing barriers related to land ownership, finance, technology and market access is critical for unlocking women's full contribution to agribusiness. Investments in education, digital agriculture, climate resilience and collective enterprises can empower women and transform rural economies. As global agriculture faces challenges related to climate change, food insecurity and rural poverty, empowering women in agribusiness offers a pathway toward resilient and equitable development. Supporting women-led innovation in smallholder value chains will play a crucial role in achieving sustainable agricultural growth and inclusive prosperity.

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Status of Fruit Crops in Himachal Pradesh: Area, Production, Productivity and Kinnaur's Contribution (2024-25)

Article ID: 73751

Arun Kumar¹, Durga Prashad Bandhari¹

¹Krishi Vigyan Kendra (KVK) Kinnaur, Sharbo, Reckong Peo, Kinnaur - Himachal Pradesh.



Himachal Pradesh, India's premier temperate fruit-producing state, recorded a total fruit production of 6,48,325 metric tonnes (MT) from 2,37,368 hectares (ha) in 2024-25, giving an overall productivity of 2.73 MT/ha. This article analyses the area, production, productivity, and percentage share of all 37 fruit species cultivated in the state, with a special focus on Kinnaur district. Although Kinnaur accounts for only 5.3% of Himachal Pradesh's total fruit area, it contributes 15.0% of total production, a testament to its outstanding agro-ecological conditions. Apple productivity in Kinnaur (8.84 MT/ha) is more than double the state average (4.32 MT/ha). This article is intended as a scientific reference for KVK Kinnaur, Horticulture Department officers, and the farming community of Kinnaur.

Keywords: Himachal Pradesh, Kinnaur, fruit crops, apple, walnut, almond, area, production, productivity, percentage share.

Introduction

Himachal Pradesh is rightfully called the 'Fruit Bowl of India'. Its mountainous terrain, particularly the belt spanning 1,000 to 3,500 metres above sea level, is ideally suited for temperate fruits such as apple, pear, plum, peach, apricot, almond, and walnut. The fruit industry forms the backbone of rural livelihoods in the state and contributes significantly to the state's GDP. According to 2024-25 data, 37 fruit species are cultivated across 2,37,368 ha in Himachal Pradesh, yielding a total of 6,48,325 MT. A district-wise analysis of these figures reveals which district contributes how much to each crop and at what level of productivity. Kinnaur district is known for its unique geography, cold-arid climate, and fertile valleys, contributes 15.0% of Himachal Pradesh's total fruit production from only 5.3% of its fruit area. This high productivity is the result of scientific horticultural practices promoted through institutions such as KVK Kinnaur.

Fruit Cultivation in Himachal Pradesh: An Overview

1. Area Distribution: The total fruit area in Himachal Pradesh is 2,37,368 ha. Apple dominates with 1,16,338 ha (49.0% of total fruit area). Mango occupies the second position at 42,503 ha (17.9%), followed by citrus crops (Orange/Kinnow, Malta, Lime, Galgal) at approximately 26,586 ha combined (11.2%). Among dry/nut fruits, walnut (4,133 ha) and almond (4,071 ha) are noteworthy, while plum (9,089 ha) leads the stone-fruit category.

Area Distribution of Fruit Crops in HP — Total: 2,37,368 ha

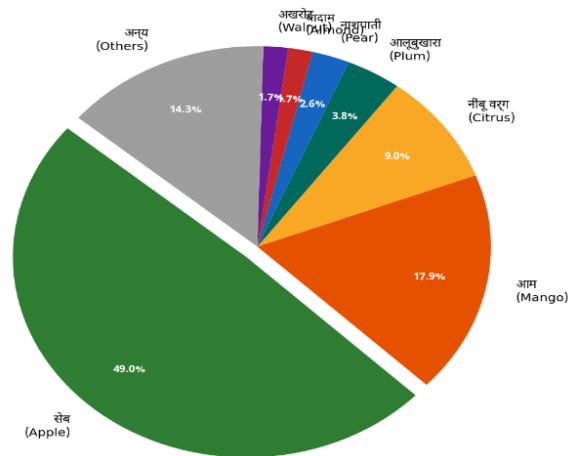


Fig. 1: Area Distribution of Fruit Crops in Himachal Pradesh (2024-25)

2. Production Distribution: Total fruit production in Himachal Pradesh is 6,48,325 MT. Apple alone accounts for 5,02,948 MT, an overwhelming 77.6% of total output. Mango is a distant second at 44,933 MT (6.9%), followed by pear 16,584 MT (2.6%), plum 14,974 MT (2.3%), and Orange/Kinnow 14,644 MT (2.3%). Despite covering only about 0.025% of the fruit area, hazelnut (5 ha, 5 MT) and olive (13 ha, 7 MT) represent emerging possibilities.

Production Distribution of Fruit Crops in HP — Total: 6,48,325 MT

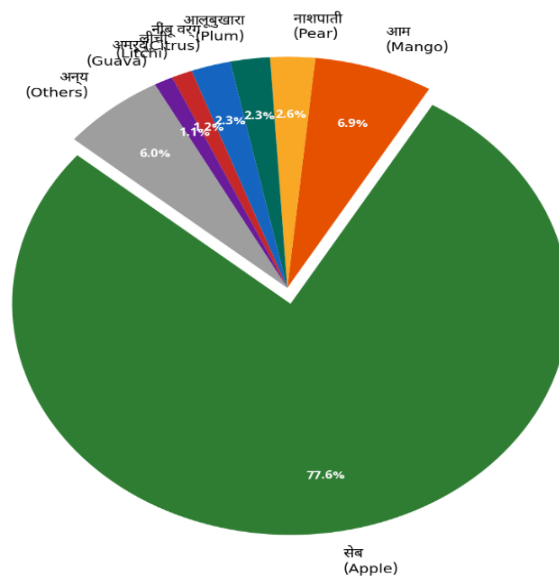


Fig. 2: Production Distribution of Fruit Crops in Himachal Pradesh

Area, Production and Productivity

Table 1: Area, Production, Productivity and Kinnaur's % Share in Himachal Pradesh for Key Fruit Crops (2024-25):

Fruit Crop	Himachal Pradesh			Kinnaur District			Kinnaur % of HP	
	Area (ha)	Prod. (MT)	MT/ha	Area (ha)	Prod. (MT)	MT/ha	Area %	Prod. %
Apple	1,16,338	5,02,948	4.32	10,937	96,636	8.84	9.4	19.2
Plum	9,089	14,974	1.65	14	5	0.36	0.2	0.0
Peach	4,753	3,348	0.70	70	8	0.11	1.5	0.2
Apricot	3,117	4,355	1.40	324	367	1.13	10.4	8.4
Pear	6,278	16,584	2.64	81	90	1.11	1.3	0.5
Cherry	347	1,777	5.12	18	3	0.17	5.2	0.2
Almond	4,071	1,084	0.27	932	149	0.16	22.9	13.7
Walnut	4,133	1,880	0.45	219	104	0.47	5.3	5.5
Grapes	60	95	1.58	25	65	2.60	41.7	68.4

Persimmon	1,110	1,784	1.61	23	8	0.35	2.1	0.4
Kiwi	257	965	3.75	7	3	0.43	2.7	0.3
Mango	42,503	44,933	1.06	0	0	—	0.0	0.0
Litchi	6,955	7,639	1.10	0	0	—	0.0	0.0
HP TOTAL	2,37,368	6,48,325	2.73	12,656	97,471	7.70	5.3	15.0

Source: Directorate of Horticulture, Himachal Pradesh – District-wise Area and Production Statistics, 2024-25.

Kinnaur: A High-Productivity Hub

1. Area Distribution in Kinnaur: Kinnaur has a total registered fruit area of 12,656 ha, 5.3% of Himachal Pradesh's fruit area. Apple dominates at 10,937 ha (86.4%). The remaining area is shared by almond 932 ha (7.4%), apricot 324 ha (2.6%), walnut 219 ha (1.7%), pear 81 ha (0.6%), and grapes 25 ha (0.2%). The concentration of area under a few high-value crops reflects the specialised nature of horticulture in Kinnaur.

Area Distribution of Fruit Crops in Kinnaur — Total: 12,656 ha

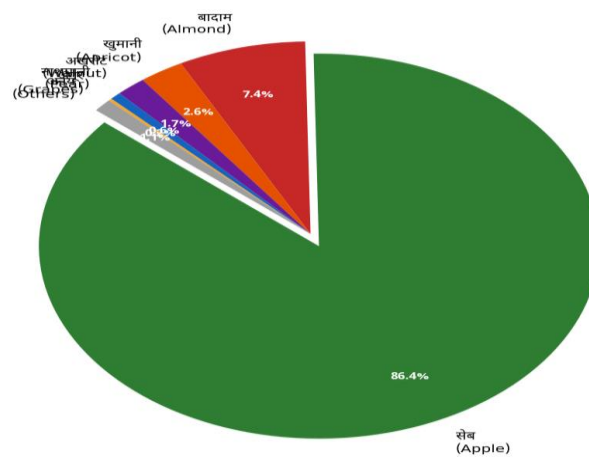


Fig. 3: Area Distribution of Fruit Crops in Kinnaur District (2024-25) — Total: 12,656 ha

2. Why Does Kinnaur Outperform the HP Average: Kinnaur's overall fruit productivity stands at 7.70 MT/ha, nearly three times the Himachal Pradesh average of 2.73 MT/ha. The key drivers are:

- Ideal high-altitude climate:** Elevations of 2,000-3,500 m provide the precise temperature regime and chilling hours required for premium temperate fruit development.
- Natural colour development:** The intense solar radiation and low night temperatures in Kinnaur drive excellent anthocyanin pigmentation in apple skin, commanding premium market prices.
- Low pest and disease pressure:** The cold-arid conditions in upper Kinnaur reduce incidence of major fungal diseases compared to lower-altitude orchards.
- Scientific extension:** KVK Kinnaur's programmes in precision nutrient management, canopy management, and post-harvest handling have directly enhanced farm-level productivity.

Productivity Comparison: HP Average vs. Kinnaur (MT/ha)

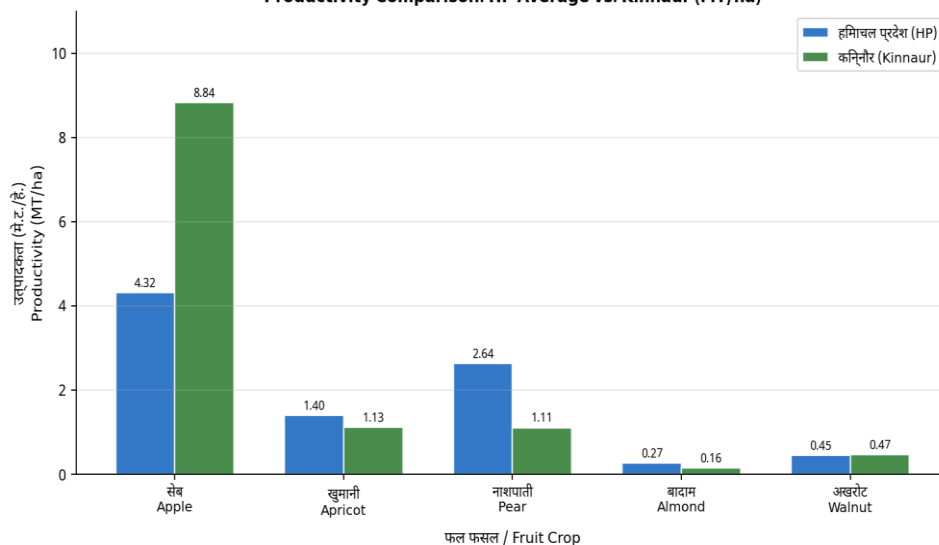


Fig. 4: Productivity Comparison, HP Average vs. Kinnaur for Key Fruit Crops (MT/ha), 2024-25

3. Kinnaur's Percentage Share in Himachal Pradesh: Table 1 and Fig. 5 together reveal a striking picture. Kinnaur, with just 5.3% of Himachal Pradesh's fruit area, contributes:

- 19.2% of HP's total apple production (96,636 MT out of 5,02,948 MT)
- 22.9% of HP's total almond area (932 ha out of 4,071 ha)
- 68.4% of HP's total grape production (65 MT out of 95 MT)
- 13.7% of HP's total almond production (149 MT out of 1,084 MT)
- 10.4% of HP's total apricot area (324 ha out of 3,117 ha).



This extraordinary contribution relative to area share confirms that Kinnaur's agro-ecological conditions are uniquely suited to certain high-value temperate crops.

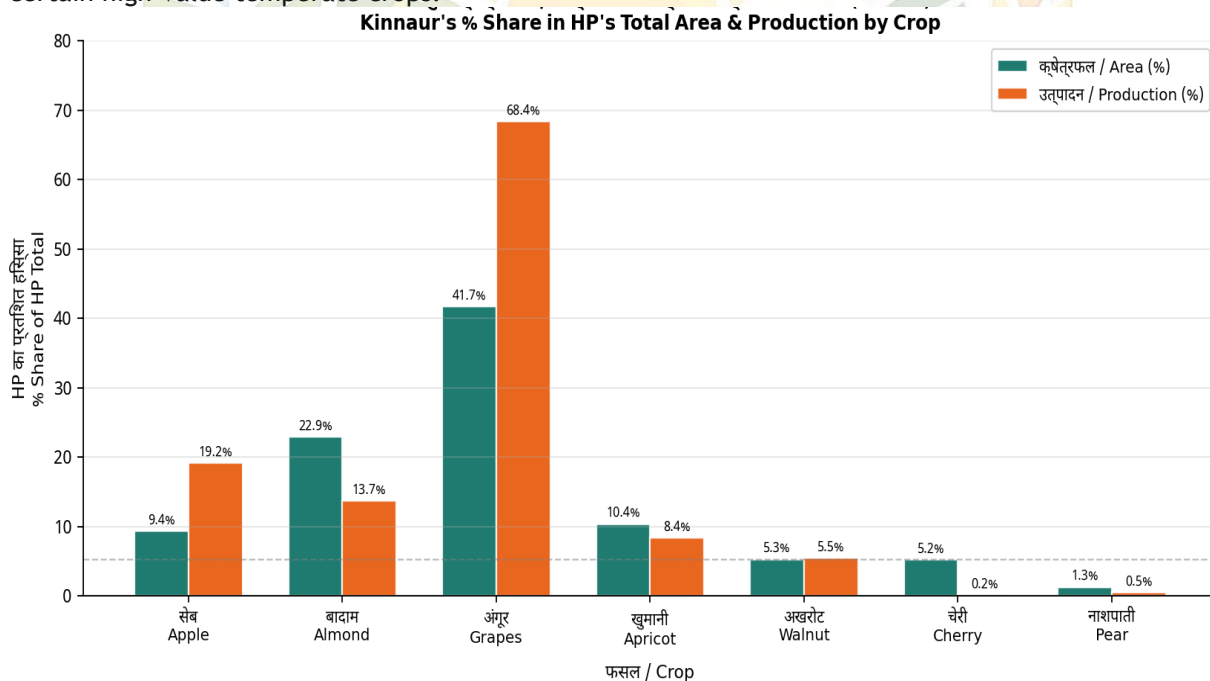


Fig. 5: Kinnaur's % Share in Himachal Pradesh's Total Area & Production by Crop (2024-25)

Crop-Wise Analysis

1. Apple (*Malus x domestica*): Apple is the most important fruit crop of Himachal Pradesh, cultivated on 1,16,338 ha with a production of 5,02,948 MT (productivity 4.32 MT/ha). In Kinnaur, 96,636 MT of apple is produced from 10,937 ha, a remarkable productivity of 8.84 MT/ha, more than double the state average. Kinnaur apple is internationally recognised for its deep red colour, characteristic sweetness, and long shelf life. Kinnaur contributes 9.4% of HP's apple area but 19.2% of its apple production, underscoring the productivity premium of high-altitude orchards.

2. Mango (*Mangifera indica*): Mango is grown in the lower-altitude, subtropical districts of Himachal Pradesh, mainly Kangra, Bilaspur, Una, and Sirmaur. State-wide area is 42,503 ha with production of 44,933 MT (productivity 1.06 MT/ha). Kinnaur's high-altitude cold climate is unsuitable for mango, and no area is recorded for this crop in the district.

3. Almond (*Prunus amygdalus*): Almond is grown on 4,071 ha across Himachal Pradesh with a production of 1,084 MT. Kinnaur alone accounts for 932 ha (22.9% of HP's almond area), the single largest district contributor and produces 149 MT (13.7% of HP total). The low productivity (0.16-0.27 MT/ha in both HP and Kinnaur) reflects dominance of traditional seedling orchards; introduction of improved grafted varieties can substantially raise yields.

4. Walnut (*Juglans regia*): Walnut is cultivated on 4,133 ha in Himachal Pradesh, producing 1,880 MT. Kinnaur contributes 219 ha and 104 MT (5.3% area, 5.5% production). 'Kinnaur Walnut' is prized for its large kernel, thin shell, and excellent flavour and is a strong candidate for Geographical Indication (GI) certification. Expanding the area under improved varieties such as Eureka and Chandler in the Nichar and Kalpa blocks of Kinnaur could significantly raise district-level output.

5. Apricot (*Prunus armeniaca*): Apricot is a traditional crop of Kinnaur, cultivated since time immemorial in its upper valleys. HP-wide area is 3,117 ha with production of 4,355 MT (1.40 MT/ha). Kinnaur contributes 324 ha (10.4% of HP area) and 367 MT (8.4% of HP production). The crop offers three distinct commercial streams: fresh fruit, dried apricot (sun-dried or mechanically dried), and apricot kernel oil, providing multiple income avenues for Kinnaur farmers.

6. Grapes (*Vitis vinifera*): Grapes are cultivated on a modest 60 ha across Himachal Pradesh, yet Kinnaur contributes an impressive 25 ha (41.7% of HP area) and produces 65 MT, 68.4% of HP's entire grape output. Kinnaur grapes are concentrated in the Pooh block, where the dry, sunny climate is ideal for wine-quality fruit. Development of a structured grape value chain, including wine production and sun-dried raisins, represents a high-potential opportunity for Kinnaur's farmers.

7. Pear, Cherry, Kiwi and Persimmon: Pear (6,278 ha, 16,584 MT, 2.64 MT/ha) is Himachal Pradesh's third most productive temperate fruit after cherry (5.12 MT/ha). Kinnaur holds 81 ha pear area with 90 MT production. Cherry (347 ha, 1,777 MT, 5.12 MT/ha) is the highest-productivity temperate fruit in HP. Kiwi (257 ha, 965 MT) and Persimmon (1,110 ha, 1,784 MT) are emerging crops with untapped potential in Kinnaur's mid-altitude belts.

Recommendations and Way Forward

Based on the foregoing analysis, the following measures are recommended:

1. Enhancing apple productivity: Kinnaur's 8.84 MT/ha far exceeds HP's average of 4.32 MT/ha. Replicating Kinnaur's best practices, high-density planting, precision zinc and boron nutrition, timely canopy management, and improved rootstocks, in other apple-growing districts (Shimla, Kullu, Mandi) can raise state-wide productivity.

2. Promoting almond and walnut: Kinnaur holds 22.9% of HP's almond area. Replacing traditional seedling orchards with improved grafted varieties can raise almond productivity 3-4 fold. For walnut, expansion of thin-shelled varieties under the HP Walnut Development Scheme should prioritise Kinnaur's Nichar and Kalpa blocks.

3. GI Certification: 'Kinnaur Apple', 'Kinnaur Walnut', and 'Kinnaur Apricot' should be fast-tracked for Geographical Indication (GI) certification to enable premium market access and protect the unique brand identity of Kinnaur produce.

4. Grape value chain in Pooh block: With 68.4% of HP's grape production, Kinnaur has the critical mass to support a structured grape processing industry. Establishment of a small wine/raisin processing unit in Pooh, under MIDH or NABARD funding, deserves priority consideration.

5. Post-harvest infrastructure: CA (Controlled Atmosphere) storage, pre-cooling facilities, and cold-chain linkages are critically needed in Kinnaur to reduce post-harvest losses and extend market reach of apple and other perishable fruits. Diversification into kiwi, cherry, and persimmon: KVK Kinnaur should establish demonstration plots of these crops in the mid-altitude belts (1,200-2,000 m) of Nichar and Kalpa blocks to expose farmers to diversification options beyond apple.

Conclusion

Himachal Pradesh's fruit sector 2,37,368 ha under cultivation and 6,48,325 MT of annual production, is the country's foremost temperate fruit economy. Apple dominates both in area (49%) and production (77.6%). Kinnaur district, despite accounting for only 5.3% of the state's fruit area, delivers 15.0% of its production, driven by apple productivity (8.84 MT/ha) that is more than double the state average. Kinnaur's commanding position in almond area (22.9% of HP) and grape production (68.4% of HP) further demonstrates the district's unique agro-ecological comparative advantage. With targeted investment in GI certification, post-harvest infrastructure, varietal improvement, and value-chain development, Kinnaur is poised to strengthen its role as Himachal Pradesh's most productive horticultural district.

Goat Milk: A Nutritional Powerhouse and a Microbiological Frontier

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Amaranath Gundluru¹, M. Subhosh Chandra², Kimeera Ambati³
¹Research Scholar, Department of Microbiology, Yogi Vemana University, Kadapa.

²Associate Professor, Department of Microbiology, Yogi Vemana University, Kadapa.

³Assistant Professor, Dept. of Home Science, Sri Padmavati Mahila Visvavidyalayam, Tirupati.

Abstract

Goat milk has emerged over the past five years as a subject of intensifying scientific scrutiny, spanning nutritional biochemistry, dairy microbiology, probiotic science, and food safety. This article synthesises findings from peer-reviewed literature published between 2020 and 2025, drawing together evidence on goat milk's distinctive macro- and micronutrient profile, its complex native microbial communities, the probiotic potential of lactic acid bacteria (LAB) isolates, and the persistent public health risks of raw milk consumption. Tables are provided to contextualise key comparative data. The overall picture is one of a food product that is genuinely nutritionally distinctive, rich in microbiological promise, and inseparable from the imperative of thermal processing as a safety intervention.

Keywords: goat milk · nutrition · microbiology · probiotics · food safety · lactic acid bacteria.

Introduction

For centuries, goat milk has served as a nutritional cornerstone across Mediterranean, Middle Eastern, and South Asian communities. Yet only in the last decade has rigorous science begun to match the anecdotal reverence for this ancient food. The years 2020-2025 have produced a particularly rich body of literature, illuminating goat milk not simply as a cow-milk alternative, but as a distinct biological product with unique nutritional architecture and a complex microbial ecology. This article synthesises the current state of knowledge, drawing on peer-reviewed research across the intersecting fields of nutrition science, dairy microbiology, and food safety.

Key Statistics at a Glance

Global dairy goats	Articles reviewed (2025)	Pasteurised milk safety	Raw milk pathogen rate
~203 million	84 of 126 eligible	86.8% satisfactory	36.4% incidence
Producing 15.26 million tonnes annually	PRISMA review, profiling	Canadian surveillance, 699 samples, 2019-2023	Listeria & Staphylococcus dominant – India, 2024

Nutritional Profile

1. Macronutrients and Digestibility: Goat milk is considered a potential source of various macro- and micronutrients. Compared to bovine milk, it offers a markedly different fat globule geometry and casein profile that underpin its clinically relevant digestibility advantage. The lipids in goat milk provide better digestibility due to small fat globule size and a high proportion of short- and medium-chain fatty acids (MCTs). Furthermore, the β -casein/ α s1-casein ratio – approximately 70:30 – closely mirrors that of human milk, resulting in superior sensitivity to protease enzymes during gastric digestion.

Research into goat milk proteins has also expanded considerably. Compared to cow milk proteins, goat milk proteins contain higher levels of certain amino acids such as tryptophan and cysteine, while maintaining similar overall nutritional properties. They also exhibit superior functional properties including better emulsifying and foaming characteristics, making them attractive for developing functional food products. Immunologically, goat milk contains higher amounts of conjugated linoleic acids, playing important roles in immune stimulation, growth promotion, and disease prevention.

Nutrient	Goat milk	Cow milk	Clinical / nutritional note
Energy (kcal / 100 ml)	69	61	Slightly higher due to fat content
Total fat (g)	4.1	3.3	Higher MCT proportion aids absorption
MCT proportion of fat	~35%	~15%	Goat significantly higher; MCTs are rapidly metabolised
Protein (g)	3.6	3.2	Complete amino acid profile; higher Trp and Cys
β -casein : α s1-casein ratio	70 : 30	40 : 60	Goat closer to human milk; superior digestibility
Lactose (g)	4.2	4.7	Slightly lower; better tolerance in sensitive individuals
Conjugated linoleic acid	Higher	Lower	Immune stimulation, growth promotion, disease prevention
Fat globule size	Smaller	Larger	Smaller globules improve lipase access and digestion rate

2. Minerals and Vitamins: Goat milk contains higher calcium, magnesium, and phosphorus levels than cow milk, with particular relevance for bone health. Selenium concentrations are also elevated, supporting antioxidant immune function. Comparative profiling confirms higher concentrations of EPA and DHA, copper, magnesium, manganese, and iodine. However, goat milk contains lower levels of vitamin D, B12, and folate – an important consideration for clinicians advising exclusive or prolonged goat milk consumption.

Table 2. Selected vitamin and mineral comparison: goat milk vs cow milk. Sources: Gecaj et al. 2021; Lauková et al. 2022; comparative retail profiling data (Thibodeau et al. 2025):

Micronutrient	Direction vs cow	Relative level	Clinical relevance
Calcium (Ca)	Higher	↑	Bone density, nerve function
Magnesium (Mg)	Higher	↑	Muscle function, metabolic regulation
Phosphorus (P)	Higher	↑	Energy metabolism, skeletal mineralisation
Selenium (Se)	Higher	↑	Antioxidant defence, immune stimulation
Copper (Cu)	Higher	↑	Iron absorption, enzyme cofactor
Iodine (I)	Higher	↑	Thyroid function; caution at excessive intake
EPA / DHA (omega-3)	Higher	↑	Cardiovascular health, anti-inflammatory
Zinc (Zn)	Lower	↓	Immune defence, wound healing
Vitamin B12	Lower	↓	Neurological function; supplementation may be needed
Folate	Lower	↓	Cell division; critical in pregnancy
Vitamin D	Lower	↓	Bone metabolism, immune modulation
Vitamin A	Comparable	≈	Vision, epithelial integrity, immunity

Microbiology of Goat Milk

1. Native Microbial Communities: Modern next-generation sequencing has transformed understanding of goat milk microbiota. A landmark 2025 systematic review (Monareng et al.) identified Proteobacteria, Firmicutes, and Bacteroidetes as dominant phyla, with species such as *Bacillus* and *Pseudomonas* playing crucial roles in both fermentation and spoilage. Research from India (2024) found Firmicutes dominant at 67.47% relative abundance, with *Bacillus* as the leading genus at 28.32%. Seasonal dynamics add considerable complexity: *Listeria* spp. predominate in winter months, while *Staphylococcus* spp. dominate in warmer seasons – with direct implications for seasonal farm hygiene protocols and shelf-life modelling.

Milking and cleaning practices exert a measurable influence on microbiota composition. Research from Oregon State University (2025) demonstrated that differences in hygiene procedures at small-scale farms significantly altered the microbial quality of raw goat milk, underscoring the importance of standardised protocols even at the artisanal scale.

Table 3. Dominant bacterial phyla in raw goat milk and their functional roles. Based on pooled next-generation sequencing studies (Monareng et al. 2025; Thibodeau et al. 2025; ScienceDirect 2024). Values represent typical ranges; composition varies with season, breed, geography, and milking hygiene.

Bacterial phylum	Approx. abundance	Key genera	Role in goat milk
Firmicutes	~47%	<i>Bacillus</i> , <i>Lactobacillus</i> , <i>Staphylococcus</i>	Fermentation, spoilage, probiotic potential; dominant phylum
Proteobacteria	~28%	<i>Pseudomonas</i> , <i>Enterobacter</i>	Psychrotrophic spoilage; <i>Pseudomonas</i> linked to off-flavours
Bacteroidetes	~12%	<i>Bacteroides</i> , <i>Prevotella</i>	Commensal communities; environmental contaminants
Actinobacteria	~8%	<i>Corynebacterium</i> , <i>Brevibacterium</i>	Skin-associated flora; ripening microbiota in cheese
Other phyla	~5%	Diverse	Variable; environment- and season-dependent

2. Probiotic Potential of Lactic Acid Bacteria: One of the most exciting frontiers emerging from recent literature is the probiotic potential of lactic acid bacteria (LAB) native to goat milk. *Lactobacillus* is the predominant genus employed in goat milk fermentation, endowing products with gut microbiota regulation, anti-inflammatory and hypocholesterolaemic effects, antioxidant properties, hypotensive effects, and anti-obesity functions (Chen et al., 2023). Fermented goat milk maintains a better nutritional profile than fermented cow milk, with higher values of protein, minerals (Ca, Mg, Fe, Cu, Zn and Se), vitamins (A, D3 and B12), and certain fatty acids.

A 2023 screening study (Yang et al.) isolated 46 LAB strains from raw goat milk and identified *Enterococcus faecalis* and *Lactococcus lactis* strains with bacteriocin-like activity against *Staphylococcus aureus*, *Listeria monocytogenes*, and *Bacillus cereus*. Szopa et al. (2023) demonstrated that fermented caprine milk can serve as a suitable probiotic matrix, with *Lactobacillus rhamnosus* viability enhanced by collagen hydrolysate supplementation. Animal model studies (2024)

have begun exploring fermented goat milk's role in obesity prevention, with promising findings relating to adiposity modulation.

Table 4. Key lactic acid bacteria (LAB) genera in goat milk and their associated functional benefits. Sources: Chen et al. 2023; Yang et al. 2023; Szopa et al. 2023; Caponio et al. 2025.

LAB genus / species	Role in fermentation	Principal health benefit
<i>Lactobacillus</i> spp.	Acid production, flavour development	Gut microbiota regulation, hypocholesterolaemic, antioxidant, anti-obesity
<i>Lactococcus lactis</i>	Bacteriocin (nisin) production	Anti-pathogenic activity vs <i>Listeria</i> and <i>Staphylococcus</i>
<i>Enterococcus faecalis</i>	Bacteriocin production	Broad-spectrum antimicrobial; active vs <i>Bacillus cereus</i> and <i>Listeria</i>
<i>Streptococcus thermophilus</i>	Starter culture, yoghurt	Lactose tolerance improvement; proteolytic activity
<i>L. rhamnosus</i>	Probiotic vehicle	Gut homeostasis; improved survival during gastrointestinal transit
<i>L. plantarum</i> C4	Fermented milk production	Antioxidant activity; immune stimulation; >10 ⁷ CFU/ml viability after 5 weeks
<i>L. delbrueckii</i> subsp.	Yoghurt starter	Adiposity modulation in diet-induced obesity (murine, 2024)

3. Food Safety: Pathogens in Raw vs Pasteurised Milk: The enthusiasm for raw goat milk in certain wellness communities stands in stark contrast to the weight of microbiological evidence. Raw goat milk provides a favourable environment for pathogenic microbes including *Campylobacter*, *Salmonella*, *Yersinia*, *Listeria*, *Escherichia coli* O157, and *Staphylococcus aureus*. A study of raw goat milk samples in Rajasthan, India (2024) found a 36.36% incidence of bacterial pathogens, with *Listeria* spp. and *Staphylococcus* spp. emerging as the most prevalent. *Listeria monocytogenes* was detected in 3.75% of goat milk samples, and antimicrobial resistance was documented in *Bacillus cereus* and *Staphylococcus xylosum* isolates.

A 2023-2024 multi-state *Salmonella* Typhimurium outbreak in the United States – affecting 171 individuals across five states – was linked to commercially distributed raw dairy products, with the dairy voluntarily recalling its products one week after initial outbreak identification. Unpasteurised milk has also been documented as a vehicle for HPAI A(H5N1) virus in dairy cattle, adding an emerging zoonotic dimension to existing food safety concerns.

By contrast, a four-year Canadian surveillance study (CFIA, 2019-2023) of 699 pasteurised goat, sheep, and water buffalo milk samples found no *Salmonella* or *Listeria monocytogenes* in any tested sample, with 86.8% rated satisfactory overall – a compelling quantitative argument for thermal processing as the primary safety intervention.

Table 5. Major pathogenic microorganisms of concern in raw goat milk, with associated diseases, risk severity, and pasteurisation efficacy. Sources: CDC 2023; CFIA 2024; FDA guidance; Sepahvand et al. 2022.

Pathogen	Associated disease	Severity	Pasteurisation note
<i>Listeria monocytogenes</i>	Listeriosis, meningitis, miscarriage	High	Effectively eliminated at standard pasteurisation temperatures
<i>Salmonella</i> spp.	Salmonellosis, enteric fever	High	Destroyed by pasteurisation; linked to 2023-2024 US outbreak (raw)
<i>E. coli</i> O157:H7	Haemolytic uraemic syndrome, bloody diarrhoea	High	Heat-sensitive; eliminated by pasteurisation
<i>Campylobacter jejuni</i>	Campylobacteriosis, Guillain-Barré syndrome	High	Heat-labile; consistently eliminated
<i>Brucella melitensis</i>	Brucellosis, endocarditis, hepatic abscess	High	Pasteurisation highly effective; zoonotic risk from raw milk
<i>Staphylococcus aureus</i>	Food poisoning, toxic shock syndrome	Moderate-High	Bacteria killed but heat-stable toxins may persist
<i>Bacillus cereus</i>	Emetic / diarrhoeal syndrome	Moderate	Spores survive pasteurisation; risk from post-process recontamination
<i>Cryptosporidium</i> spp.	Cryptosporidiosis, profuse diarrhoea	Moderate	Destroyed by pasteurisation; oocysts resistant to some disinfectants

Safety Comparison: Raw vs Pasteurised Goat Milk

Raw goat milk: 36.4% pathogen incidence (*Listeria* + *Staphylococcus* predominant; India, 2024) vs Pasteurised goat milk: 0% *Salmonella*, 0% *L. monocytogenes* detected across 699 samples (Canada, 2019-2023). Pasteurisation remains the single most effective intervention for eliminating milk-borne pathogens.

Research Outlook and Future Directions

The next phase of goat milk research will be defined by methodological sophistication. A 2025 systematic review (Monareng et al.) identified the need for enhanced multi-omics techniques, given challenges including host RNA and protein interference, low microbial biomass, and limited goat-specific reference databases. Integration of metagenomics, metabolomics, metaproteomics, and metatranscriptomics is recommended to optimise probiotic development, spoilage prevention strategies, and overall milk quality and safety.

On the clinical nutrition front, the health claims surrounding goat milk – while biologically plausible – require more robust human intervention trials to satisfy regulatory nutritional standards. The fermented goat milk sector is expanding rapidly, with 2024 studies exploring applications in obesity prevention and gut microbiota modulation. Breed-specific compositional differences, the influence of pasture-based versus intensive feeding systems, and geographic variation in microbial communities remain underexplored areas offering significant research opportunity.

Conclusion

Goat milk occupies a fascinating intersection of ancient practice and cutting-edge science. The literature of the past five years has meaningfully advanced understanding across three axes: confirming and extending the nutritional advantages of goat milk over bovine counterparts (particularly in digestibility, mineral richness, and fatty acid profile); uncovering a rich and dynamic microbial ecology with real probiotic applications; and reinforcing the non-negotiable importance of pasteurisation as a public health safeguard against a catalogue of serious pathogens. As multi-omics approaches become more accessible and clinical trial infrastructure improves, the coming decade promises to resolve many remaining questions about one of the world's oldest food sources.

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From Tiny Sprouts to Trillion-Rupee Dreams: The Silent Revolution in Indian Seed Production

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Dr. K. Lakshmiprasanna¹

¹Assistant Professor, Department of Seed Science and Technology, SRTC, PJTAU, Rajendranagar-030.

Today, India's seed sector is witnessing a remarkable transformation. What was once largely dependent on traditional farmer-saved seeds has now evolved into a dynamic, technology-driven industry. The Indian seed market, currently valued at more than 4.5 billion dollars, is projected to reach nearly 7 billion dollars by 2030. India is now ranked among the top seed-producing nations in the world and is steadily emerging as a global hub for quality seed production and exports.

Seeds Meet Science and Technology

Modern seed production is no longer confined to sowing, harvesting, and processing. It has become a highly specialized scientific enterprise where precision and genetic purity are of utmost importance. Advanced technologies such as drones and remote sensing are increasingly being used in seed production fields. These drones help identify rogue plants, or off-type plants, that may reduce the genetic purity of seed lots. By detecting such plants early, seed producers can maintain high-quality standards.

Artificial Intelligence is also entering the seed sector. AI-based systems are now capable of predicting germination potential, monitoring seed health, and managing supply chains efficiently so that seeds reach farmers at the right time before the onset of monsoon rains.

Another fascinating development is robotic pollination. In hybrid seed production, pollination is a critical and labor-intensive operation. Researchers and companies are experimenting with robotic systems that can assist in precise pollination, especially in crops where labor shortages are becoming a major challenge.

Climate-Resilient Seeds for Changing Weather

Today, agricultural universities, the Indian Council of Agricultural Research (ICAR), and private seed innovators are essentially engineering survival gear for plants. They are breeding new crop varieties that can withstand intense heat, survive prolonged droughts, and even hold their breath underwater during sudden floods. Scientists are also focusing on short-duration crops that grow fast, allowing farmers to harvest and beat unpredictable weather before it strikes. But it's not just about survival it's about health. New biofortified seeds are being packed with essential nutrients like iron, zinc, and vital vitamins, tackling hunger and malnutrition at the exact same time.

Towards Sustainable Seed Production

Sustainability is now becoming a central theme in modern agriculture, and the seed sector is also adapting to eco-friendly practices. Traditionally, chemical seed treatments were widely used to protect seeds from pests and diseases. However, many seed companies are now shifting towards biological seed treatments that utilize beneficial microorganisms and bio-inoculants. These eco-friendly treatments not only protect seedlings from soil-borne pathogens but also enhance nutrient uptake and plant vigor. Water-saving technologies are also gaining momentum. Seed production farms are increasingly adopting drip irrigation systems, which can significantly reduce water consumption while maintaining productivity. Such sustainable approaches are essential for conserving soil health, water resources, and environmental quality for future generations.

Challenges Before the Seed Industry

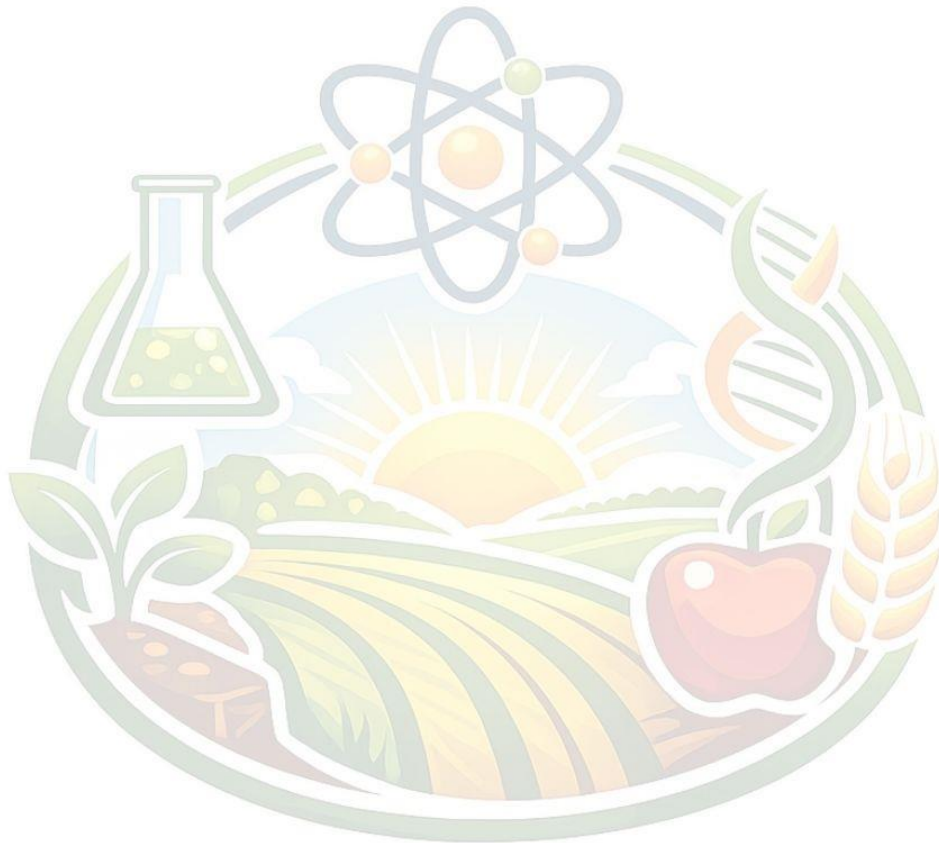
1. Smallholder farmers often lack objective data on which seeds suit their specific soil and microclimate, leaving them dependent on local dealers who push brands based on their own profit margins.
2. High-value seed crops require rapid, precise drying immediately after harvest to remain viable. However, frequent rural power outages and fuel shortages often cause entire batches to rot at the farm gate.
3. The widespread sale of fake or substandard seeds packaged in counterfeit branding leads to massive crop failures. Legal recourse for farmers is slow and heavily weighted against them.
4. While public laboratories develop breakthrough climate-smart and biofortified seeds, weak distribution networks in remote and dryland regions prevent these innovations from reaching the farmers who need them most.

India's Global Seed Ambitions

India possesses enormous potential in seed production due to its diverse agro-climatic conditions. The country can produce seeds of a wide range of crops under different environmental conditions. Coupled with comparatively low production costs and skilled manpower, this gives India a strong competitive advantage in the global seed market. Currently, India exports seeds to more than 100 countries across Asia, Africa, and Latin America. The nation is now aiming to increase its seed exports substantially in the coming years.

As India moves forward in its journey towards agricultural modernization, the seed industry will play a central role in ensuring food security, nutritional security, and farmers' prosperity. The future of agriculture does not merely depend on machinery or chemicals it begins with a healthy, vigorous seed.

Indeed, the tiny seed has become the foundation of India's trillion-rupee agricultural dreams.

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Eco-Friendly Mulches for Healthier Vegetable Gardens

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Debiya Leitanthem¹, Osi Siram²

¹Ph.D. Research Scholar, Department of Horticulture (Vegetable Science), College of Agriculture, Central Agricultural University, Imphal-795004, Manipur.

²Ph.D. Research Scholar, Department of Agronomy, College of Agriculture, Central Agricultural University, Imphal-795004, Manipur.

Introduction: Role of Mulching in Sustainable Vegetable Production

Organic vegetable farming involves management of numerous of production factors out of which organic mulch plays an important role in soil fertility and sustainability. The term "mulch" originates from a Germanic word meaning "soft to decay" which outwardly described the practice of covering soil with organic matter and agricultural waste, such as straw, leaves, compost, and grass clippings. Mulch refers to any layer of organic plant remains or synthetic materials spread over the soil surface (Ranjan *et al.*, 2017). So, mulching is a traditional practice that helps retain soil moisture, suppress weeds, regulate soil temperature and create a beneficial microclimate for plants. This technique is especially valuable in horticulture, where it promotes better growth, development and yields while serving as an effective method for conserving soil and water (Barche *et al.*, 2015). The application of organic mulches mitigates soil erosion and stabilizes soil temperature while providing a sustained release of nutrients through gradual decomposition. Additionally, these materials enhance the broader landscape ecosystem by suppressing pathogens and pests, fostering beneficial soil biota and neutralizing environmental contaminants.

Environmental Concerns Associated with Synthetic Mulches

Vegetable farming has evolved from using basic black, clear and white mulches to a broader palette of black, white, green, brown, red, silver and blue films, each coloured to enhance light absorption and crop growth (Amare and Desta, 2021). Although plastic mulches provide more advantages for vegetable mulching than the organic mulches, it is not considered environmentally friendly. Continuous reliance on polyethylene-based horticultural mulch films has generated significant environmental pollution regarding long-term plastic contamination. Some of the most widely used non-biodegradable plastic mulches include regular polyethylene (PE), low-density polyethylene (LDPE), linear low-density polyethylene (LLDPE) and high-density polyethylene (HDPE) (Madrid *et al.*, 2022). Plastic mulches affects the soil microclimate and soil temperature eventually damaging the soil micro-organisms Beneath the soil, large plastic mulch fragments are broken down into microplastics (1 to 100 µm) and nanoplastics (less than 1 µm). This degradation is driven by microbial activity, chemical erosion from acids and alkalis, and mechanical damage from animals chewing and swallowing the debris. The accumulation of microplastics in soil directly and indirectly impairs crop growth and development. Mechanically, these particles adhere to seed coats and seedling root systems which can inhibit crucial processes like water absorption and respiration, thereby disrupting early germination and bud development. Additionally, polyethylene microplastics alter the surrounding soil matrix and impact soil biota, creating indirect ecological pressures that further compromise plant health (Qiang *et al.*, 2023).

Types and Sources of Eco-Friendly Organic Mulches

Organic mulches are mainly of two types. The first one is the live mulch which uses a living cover crop and consists of grasses like perennial ryegrass (*Lolium perenne* L.), cereals particularly rye (*Secale cereale* L.) and various legumes, including white clover (*Trifolium repens* L.), red clover (*Trifolium pratense* L.), hairy vetch (*Vicia villosa* Roth.) and serradella (*Ornithopus sativus* Brot.). These are mostly used for perennial vegetables like rhubarb and transplanted ones like tomato, chilli, cabbage etc. Ideal living mulches are characterized by rapid emergence, quick ground cover, short height, low water and nutrient demands (Barche *et al.*, 2015). The second one is the dead much or the organic mulch which are derived from natural origin materials and can decompose easily naturally. Examples are bark chips, mushroom waste, grass clippings, wheat or paddy straw, plant leaves, compost, rice hulls, sawdust etc. These mulches are particularly efficient at mitigating soil temperatures. Furthermore, their gradual decomposition supplements minor quantities of nutrients to the soil and sustains the soil microbial community responsible for enhancing soil structure.

Impact of Organic Mulches on Soil Fertility and Yield

1. Temperature Regulation & Water Conservation- Mulches blocks sunlight penetration and preventing the sun from overheating the soil and helping to maintain an ideal soil temperature. It also reduces water evaporation by shielding the soil surface from direct sunlight.

2. Weed Control & Erosion Protection- It suppresses weeds as the physical barrier of mulch blocks light from reaching the soil which prevents weed seeds from germinating and growing. Without oxygen and moisture, the weeds dry up and

eventually die. Mulch protects the soil surface from being washed away by heavy rain or blown away by strong winds preventing soil erosion. Moreover, it enhances infiltration by slowing down rainwater runoff, and increasing overall soil moisture for plants.

3. Soil Improvement- As organic mulches slowly decompose, they add organic matter and carbon to the soil. This keeps the soil loose and fragile, which promotes deeper root penetration and better nutrient uptake. The decaying material provides food for beneficial microorganisms and earthworms.

4. Yield boost- As vegetable crops are heavy nutrient feeders for good yield, decaying of organic mulches provides additional nutrients and live mulches especially the legumes help in supplying Nitrogen for healthy vegetative growth. This ultimately leads to increasing yield of vegetables with organic mulching. The yield of tomato and okra increased by 100 and 200 % in straw mulch (6 t/ha) applied condition than over control treatment (Gupta and Gupta, 1987).

Conclusion

The adoption of on-farm organic mulches including crop residues, composted leaves and alternative organic waste should be promoted as a sustainable agricultural practice. Because these materials are inexpensive byproducts that would otherwise be discarded, they represent a highly cost-effective option for the farmers. Organic mulches deliver agronomic benefits to vegetable production comparable to those of synthetic plastics, but without the associated environmental degradation. Consequently, there is immense potential to expand organic mulching to enhance crop yields while simultaneously conserving soil and water resources. The farmers should be made aware of the multiple benefits of organic mulches along with the detrimental effects of plastic mulches. Vegetable farmers should be advised to use organic mulches and cover crops (legumes) for sustaining soil health and improving soil properties.

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Top Working in Mango

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Dr. D. Rajani¹

¹Assistant Professor, College of Agriculture, Rajendranagar, PJTAU.

The most of the mango orchards in South India are old unproductive and of seedling origin. The productivity of these orchards is very low. The selected unproductive trees desired to be top worked are headed back in February-March. Trees are prepared for grafting by sawing the branches off in July, thus enabling the new growth to benefit from the spring surge. All the branches are cut at a height of 1 to 1.5 metres above the ground. Other activities like basins and irrigation channels should be prepared. Mulching should be done around the basins.

Full dose of single super phosphate (3.00 kg/tree) and half dose of urea (1.25 kg per tree) in basins should be applied at the end of February. Careful observation for infestation of stem borer insect pest in trees should be taken care. The cut ends are treated with Bordeaux paste. Many shoots emerge within a short time below the stubs. Out of these, 3-4 vigorous shoots per branch or limb are selected and remaining are removed in June-July with outwardly growth per pruned branch should be retained. Plant should be protected from the incidence of different diseases and pests.

These shoots make fast growth and reach a suitable thickness (pencil). These suitable for grafting by August-September of the same year. Select the best sprouts of each stub and graft them with the desired cultivar. Wedge grafting on selected apical stock-shoots of beheaded tree to be undertaken within 5-10 weeks period, when copper red leaves of new stock-shoots turned to green colour, coupled with 5-10 mm diameter of stock. A matured scion stick of same size was selected for grafting.

After the graft union is wrapped tightly with PVC tape, the graft should also be wrapped up tightly with this tape. New grafted plant must be secure from die-back disease, over exposed to sunlight, pest and disease. About three months after grafting, it will be noticed that the eye is starting to swell under the tape. When this eye presses against the tape, a small opening is made with a razor blade so that the eye can grow out. This should not be done too early. Usually only one eye will sprout, but if more begin to swell, they are treated in the same manner.

The wrapping tape is removed gradually, after the sprout has grown out properly from the scion and the leaves are already green. Vigorous shoots should be pruned from branch. About six months after grafting, the best and strongest shoots are selected and the weaker ones removed or corrected by pruning. Four new branches are selected for future development into the main scaffolding. Top-worked trees come into bearing within three years, depending upon the grafted cultivar. Unsuccessful grafts are removed and regrafted.

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Dynamic Temporal Agronomy: Time-Synchronized Input Pulsing Strategies for Oilseed Crop Productivity under Variable Climate Regimes

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Kumar Raj¹, Vishal Sharma², Rajesh Singh³, Akankhya Pradhan⁴

¹Ph.D. Scholar, Department of Agronomy, Naini Agricultural Institute, SHUATS, Prayagraj 211007, Uttar Pradesh, India.

²Young Professional, Division of Environmental Sciences ICAR-IARI, New Delhi.

³Professor, Department of Agronomy, Naini Agricultural Institute, SHUATS, Prayagraj 211007, Uttar Pradesh, India.

⁴Ph.D. Scholar, Department of Agronomy, Naini Agricultural Institute, SHUATS, Prayagraj 211007, Uttar Pradesh, India.

Abstract

Oilseed production systems are increasingly exposed to erratic rainfall, terminal heat, altered evaporative demand, and rising input costs, yet field agronomy still relies heavily on fixed calendar schedules for irrigation, fertilization, and crop protection. This article develops the concept of Dynamic Temporal Agronomy (DTA), an agronomic framework that treats timing as a primary management variable and synchronizes input pulses with crop phenology, short-term climate signals, and soil resource dynamics. Evidence from recent literature on precision sensing, real-time nitrogen management, phenology-aware decision support, water-saving technologies, and oilseed-specific nutrient responses indicates that the effectiveness of inputs depends not only on dose but also on the temporal match between demand and delivery. DTA therefore proposes stage-specific micro-pulsing of water, nitrogen, sulfur, and foliar or biostimulant inputs, guided by thermal time, soil moisture thresholds, nutrient status, and weather forecasts. The framework is especially relevant for rapeseed-mustard, soybean, sunflower, and groundnut, where reproductive stages show strong sensitivity to stress and where asynchronous nutrient or water supply can reduce oil accumulation, nutrient-use efficiency, and economic returns. This paper synthesizes global and Indian oilseed production trends, formulates practical synchronization indicators, presents a crop-stage matrix for field deployment, and outlines a research agenda linking DTA with sensors, variable-rate technologies, crop models, and climate advisories. Rather than replacing sound agronomy, DTA reorganizes it around the question of exactly when to apply each input for maximum productivity, resilience, and resource-use efficiency.

Keywords: oilseeds; rapeseed-mustard; soybean; groundnut; sunflower; precision agronomy; phenology; nitrogen timing; irrigation scheduling; climate-smart agriculture.

Introduction

Oilseeds occupy a strategic position in food systems because they supply edible oil, protein-rich meal, industrial feedstocks, and farm income. FAO reported that oil crops were among the fastest-growing primary crop groups and that global oil-crop production reached about 1.2 billion tonnes in 2024, with major gains since 2010 driven especially by oil palm fruit and soybean expansion. FAO also reported rapeseed production at roughly 92 million tonnes in 2023, underscoring the continuing global importance of Brassica oilseeds.

Recent market intelligence further shows the continued dominance of soybean among major traded oilseeds. USDA's April 2026 oilseed outlook lists MY 2024/25 soybean production at 428.15 million metric tons, rapeseed at 86.24 million metric tons, and sunflowerseed at 53.01 million metric tons. In India, FAS New Delhi projected MY 2024/25 total oilseed production at 42.9 million metric tons, with soybean at 12.9 MMT, rapeseed-mustard at 11.7 MMT, and groundnut at 7.2 MMT.

Despite the strategic importance of oilseeds, field management is still commonly organized through static calendars: basal fertilizer at sowing, one or two topdressings at predetermined intervals, and irrigation by fixed turns or accumulated farmer experience. Such approaches work only when seasonal weather and crop development follow predictable trajectories.

This mismatch between crop demand and input timing is agronomically important because oilseed crops are highly stage-sensitive. Rapeseed and mustard often respond strongly to nitrogen and sulfur synchronization; groundnut responds to moisture and calcium availability during pegging and pod development; soybean depends on synchronized canopy retention, biological nitrogen fixation, and reproductive moisture availability; and sunflower is sensitive to water deficits during head development and grain filling.

The present article develops Dynamic Temporal Agronomy (DTA) as a new agronomic perspective for oilseed systems. DTA is defined here as the design of small, strategically timed input pulses that are synchronized with phenological stages, weather signals, and soil resource dynamics in order to maximize the overlap between supply and crop demand.

Why is a Time-Synchronized Paradigm Needed?

The first argument for DTA is physiological. Oilseed crops do not consume water and nutrients at a constant rate across their life cycle. Demand curves are dynamic, and critical windows often account for a disproportionate share of final yield and oil quality.

The second argument is resource efficiency. Reviews on real-time nitrogen monitoring show that sensors, GIS-GPS integration, variable-rate technologies, and crop models can improve the precision of nitrogen use while reducing waste and environmental losses. A recent systematic review of 51 studies concluded that precision agriculture significantly improves nutrient-use efficiency and yields, while sensor and IoT reviews show that continuous soil and crop monitoring now enables targeted irrigation and fertilization.

The third argument is risk management. Under variable climate regimes, the economic penalty from a mistimed operation can be greater than the penalty from a moderate under-dose.

Conceptual Architecture of Dynamic Temporal Agronomy

Dynamic Temporal Agronomy is based on four linked principles. First, time must be treated as an explicit agronomic input rather than as an implicit background condition. Second, all major input decisions should be tied to phenological state and not merely to days after sowing. Third, climate signals should modify timing rules in real time. Fourth, management should operate in pulses—small, deliberate applications or actions—rather than inflexible seasonal blocks.

The DTA cycle begins with signal capture: short-range weather forecasts, rainfall probabilities, accumulated growing degree days, soil moisture thresholds, mineral nitrogen status, or canopy proxies such as NDVI and chlorophyll indices. These signals are interpreted relative to the crop stage. A decision engine then selects the next pulse in terms of type, amount, and placement. The crop response is subsequently monitored and used to revise the next pulse.

Agronomic Mechanisms Underpinning DTA

Phenology alignment. Calendar dates do not provide physiological equivalence across seasons. A crop sown 10 days later under warmer conditions may reach flowering sooner than expected, whereas cold spells may delay development despite elapsed days. Phenology-aware management therefore uses thermal time, node or leaf stage, canopy closure, flowering initiation, or pod-fill onset to align operations with actual developmental status.

Nutrient synchronization. Nitrogen and sulfur timing is especially critical in Brassica oilseeds. A 2023 meta-analysis on winter oilseed rape concluded that fertilizer management was the most important factor governing the effectiveness of nitrogen application and recommended either controlled-release basal N or a combination of basal and topdressed N. A three-year experiment in winter oilseed rape also showed that sulfur should be synchronized with nitrogen because both nutrients jointly govern physiological performance and yield formation.

Moisture synchronization. Water deficits do not carry equal penalties at all stages. Moisture stress at flowering, pod set, or seed filling commonly damages sink formation, assimilate transport, and final oil deposition more severely than comparable deficits in earlier vegetative phases.

Placement and pulse size. DTA favors smaller but better-positioned pulses when the probability of efficient uptake is high. Root-zone or banded placement can reduce losses and improve synchronization. A 2026 study showed that root-zone N fertilization increased oilseed rape yield while reprogramming rhizosphere N cycling and strengthening soil-plant coupling.

Sensing and feedback. Reviews now show that proximal sensing, UAVs, IoT-connected sensors, and real-time nitrogen diagnostics enable repeated mid-season decisions.

Technology Layer for Operationalizing DTA

DTA is conceptually simple but operationally strengthened by digital tools. Proximal sensing and precision-agriculture reviews show that multispectral, hyperspectral, and ground-based devices are increasingly able to diagnose canopy condition, chlorophyll status, biomass, and stress. Sensor-IoT integration further enables near-continuous monitoring of soil moisture, EC, pH, and microclimate.

For nitrogen management, recent reviews indicate that leaf color charts, optical sensors, UAV imagery, variable-rate technologies, and crop models collectively support real-time N decisions. Similar logic applies to irrigation, where telemetry-linked soil-moisture sensors and weather forecasts can convert irrigation from a turn-based to a threshold- and stage-based intervention.

In oilseed rape specifically, recent work has demonstrated imagery-supported N recommendation frameworks, including in-season variable-rate topdressing supported by UAV multispectral imagery.

Constraints and Practical Caveats

The DTA framework is not free of constraints. Reliable temporal agronomy depends on timely information, and many farmers still face weak access to local weather forecasts, calibrated sensors, or laboratory diagnostics.

Temporal optimization can also increase management complexity. More frequent but smaller interventions may raise transaction costs unless supported by mechanization, fertigation, or coordinated custom-service provision.

Finally, DTA must be interpreted as a decision framework rather than a rigid recipe. The exact pulse strategy will differ among irrigated rapeseed, rainfed mustard, post-rainy groundnut, and soybean grown under monsoon uncertainty.

Production Context and Strategic Relevance

Table 1. Selected production context for oilseed systems using recent FAO and USDA/FAS sources:

Indicator	Value	Period	Implication for DTA
Global oil-crop production	≈1.2 billion t	2024	Large sectoral scale justifies precision gains in timing and efficiency.
Global rapeseed production	≈92 million t	2023	Rapeseed remains a major target crop for timing-sensitive nutrient and water management.
Selected production soybean	428.15 million t	MY 2024/25	Soybean dominates oilseed markets and sets the benchmark for productivity gains.
Selected production rapeseed	86.24 million t	MY 2024/25	Supports focus on time-sensitive N, S, and water strategies.
Selected production sunflowerseed	53.01 million t	MY 2024/25	Highlights broader applicability of DTA beyond Brassica crops.
India total oilseed output	42.9 million t	MY 2024/25	Improved timing can contribute to edible-oil self-reliance and profitability.

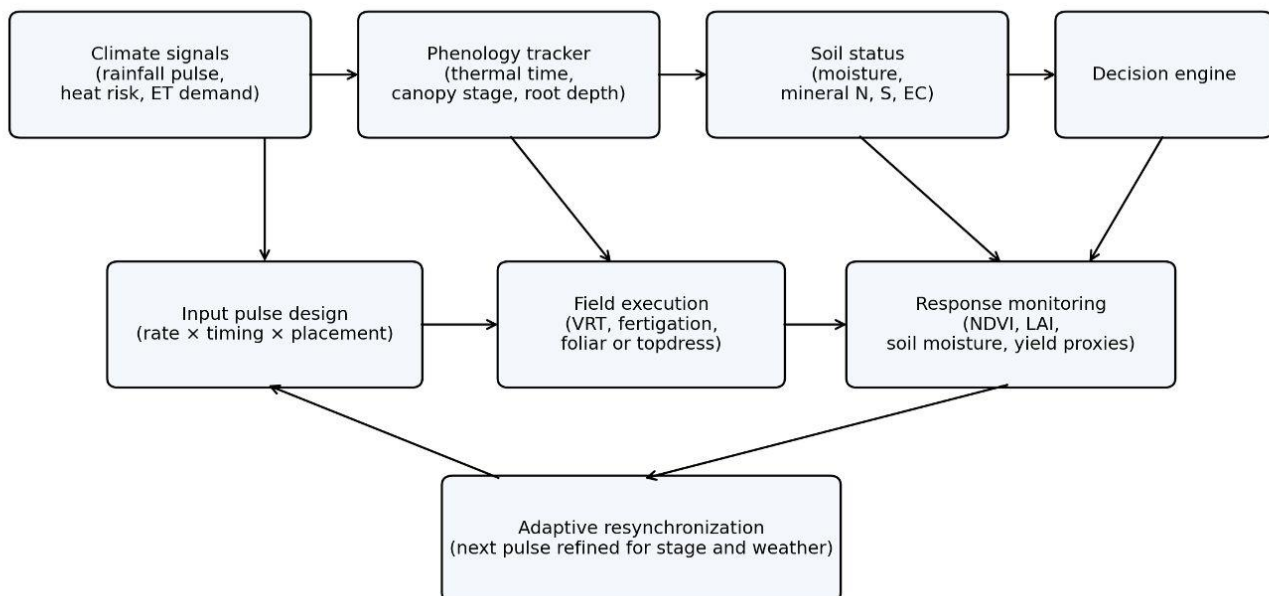


Figure 1. Proposed Dynamic Temporal Agronomy framework for time-synchronized input pulsing in oilseed systems.

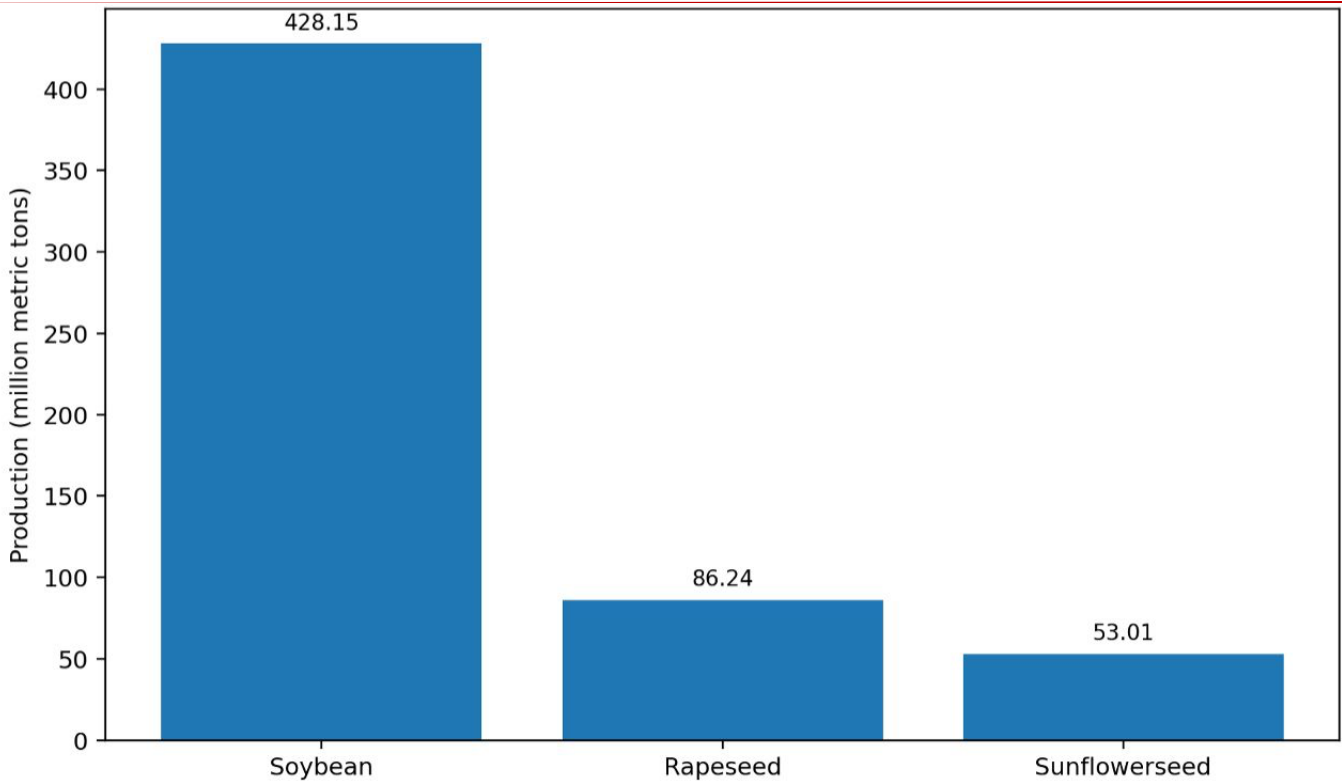


Figure 2. Selected global major oilseed production in MY 2024/25.

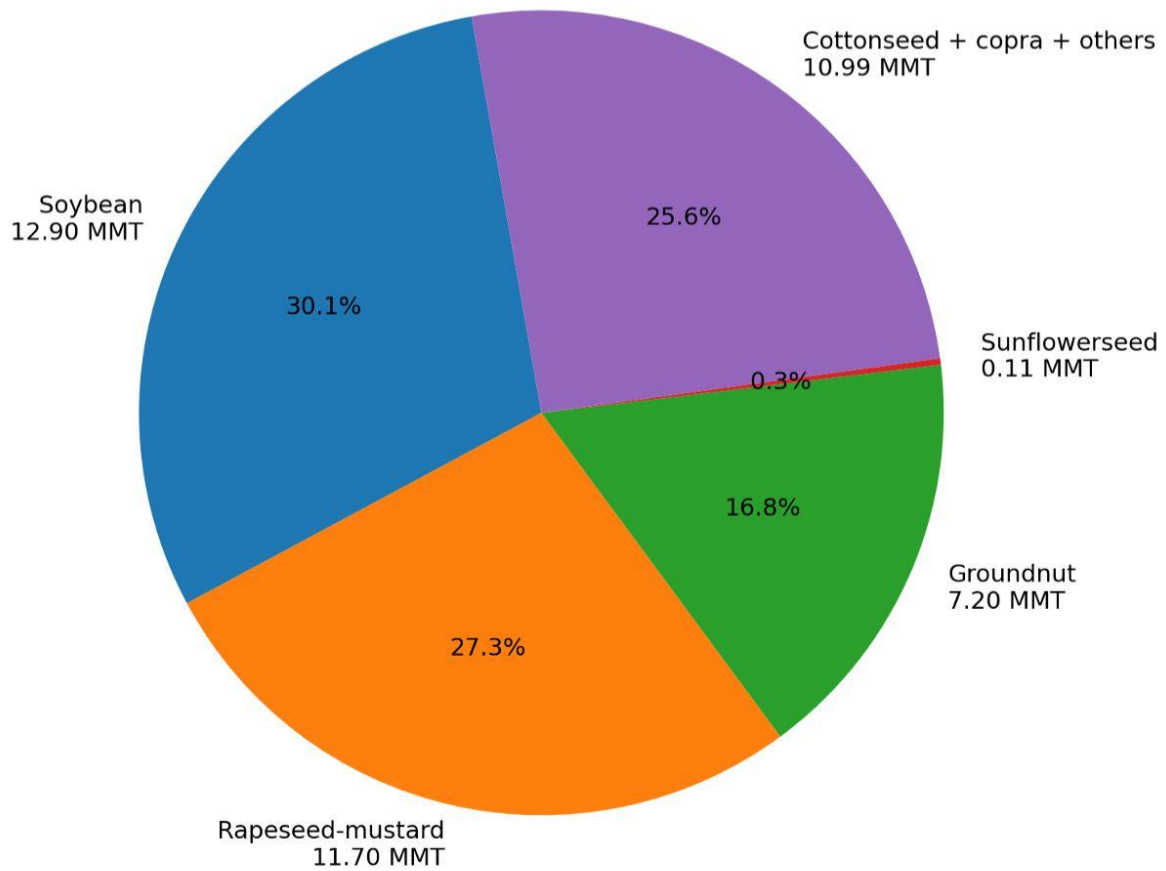


Figure 3. Illustrative composition of India's MY 2024/25 oilseed output.

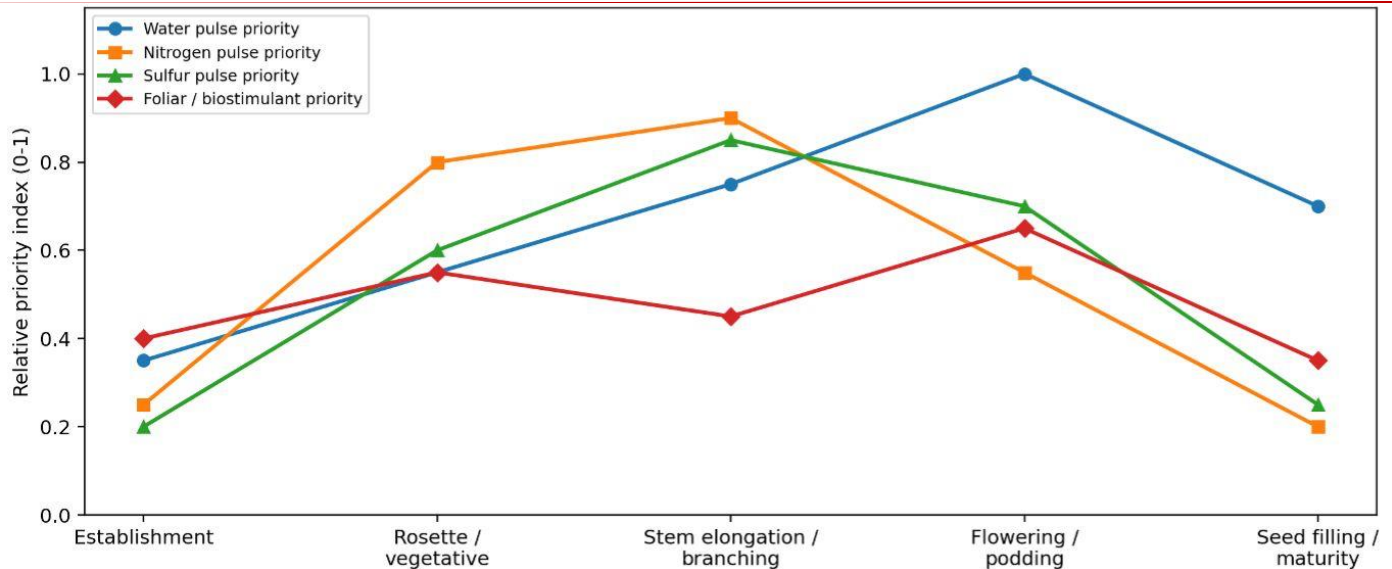


Figure 4. Illustrative pulse-priority windows across oilseed growth stages.

1. Growing Degree Days (GDD): $GDD = \sum [(T_{max} + T_{min}) / 2 - T_{base}]$
2. Crop Water Productivity: $WP = Y / ET_a$
3. Agronomic Nitrogen Use Efficiency: $ANUE = (Y_N - Y_0) / N_{applied}$
4. Synchronization Index: $SI = \sum (D_t \times S_t \times C_t) / n$

Stage-Specific Input Pulsing in Major Oilseed Crops

Table 2. Illustrative stage-wise input pulsing matrix for selected oilseed crops:

Crop / stage	Primary physiological target	Candidate pulse	Timing cue	Expected benefit
Rapeseed-mustard: rosette to stem elongation	Rapid canopy expansion, branch and sink establishment	Split N + S pulse; optional micronutrient correction	Thermal-time threshold plus soil moisture adequacy	Higher NUE and stronger reproductive capacity
Rapeseed-mustard: early flowering to pod set	Pollination, pod retention, assimilate support	Moisture pulse; foliar rescue only if diagnosed	Forecasted heat event or dropping root-zone moisture	Reduced pod abortion and better seed set
Soybean: vegetative to early reproductive	Canopy retention and reproductive transition	Moisture pulse; corrective nutrition only under deficiency	Flower initiation and rainfall gap > critical threshold	Improved pod initiation and reduced flower drop
Groundnut: pegging to pod development	Peg penetration and pod filling	Moisture pulse; calcium or gypsum placement where appropriate	Pegging onset and light-textured soil drying	Improved pod filling and harvest quality
Sunflower: bud initiation to grain filling	Head development and oil deposition	Deficit-avoidance irrigation pulse; stage-specific nutrient support	High VPD or low available soil water during reproductive stage	Stabilized achene set and oil accumulation

Future Research Priorities and Multidimensional Optimization in Dynamic Temporal Agronomy (DTA)

Future research on Dynamic Temporal Agronomy (DTA) should prioritize rigorously designed multi-environment experiments that compare conventional calendar-based scheduling with stage-synchronized input pulsing across diverse and contrasting climate regimes, while simultaneously advancing beyond dose-centric approaches toward the joint optimization of pulse timing, pulse size, and input placement. Integrating process-based crop models with short-term weather forecasting systems can enable event-based, real-time agronomic advisories that enhance decision precision under climatic uncertainty. In parallel, there is a critical need to develop and validate low-cost, scalable threshold indicators suitable for smallholder systems—such as soil tactile assessment, tensiometers, leaf color charts, and probabilistic rainfall cues—to democratize access to temporal precision. Importantly, future evaluations of DTA should extend beyond seed yield to include comprehensive performance metrics such as oil content, fatty-acid composition,

nutrient-use efficiency, water productivity, and overall farm profitability, ensuring that the framework delivers multidimensional agronomic, economic, and quality benefits.

Conclusion

Dynamic Temporal Agronomy provides a useful agronomic lens for redesigning oilseed management under climate variability. Its novelty lies not in introducing a new input, but in reorganizing agronomic decision-making around temporal fit: matching water, nutrients, and supplementary inputs to the moments when crops can use them most effectively and when the environment is least likely to dissipate them.

Evidence from recent work on precision sensing, real-time nitrogen management, sulfur synchronization, oilseed-specific nutrient responses, and adaptive irrigation supports the central proposition that timing strongly conditions input effectiveness.

For oilseed crops, especially rapeseed-mustard, soybean, groundnut, and sunflower, time-synchronized pulsing can improve productivity, efficiency, and resilience simultaneously.

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Silent Decline of Pollinators: A Growing Threat to Indian Agriculture

Article ID: 73757

Rittik Sarkar¹

¹Department of Entomology and Agricultural Zoology, Institute of Agricultural Sciences, Banaras Hindu University, Varanasi 221005, India.

Abstract

Pollinators are indispensable components of agricultural and natural ecosystems, contributing significantly to crop productivity, biodiversity conservation, and ecological stability. In India, nearly 75% of flowering plants and a substantial proportion of food crops depend directly or indirectly on insect mediated pollination for successful reproduction and yield enhancement (IPBES, 2016). However, recent decades have witnessed an alarming decline in pollinator diversity and abundance due to habitat destruction, indiscriminate pesticide use, climate change, air pollution, invasive species, diseases, and artificial light pollution. This emerging pollination crisis poses serious threats to food security, nutritional quality, ecosystem resilience, and rural livelihoods. Pollinator decline affects major agricultural crops including fruits, vegetables, oilseeds, pulses, spices, and plantation crops, thereby influencing both productivity and economic sustainability. India, despite being a mega-biodiverse country, still lacks sufficient pollinator research, monitoring programmes, and policy level interventions for long-term conservation. Recent innovations including floral interventions, habitat restoration kits, smart beehives, AI-based pollinator monitoring systems, and pollinator friendly agricultural practices are offering new opportunities for conservation and sustainable crop production. This article highlights the causes, impacts, and future conservation strategies associated with pollinator decline in India and emphasizes the urgent need for integrated approaches involving farmers, researchers, policymakers, and local communities to safeguard pollinator diversity and agricultural sustainability.

Keywords: Pollinators, pollination crisis, honey bees, biodiversity, pesticides, climate change, food security, pollinator conservation.

Introduction

Pollination is one of the most vital ecological services sustaining global agriculture and biodiversity. The transfer of pollen grains from anther to stigma ensures fertilization, seed formation, fruit development, and genetic continuity in flowering plants. Although pollination can occur through wind, water, and animals, insects remain the most efficient and dominant pollinators in terrestrial ecosystems (Adit *et al.*, 2024).

India, being an agrarian economy, depends heavily on pollinator mediated agriculture. Crops such as mustard, sunflower, apple, almond, cucurbits, pigeon pea, coffee, cardamom, and numerous fruits and vegetables rely substantially on insect pollination for higher yield and improved quality. Globally, nearly 75% of food crops depend on animal pollination, while insect pollinators contribute significantly to the reproduction of around 87.5% of flowering plants (IPBES, 2016; Ollerton *et al.*, 2011).

The economic value of pollination services in India is enormous. Animal pollinated crops contribute nearly ₹4.23 lakh crores to Indian agriculture, accounting for around 32.7% of total agricultural value, while direct insect pollination alone contributes nearly ₹1.13 lakh crores (Chaudhary and Chand, 2017). Beyond crop productivity, pollinators also support ecosystem functioning, biodiversity maintenance, and nutritional security.

Despite their ecological and economic importance, pollinator populations are declining rapidly across the world. India is also witnessing a silent decline in bees, butterflies, hoverflies, moths, beetles, and other beneficial pollinating insects due to increasing anthropogenic disturbances. Habitat destruction, pesticide misuse, climate variability, air pollution, invasive species, diseases, and changing agricultural practices are collectively intensifying the pollination crisis (Potts *et al.*, 2010).

Major Insect Pollinators in India

India supports a rich diversity of insect pollinators belonging mainly to the orders Hymenoptera, Lepidoptera, Diptera, and Coleoptera. Honey bees (*Apis cerana*, *Apis mellifera*), bumble bees (*Bombus* spp.), carpenter bees (*Xylocopa* spp.), butterflies, moths, hoverflies, wasps, and beetles are among the major pollinators contributing to agricultural and ecological sustainability (Thakur, 2023).

Among these, honey bees are considered the most efficient pollinators because of their social behaviour, floral fidelity, and large foraging range. Wild pollinators also play an equally important role by complementing managed bee populations and stabilizing pollination services under varying environmental conditions (Garibaldi *et al.*, 2013).



Figure: Honey bees play a crucial role in enhancing pollination and productivity of agricultural crops.

Causes of Pollinator Decline

Indiscriminate Use of Pesticides: Excessive and unscientific use of pesticides is one of the leading causes of pollinator decline globally. Neonicotinoids, organophosphates, carbamates, pyrethroids, and other insecticides adversely affect pollinator survival, behaviour, memory, immunity, and reproductive performance (Henry *et al.*, 2012).

Pesticides may produce direct lethal effects by causing mortality or sublethal effects such as impaired navigation, reduced foraging efficiency, suppressed immunity, and colony collapse. Pettis *et al.* (2012) reported that pesticide exposure increases susceptibility of honey bees to pathogens like *Nosema*. In Maharashtra, large scale mortality of *Apis mellifera* colonies was observed near pesticide-treated agricultural fields (Pashte and Patil, 2017).

Recent studies from southern India also revealed that pesticide use reduces both abundance and diversity of wild bees in agricultural landscapes (Steinhübel *et al.*, 2022). Herbicides indirectly affect pollinators by destroying flowering weeds and reducing floral resources essential for nectar and pollen collection.

Habitat Loss and Agricultural Intensification: Rapid urbanization, deforestation, infrastructure expansion, monoculture farming, and land-use changes are causing severe destruction and fragmentation of pollinator habitats. Pollinators require nesting sites, floral diversity, shelter, and suitable microclimatic conditions for survival.

Modern intensive agriculture often replaces diverse natural habitats with monoculture systems that provide floral resources only for short durations. Such simplified landscapes fail to support diverse pollinator communities throughout the year (Potts *et al.*, 2010).

In Haryana, populations of native andrenid bees declined drastically between 1990 and 2015 because of intensive agricultural practices and repeated soil disturbance (Sihag, 2023).

Air Pollution and Heavy Metal Contamination: Air pollution is increasingly recognized as a hidden driver of pollinator decline. Pollutants such as ozone, nitrogen oxides, diesel exhaust particles, and particulate matter interfere with floral scent signals used by pollinators for locating flowers (Leonard *et al.*, 2019).

Exposure to polluted air impairs learning, memory, and olfactory responses in honey bees, reducing their foraging efficiency. Heavy metals such as lead (Pb), cadmium (Cd), and arsenic (As) can accumulate in bee tissues through contaminated nectar and pollen, adversely affecting immunity and reproduction (Perugini *et al.*, 2011).

Artificial Light Pollution: Artificial Light at Night (ALAN) is emerging as an overlooked ecological threat to insect pollinators, especially nocturnal species such as moths. Excessive nighttime illumination disrupts insect orientation, mating behaviour, oviposition, and navigation.

ALAN also alters flowering phenology in many plant species by inducing early flowering and extending growing periods (Zheng *et al.*, 2021). Such disturbances weaken natural plant-pollinator interactions and reduce reproductive success in both plants and pollinators.

Diseases, Parasites, and Invasive Species: Pollinator populations are also threatened by emerging diseases, parasites, predators, and invasive species. Pathogens such as *Nosema*, Varroa mites, and viral infections severely weaken honey bee colonies.

The recent report of invasive Small Hive Beetle (*Aethina tumida*) in India has raised serious concerns regarding honey bee health and apiculture sustainability (Kumaranag *et al.*, 2025). Invasive plant species may also alter floral composition and disrupt native pollinator networks.

Table 1. Major Causes of Pollinator Decline in India:

Cause	Major Effects on Pollinators
Pesticides	Mortality, impaired navigation, colony collapse
Habitat loss	Loss of nesting and floral resources
Climate change	Phenological mismatches
Air pollution	Reduced olfactory efficiency
Artificial lighting	Behavioural disruption
Diseases & invasive species	Colony weakening and mortality

Impacts of Pollinator Decline

Declining pollinator populations pose serious threats to agricultural productivity, ecosystem stability, and human nutrition. Reduced pollination decreases fruit set, seed formation, crop yield, and quality in pollinator-dependent crops. Economic losses associated with pollinator decline are expected to rise sharply in future. Studies suggest that global crop prices may increase significantly if pollinator populations continue declining (Uwingabire and Gallai, 2024).

Pollinator decline also affects biodiversity conservation because many wild plants depend on insects for reproduction. Loss of pollination services may trigger cascading ecological effects, including reduced plant diversity, habitat degradation, and weakening of food webs (Potts *et al.*, 2010).

Furthermore, pollinator-dependent crops are rich sources of vitamins, minerals, proteins, and antioxidants. Declining pollination may therefore negatively affect nutritional security and human health.

Conservation Strategies for Pollinator Protection

Pollinator Friendly Agricultural Practices: Adopting pollinator-friendly farming practices is essential for sustaining pollinator diversity. Judicious pesticide use, Integrated Pest Management (IPM), avoidance of pesticide spraying during flowering periods, and use of selective pesticides can substantially reduce pollinator mortality.

Maintaining flowering strips, hedgerows, agroforestry systems, and diversified cropping patterns can provide continuous floral resources and nesting habitats for pollinators.

Habitat Restoration and Floral Interventions: Habitat restoration programmes are increasingly gaining attention in India. Floral interventions involving co-flowering plants such as marigold and red gram have successfully enhanced pollinator abundance and crop productivity in moringa plantations of Tamil Nadu (Dhandapani *et al.*, 2024).

India's first Pollinator Habitat Restoration Kit released by ICAR-Directorate of Floricultural Research, Pune, in 2025 represents a significant initiative towards restoring pollinator habitats in agroecosystems.

Technology Based Pollinator Monitoring: Emerging digital technologies are opening new opportunities for pollinator conservation. Artificial intelligence, machine learning, smart sensors, and automated monitoring systems are now being used for real-time pollinator recognition and hive monitoring.

The AmoHive project and AI-based visual recognition systems can monitor bee activity, colony health, diseases, swarming behaviour, and environmental stress under field conditions (Punith and Champa, 2024).

Table 2. Important Conservation Strategies for Pollinator Protection:

Strategy	Expected Benefits
Integrated Pest Management	Reduced pesticide exposure
Floral strips and habitat restoration	Improved floral resources
Pollinator-friendly farming	Enhanced pollinator diversity
Smart hive monitoring	Early disease detection
Awareness programmes	Community participation

Future Outlook

The future of sustainable agriculture and food security is closely linked with pollinator conservation. Protecting pollinators will require integrated approaches combining ecological restoration, sustainable farming, climate adaptation, pollution reduction, scientific monitoring, and policy level commitment.

Greater emphasis must also be placed on conserving wild pollinators, which often receive less attention than managed honey bees despite their immense ecological importance. Strengthening pollination research in India, especially long-term ecological monitoring and native pollinator studies, will be essential for addressing the emerging pollination crisis (Adit *et al.*, 2024).

Conclusion

Pollinators are silent architects of agricultural productivity, biodiversity conservation, and ecosystem stability. Their ongoing decline represents a major ecological and agricultural crisis with serious implications for food security, economy, and environmental sustainability.

In India, multiple interacting factors including pesticides, habitat destruction, climate change, air pollution, invasive species, and artificial lighting are accelerating pollinator loss. Immediate and coordinated action involving researchers, farmers, policymakers, industries, and local communities is essential to reverse this trend.

Conservation oriented agriculture, habitat restoration, pollinator-friendly policies, technological innovations, and public participation can collectively help protect these invaluable ecological allies. Safeguarding pollinators today is ultimately an investment in the future sustainability of Indian agriculture and global food systems.

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Microclimate Management Under Protected Agriculture

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Amisha D. Chudasama¹, Darshan L. Kothiya²
¹Msc., Department of Agricultural Meteorology, B. A. College of Agriculture, Anand Agricultural University, Anand-388 110.

²PhD Scholar, Department of Agricultural Statistics, B. A. College of Agriculture, Anand Agricultural University, Anand-388 110.

Abstract

Protected agriculture is a modern cultivation system in which crops are grown in greenhouses and polyhouses to protect them from adverse weather conditions. Its success depends on effective microclimate management, including the control of temperature, humidity, light, carbon dioxide, and air circulation. Techniques such as ventilation, shading, cooling systems, LED lighting, and IoT-based automation help maintain optimal growing conditions. Research has shown that these practices improve crop growth, yield, and produce quality. Overall, proper microclimate management plays a vital role in enhancing productivity and sustainability in protected agriculture

Keywords: Protected agriculture, Microclimate management, Greenhouse environment, Climate control systems, Internet of Things (IoT), Crop productivity.

Introduction

Protected agriculture involves cultivating crops in controlled environments and providing benefits such as extended growing seasons, weather protection, and greater control over the growing conditions. To maximize the benefits of protected agriculture, efficient microclimate management is essential. Microclimate management within these enclosed spaces involves the precise regulation of various environmental factors to create optimal conditions for plant growth. Microclimate management is essential for achieving higher yields, better quality crops, and a more sustainable agricultural system.

The greenhouse's structure, design, the type of crops and the actions of control systems play a crucial role in shaping the greenhouse microclimate. The greenhouse microclimate may be controlled by managing Ventilation, cooling, shading, Internal air circulation system, CO₂ enrichment, Light intensity, Air humidification, Dehumidification and the Internet of Things (IoT).

Kittas *et al.* (2012) concluded that the shade net had a significant impact on fruit yield and quality. Nets like B&Gr40, B40, and B49 not only increased fruit mass but also resulted in higher fruit production compared to the other nets or no shading.

Moreno *et al.* (2021) found that the marketable production and total accumulated production in the West sector of the greenhouse with the experimental cover film were 8.10 kgm⁻² and 10.0 kgm⁻², respectively. Showing an increase in tomato crop production.

Reddy *et al.* (2021) proposed that white polythene film as cladding material of poly house and without mulching is important for the cultivation of Cucumber to achieve higher production in semi-arid regions.

Khapte *et al.* (2021) observed that aerial dry biomass, vine length, stem girth, and node number per plant were higher in the naturally ventilated poly house (NVP) compared to the other structures, indicating that NVP provides a more favorable microclimate for cucumber cultivation.

Chauhan and Lunagaria (2022) found that the greenhouse provides a favorable microclimate with high photosynthetically active radiation (PAR) in the southwestern corner and effective seasonal adjustments, supporting crop growth, early yields, and water conservation.

Sotelo-Cardona *et al.* (2021) observed that plant height, yield, and lycopene content were significantly higher for tomatoes grown in coloured net houses compared to those grown in conventional net houses and open field conditions.

Kumari *et al.* (2014) inferred that tomato crops in poly houses had significantly higher fruit yield, with the greatest number of fruits (285) under black mulch and the least (205) without any mulch

Table 1: Various climate control methods used in greenhouse:

Sl No.	Parameter	To control	Equipment
1	Radiation/ Light	Increase	Incandescent lamp, fluorescent lamps, high intensity discharge lamps
		Decrease	Shade nets, black out screens
2	Temperature	Increase	Heaters, steam heating

		Decrease	Misters, foggers, roof sprinklers
		Shading	Shade nets/ screens
		Ventilation	Vents, exhaust fans
3	Relative Humidity	Increase	Humidifiers, foggers, misters
		Decrease	Heaters, Vents, dehumidifiers
4	CO ₂	CO ₂ enrichment	CO ₂ burners

Conclusion

1. Enhancing the poly house microclimate through automated climate control systems and other adjustments is essential for optimizing crop growth and yields across a wide range of crops.
2. The application of diffuse light can potentially improve the homogeneity of light distribution and other microclimatic factors such as temperature inside greenhouses.
3. The fan and pad system effectively moderates greenhouse temperatures, reducing heat exposure and increase in crop production.
4. White polythene film as cladding material for the construction of poly houses and without mulching is important to achieve higher growth and yield of crops under semi-arid regions.
5. IoT can play a vital role in enhancing agricultural practices, resulting in higher crop production and potentially more efficient resource use.

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Bioacoustic Warfare: How Roots and Microbes Communicate via Sound

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Sameena¹

¹Department of Plant Pathology, College of Agriculture, PJTAU, Rajendranagar, Hyderabad.

Summary

The rhizosphere, traditionally viewed as a zone of chemical and electrical exchange, is increasingly recognized as a sophisticated acoustic environment. Recent advancements in plant pathology and bioacoustics have revealed that plants and soil-borne organisms generate and perceive low-frequency vibrations—a process known as acoustic signaling. These "underground sounds" facilitate rapid communication between roots, beneficial fungi, and pathogenic nematodes. By harnessing these acoustic signatures, plants can preemptively trigger systemic resistance or recruit microbial allies. This article explores the mechanics of acoustic signaling in the rhizosphere and its potential as a non-invasive tool for sustainable crop protection.

Introduction

For decades, plant-microbe interactions were believed to be governed solely by the "chemical tongue" of exudates and volatiles. However, emerging research suggests that the rhizosphere is alive with sound. Soil, being a dense medium, is an excellent conductor of mechanical vibrations. Plant roots produce acoustic emissions during cell elongation and xylem cavitation, while soil organisms generate vibrations through movement and metabolic activity. This mechanical dialogue forms a crucial layer of "chemical-free" intelligence that influences plant health and pathogen defense.

The Sonic Landscape of the Soil

Communication in the dark, dense soil environment relies on mechanical waves that travel faster and further than chemical diffusions.

1. **Root "Clicking":** Growing root tips emit low-frequency clicking sounds (20-120 Hz). These sounds are not mere byproducts but serve as orientation cues for neighboring roots and soil microbes.
2. **Microbial Vibrations:** Beneficial bacteria and mycorrhizal fungi produce specific vibrational frequencies that signal their presence to the host plant, initiating the symbiotic colonization process.

Plants are "Listening"

Roots have evolved to detect and respond to specific acoustic frequencies as a form of sensory perception.

1. **Acoustic Priming:** When plants "hear" the mechanical vibrations associated with herbivore movement (such as chewing or tunneling), they prime their defense pathways. This leads to an increased production of secondary metabolites like jasmonic acid before the actual attack occurs.
2. **Directional Growth:** Experiments have shown that roots exhibit phonotropism—the ability to grow toward specific sound sources, such as the sound of running water or the vibrations of nutrient-rich microbial clusters.

Masterful Interference: Acoustic Camouflage

In the evolutionary arms race, plants and pathogens use sound to deceive one another.

1. **The Vibration Shield:** Some plant-pathogenic nematodes use acoustic cues to locate susceptible host roots. In response, certain plants may alter their root structure or xylem pressure to "silence" their acoustic signature, making them invisible to the pest.
2. **Disruptive Frequencies:** Researchers are exploring the use of "acoustic mulching"—applying specific external frequencies to the soil to jam the communication between pathogens, preventing them from aggregating or locating the host.

Why Acoustic Signalling Matters?

Shifting our focus to the physical properties of the rhizosphere offers new frontiers for precision agriculture.

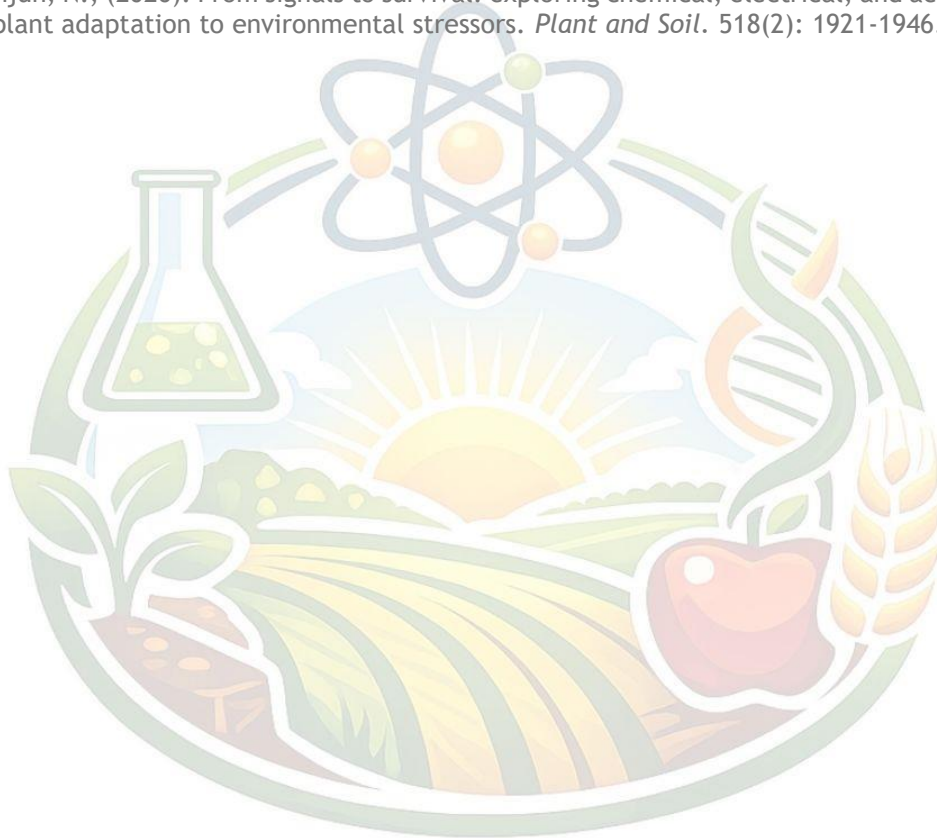
1. **Non-Invasive Monitoring:** Acoustic sensors can detect the presence of soil pests or the onset of drought stress long before physical symptoms appear on the foliage.
2. **Eco-Friendly Defense:** Utilizing sound frequencies to repel pests or attract beneficial microbes reduces the reliance on synthetic pesticides, aligning with organic farming goals.

Conclusion

Acoustic signaling represents a hidden dimension of the co-evolutionary struggle between plants and soil pathogens. By "listening in" on the rhizosphere, we gain a deeper understanding of how plants navigate their environment and defend themselves without the use of toxic chemicals. Integrating bioacoustics into modern plant pathology provides a sustainable model for crop management, allowing us to develop "smarter" crops that are tuned into the mechanical pulse of the earth.

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Makhana Cultivation: The Aquatic Superfood of India

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Shivani Jha¹, Dharmender², Ayushi Pal³

¹Young Professional-II, ICAR-National Research Centre for Makhana, Darbhanga, Bihar.

²Scientist, ICAR-National Research Centre for Makhana, Darbhanga, Bihar.

³Assistant Professor, Department of Agricultural Economics and Extension, Lovely Professional University, Jalandhar, Punjab.

Summary of Article

Makhana, scientifically known as *Euryale ferox Salisb.*, is an important aquatic crop mainly cultivated in the wetlands and ponds of Bihar. Popularly known as fox nut or gorgon nut, Makhana is gaining worldwide recognition as a nutritious superfood because of its high protein, mineral, and antioxidant content. The crop is highly suitable for flood-prone and waterlogged regions and provides livelihood support to thousands of farming families. This article highlights the botany, climate and water requirements, cultivation practices, processing, economic importance, and challenges associated with Makhana cultivation. Scientific cultivation and improved processing technologies can significantly enhance productivity and farmer income while promoting sustainable wetland agriculture.

Introduction

Makhana is one of the most important aquatic cash crops cultivated in India and holds significant economic, nutritional, and cultural importance. The crop belongs to the family Nymphaeaceae and is scientifically known as *Euryale ferox Salisb.* Bihar is the leading producer of Makhana in India, contributing nearly 85-90 per cent of the total production. Major Makhana-growing districts include Darbhanga, Madhubani, Katihar, Purnea, Saharsa, Supaul, and Kishanganj.

Makhana cultivation is traditionally practiced in ponds, wetlands, oxbow lakes, and low-lying waterlogged areas. Due to its adaptability to aquatic ecosystems, the crop plays an important role in utilizing unproductive wetlands for income generation and livelihood security. In recent years, increasing awareness regarding healthy diets and plant-based foods has greatly increased the demand for Makhana in domestic and international markets.

Makhana is rich in carbohydrates, protein, calcium, phosphorus, magnesium, potassium, and antioxidants. Because of its low fat and gluten-free nature, it is widely consumed as a healthy snack and fasting food. Mishra et. al., (2020) reported that Makhana possesses significant nutritional and medicinal properties beneficial for human health.

Botany of Makhana



Makhana is an annual aquatic herb with large floating leaves having thorny surfaces on both upper and lower sides. The leaves may attain a diameter of 1-2 meters and spread across the pond surface. The plant has a fibrous root system embedded in the muddy pond bottom.

The flowers are purple or violet in colour and bloom during summer months. After pollination, fruits develop underwater containing numerous seeds. Mature seeds sink to the pond bottom where they are manually collected by farmers. The edible white flakes are obtained after roasting and popping the seeds.

The crop completes its life cycle within one year and reproduces mainly through seeds.

Temperature and Water Requirement

Makhana grows best under warm and humid climatic conditions. The optimum temperature range for growth and development is 20°C to 35°C. High humidity, bright sunlight, and moderate rainfall favour better vegetative growth, flowering, and seed formation.

Being an aquatic crop, Makhana requires standing water throughout its growth period. Water depth ranging between 0.3 to 1.5 meters is considered ideal depending upon crop stage and cultivation practices. Proper water management is essential for controlling weeds and maintaining healthy crop growth.

The crop grows well in clayey and loamy soils rich in organic matter. Slightly acidic to neutral soil conditions are considered suitable for higher productivity.

Cultivation Practices

Makhana cultivation generally begins during December-January by broadcasting seeds in ponds or wetlands. Traditional cultivation often depends on residual seeds present in pond sediments.

After germination, seedlings spread rapidly over the water surface. Proper nutrient management and weed control are important for maintaining healthy crop growth. Organic manures and limited chemical fertilizers are applied to improve productivity.

Harvesting is one of the most labour-intensive operations in Makhana cultivation. Mature seeds are collected manually from the pond bottom during August to October. The harvested seeds are cleaned, dried, roasted, tempered, and popped to obtain edible Makhana flakes.

Processing of Makhana

Processing plays a crucial role in determining the quality, popping efficiency, and market value of Makhana. Traditionally, Makhana seeds were roasted manually and popped by striking heated seeds with wooden hammers, which required highly skilled labour and involved considerable drudgery.

With advancements in processing technology, mechanized popping systems are increasingly being adopted to improve efficiency, reduce labour dependency, and enhance product quality. In mechanized processing, harvested Makhana seeds are first cleaned, graded, and sun-dried to reduce moisture content. The seeds are then roasted in specially designed roasting units at controlled temperatures followed by tempering for a few hours to ensure uniform heat distribution inside the kernel.

After tempering, seeds are fed into mechanized popping machines where controlled pressure and impact help produce uniformly expanded white popped kernels. Mechanized popping improves recovery percentage, reduces seed breakage, and ensures better product uniformity and hygiene compared to traditional methods.

Research institutions such as ICAR-National Research Centre for Makhana are developing improved roasting and popping technologies to minimize drudgery and increase processing efficiency. Mechanization not only enhances productivity but also creates opportunities for entrepreneurship, value addition, and commercialization of Makhana-based products.

Singh et. al., (2022) found that improved processing technologies can enhance popping efficiency and market quality of Makhana.

Economic Importance of Makhana

Makhana cultivation provides employment and livelihood opportunities to thousands of rural families in Bihar and neighbouring states. The crop has high market demand because of increasing consumer preference for healthy snacks and nutraceutical foods.

Value-added products such as roasted Makhana, flavoured snacks, sweets, cookies, breakfast cereals, and energy foods are becoming increasingly popular. The Geographical Indication (GI) tag for Mithila Makhana has further enhanced its commercial identity in national and international markets.

Challenges in Makhana Cultivation

Despite its economic importance, Makhana cultivation faces several challenges such as high labour requirement, weed infestation, lack of mechanization, water management problems, and fluctuating market prices. Climate change and shrinking wetland ecosystems also threaten sustainable production.

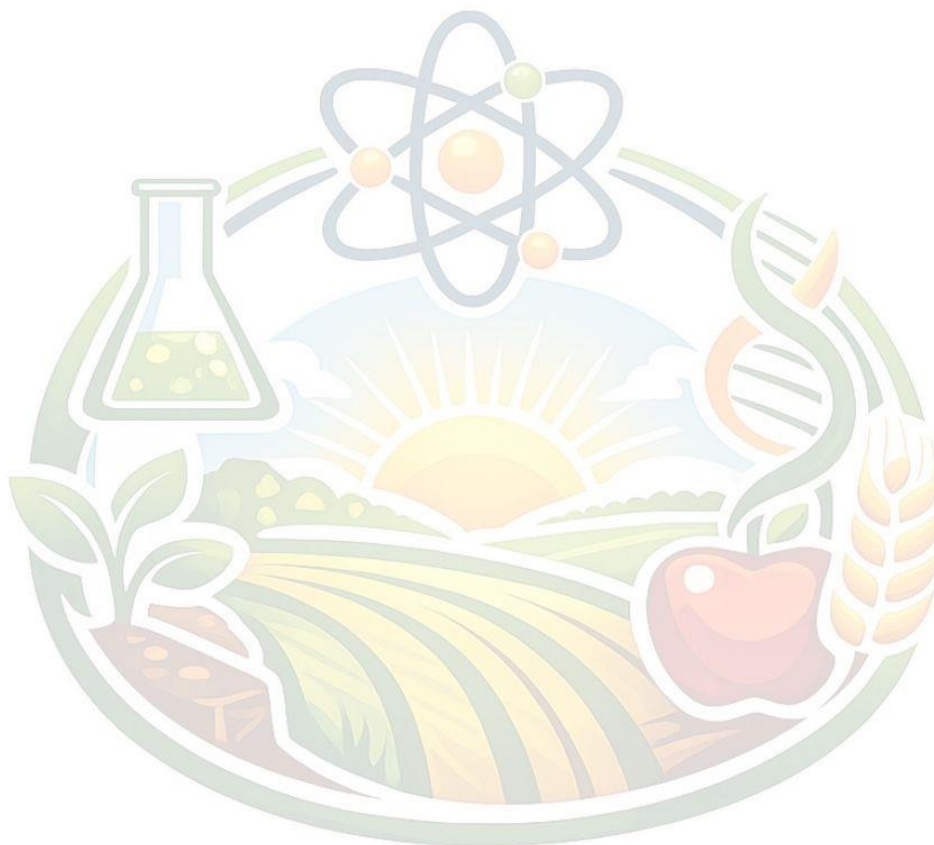
Research institutions such as ICAR-National Research Centre for Makhana are working on improved varieties, mechanization, nutrient management, and value-addition technologies to improve productivity and farmer income.

Conclusion

Makhana is a unique aquatic crop with tremendous nutritional, economic, and ecological significance. Its adaptability to wetland ecosystems and increasing global demand make it an important crop for future food and nutritional security. Scientific cultivation practices, improved processing technologies, and value addition can significantly enhance profitability and sustainability of Makhana farming in India.

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An Overview of Food Fortification

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Rutuja S. Pisal¹, Suraj N Gund², Vidhya Bharathi K. S³

¹Ph. D. Scholar, Department of Horticulture, Mahatma Phule Krishi Vidyapeeth, Rahuri, Ahilyanagar.

²Ph. D. Scholar, Department of Agril. Botany, Mahatma Phule Krishi Vidyapeeth, Rahuri, Ahilyanagar.

³Ph. D. Scholar, Division of Plant Physiology ICAR- Indian Agricultural Research Institute, New Delhi.

Abstract

Malnutrition, particularly micronutrient deficiency, remains a major public health challenge in developing countries, contributing significantly to child mortality, impaired growth, and reduced cognitive development. Deficiencies of essential nutrients such as iron, iodine, vitamin A, and vitamin D are widespread due to poor dietary diversity, inadequate intake of nutrient-rich foods, and socio-economic constraints. Food fortification has emerged as an effective, scalable, and cost-efficient strategy to address “hidden hunger” by enhancing the nutritional quality of commonly consumed foods without requiring major changes in dietary habits.

This paper highlights the concept, types, and importance of food fortification, including conventional fortification, biofortification, and dietary diversification. It also discusses the key criteria for effective fortification, along with its advantages such as wide population coverage, sustainability, and ability to address multiple micronutrient deficiencies simultaneously. However, certain limitations, including accessibility issues, cost constraints, and dependency on food systems, are also considered.

In the Indian context, regulatory support through initiatives such as the Food Safety and Standards Authority of India (FSSAI) plays a crucial role in promoting fortified foods. Overall, food fortification, when combined with other nutritional strategies, offers a practical approach to improving public health and achieving nutritional security, particularly among vulnerable populations.

Introduction

Maternal and child undernutrition remains a major public health concern, particularly in underdeveloped and developing countries. It is responsible for nearly 45% of all deaths among children under five years of age and adversely affects the physical, mental, and cognitive development of millions of people. At present, both undernutrition and overnutrition are increasingly associated with micronutrient deficiencies, especially deficiencies of vitamin A, vitamin D, iodine, iron, and other essential nutrients. Together, these deficiencies contribute to nearly 7.3% of the global burden of disease.

Micronutrient deficiency often results from the lack of a balanced diet, inadequate intake of nutrient-dense foods, poor dietary diversity, infections, gastrointestinal disorders, and blood loss during menstruation, particularly among women of reproductive age. To improve dietary intake and reduce malnutrition and micronutrient deficiency across populations, the World Health Organization (WHO) and the Food and Agriculture Organization (FAO) have identified four major strategies: food fortification, disease control measures, nutrition education, and micronutrient supplementation.

Malnutrition has become one of the most serious health challenges in developing countries. It contributes significantly to infant mortality, poor physical growth, and impaired intellectual development in children, while also lowering resistance to infectious diseases. Across the developing world, malnutrition affects nearly 800 million people, representing approximately 20% of the global population.

Among the available interventions, food fortification has demonstrated significant positive effects on health, social, and economic outcomes. Although there continues to be discussion regarding the effectiveness and safety of various fortification approaches—such as large-scale food fortification, biofortification, and point-of-use or home fortification—the strategy offers considerable benefits. These include reducing the prevalence of micronutrient deficiencies and generating broader societal and economic gains.

Food Fortification

According to the World Health Organization, food fortification is defined as the practice of deliberately increasing the content of one or more essential micronutrients (vitamins and minerals) in food in order to improve its nutritional quality and provide a public health benefit with minimal risk to health.

A common example of food fortification is the addition of iron and iodine to edible salt. Similarly, staple foods such as rice, wheat flour, edible oil, and milk can also be enriched with essential micronutrients. These staple foods are generally selected because they are consumed regularly by a large proportion of the population. Thus, food fortification has emerged as a promising strategy to combat hidden hunger, and its effectiveness has been demonstrated historically.

Fortification is the process of improving the nutritional value of commonly consumed foods such as rice, wheat, oil, milk, and salt by adding essential nutrients including iron, iodine, zinc, and vitamins A and D. In some cases, these nutrients may not be naturally present in the food, while in others they may be lost during processing and are therefore restored or enhanced. Kruger et al. (2020) highlighted the importance of fortification in addressing micronutrient malnutrition, which continues to pose a major public health risk.

Access to nutritious food is essential for maintaining health; however, this is often constrained by monotonous diets, inadequate food availability, and poor dietary balance. In this context, fortification provides an effective and practical nutritional intervention (Syeda et al., 2017).

Criteria for Effective Food Fortification

The success of a food fortification programme depends on several important criteria:

1. The intake of the nutrient should be below the desirable level in the diets of a significant proportion of the population.
2. The selected food vehicle should be commonly consumed in quantities sufficient to contribute meaningfully to the diet of the target population.
3. The addition of the nutrient should not create an imbalance among other essential nutrients.
4. The nutrient should remain stable during storage and normal use.
5. The nutrient must be physiologically available from the fortified food.
6. There should be reasonable assurance against excessive intake, thereby avoiding toxicity.

These criteria are important to ensure that fortification is both effective and safe (Venkatesh et al., 2023).

Other Criteria for Fortification

In addition to the above, certain practical considerations are also essential:

1. The food selected for fortification should be edible, acceptable, and commonly consumed by the majority of the population.
2. Fortification should not adversely affect the physical properties of the food, such as its taste, colour, texture, or overall acceptability.
3. The fortified food should be affordable, so that it remains accessible to all sections of society.

These aspects are particularly important in ensuring the consumer acceptability and public reach of fortified foods (Prema and Ramachandran, 2018).

Biofortification

The World Health Organization defines biofortification as the process of deliberately increasing the content of essential micronutrients, including vitamins and minerals, in food crops through agronomic practices, conventional plant breeding, or modern biotechnology, in order to improve the nutritional quality of the food supply and provide a public health benefit with minimal risk to health (Hritik et al., 2024).

Unlike conventional fortification, which adds nutrients during food processing, biofortification enhances the nutrient content of crops during crop growth and development itself. Therefore, it offers a sustainable and agriculture-based solution to micronutrient malnutrition.

Conventional Fortification

Conventional fortification, also referred to as enrichment, involves the addition of one or more essential nutrients to a food, whether or not these nutrients are normally present in that food, with the objective of preventing or correcting a demonstrated deficiency in the population or in specific population groups.

In this approach, the micronutrient content of processed or formulated foods is increased by adding nutrients during manufacturing or processing. This makes conventional fortification particularly suitable for foods that are centrally processed and widely distributed (Das et al., 2013).

Dietary Diversification

Dietary diversification refers to increasing both the quantity and variety of micronutrient-rich foods consumed in the daily diet. This can be achieved through better food choices as well as through traditional food preservation and processing methods that improve the nutrient content and bioavailability of foods.

Dietary diversification also involves improving food formulations and recipes to enhance the availability of specific nutrients, rather than only increasing the number of food groups consumed. This strategy is considered an important complementary approach for improving micronutrient intake (Bechoff et al., 2023).

Food Fortification Resource Centre (FFRC)

The Food Fortification Resource Centre (FFRC) was established as a dedicated platform to bring together key stakeholders from the fields of food, nutrition, and public health in order to reduce hidden hunger. These stakeholders include government departments, development organisations, academic institutions, the food industry, consumer groups, and the general public.

The centre provides technical support, advocacy, training, and capacity building at both national and state levels. It supports food safety officers, laboratory personnel, food business operators, and professionals involved in the quality assurance and quality control of fortified foods. It also addresses the regulatory requirements of the fortification sector.

In addition, the FFRC disseminates information through various resources such as technical manuals, educational materials, equipment details, premix manufacturer directories, testing procedures for fortificants, and awareness materials on the health benefits of fortified foods (Thakur et al., 2023).

Advantages and Limitations of Food Fortification

As a food-based approach, food fortification offers several important advantages over other nutritional interventions. It does not require major changes in dietary patterns, can provide a significant proportion of the recommended dietary allowance (RDA) of several micronutrients on a continuous basis, and does not depend heavily on individual compliance. Food fortification can often be integrated into the existing food production and distribution systems, making it feasible and sustainable over the long term. When consumed regularly, fortified foods help maintain the body's nutrient stores more effectively than intermittent supplementation.

Fortified foods are particularly useful in reducing the risk of multiple micronutrient deficiencies, which is especially important for growing children, who require a sustained supply of nutrients for growth and development, and for women of reproductive age, who need adequate nutrient reserves before and during pregnancy and lactation.

However, food fortification also has certain limitations. It may not be effective when large segments of the target population have limited or no access to fortified foods due to poverty, geographic isolation, or weak distribution systems. Similarly, fortification alone may not be sufficient where micronutrient deficiencies are severe, or where infections increase the body's metabolic demand for nutrients.

In addition, several technological, safety, and cost-related factors may restrict the implementation of fortification programmes. Therefore, successful fortification programmes require not only an assessment of their likely nutritional impact, but also careful evaluation of their feasibility in a specific context. Furthermore, such programmes should be supported and monitored through appropriate legislation and regulation.

Advantages of Food Fortification

Food fortification offers several notable benefits:

1. It can be introduced relatively quickly and can improve nutritional status within a short period.
2. It provides micronutrients in appropriate and safe amounts, making it generally safer than supplementation when properly regulated.
3. Fortification of widely consumed staple foods can improve the nutritional status of large populations, including both poor and affluent groups.
4. It does not require major changes in food habits or active compliance from individuals.
5. Several micronutrients can be added to the same food, allowing the management of multiple deficiencies simultaneously.
6. It is often more cost-effective than many other nutritional interventions, especially when an appropriate food production and distribution system is already in place.
7. It helps reduce the occurrence of micronutrient deficiencies and improve the overall nutritional status of individuals.
8. It can be implemented on a large scale, making it suitable for public health programmes.
9. The number of micronutrients added is usually small and carefully regulated, reducing the likelihood of overconsumption.
10. Fortification is generally designed in such a way that the taste, texture, and appearance of the food remain unchanged.

These advantages have made food fortification one of the most practical and effective public health nutrition strategies (Neufeld and Friesen, 2018).

Limitations of Food Fortification

Despite its benefits, food fortification also has several limitations:

1. A particular fortified food item may not be consumed by all members of the target population.
 2. Although everyone may be exposed to increased micronutrient levels, not everyone necessarily requires them.
 3. Infants and young children, who consume relatively small amounts of food, may not obtain adequate micronutrients from universally fortified staple foods alone.
 4. Fortified foods may not always reach the poorest sections of society because of low purchasing power and underdeveloped distribution systems.
 5. People from low-income groups often suffer from multiple micronutrient deficiencies, and fortified foods alone may not provide sufficient amounts of all required nutrients.
 6. The nature of the food vehicle or fortificant may limit the amount of nutrient that can be added. For example, some iron fortificants may alter the colour or flavor of foods or interact negatively with nutrients such as vitamin A and iodine.
 7. Although fortification is relatively cost-effective, it still involves significant costs related to technology, production, quality control, and programme implementation, which can limit its reach in developing countries such as India.
 8. Excessive dependence on food fortification may reduce emphasis on the importance of dietary diversity, which remains essential for long-term nutritional well-being.
 9. The fortification process may also involve substantial initial investment, including trials for determining micronutrient levels, testing physical characteristics and taste, and evaluating consumer purchasing capacity.
- Thus, while food fortification is highly beneficial, it should be viewed as one component of a broader nutrition strategy, rather than a complete standalone solution.

Food Fortification Logo by FSSAI

The Food Safety and Standards Authority of India (FSSAI) has developed a comprehensive set of regulations for food fortification under the Food Safety and Standards (Fortification of Foods) Regulations, 2016.

These regulations establish standards for fortified foods and encourage their production, manufacture, distribution, sale, and consumption. They also define the role of FSSAI in promoting food fortification and creating the framework for making fortification more widely adopted, and where appropriate, mandatory.

These regulations form the basis for strengthening food fortification initiatives at the national level in India.

Conclusion

In conclusion, food fortification remains one of the most effective and practical strategies for improving the nutritional quality of foods and addressing micronutrient deficiencies, especially among vulnerable populations. By adding essential vitamins and minerals to staple foods, fortification helps bridge specific dietary gaps without requiring major changes in food habits or food systems.

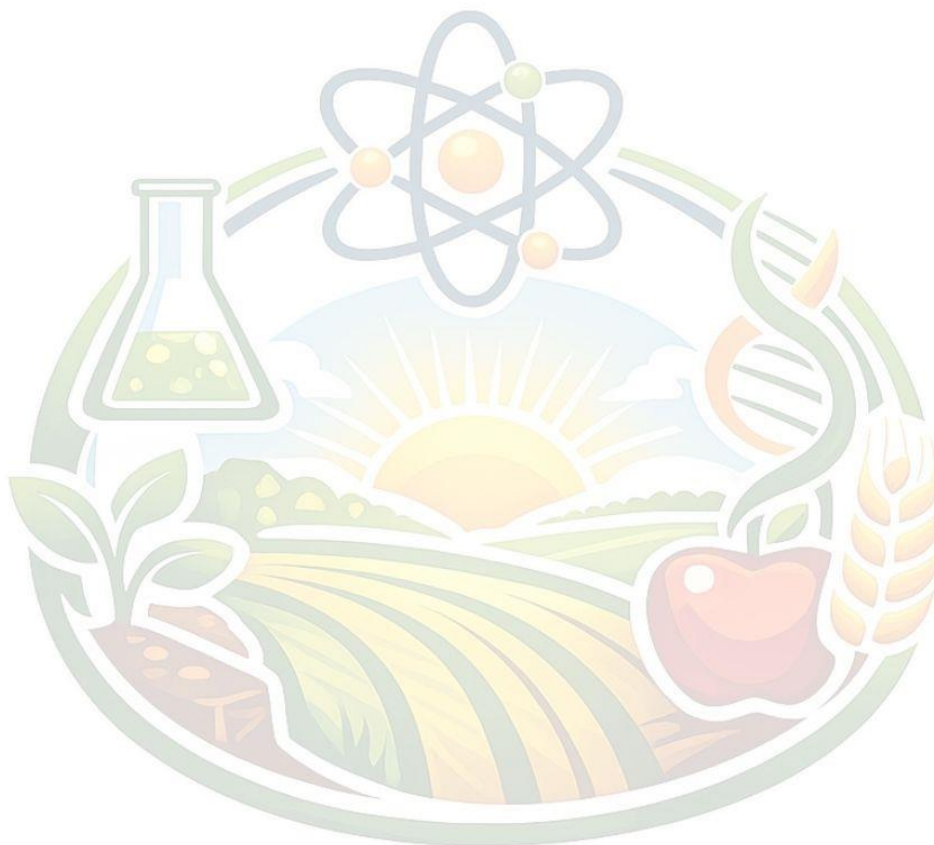
Moreover, food fortification is cost-effective, scalable, and adaptable, making it an important public health intervention, particularly in areas where access to diverse and nutrient-rich foods is limited. As scientific advancements continue to improve fortification technologies and as national and global partnerships strengthen implementation efforts, food fortification is likely to play an increasingly important role in the fight against malnutrition.

Overall, it contributes significantly to the broader goal of improving public health, nutritional security, and human well-being worldwide.

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Spent Mushroom Substrate: Present and Future Perspectives for Green Applications

Article ID: 73762

 Rajvardhan K. Patil¹, Parmanand Sahu¹, Debabandya Mohapatra¹, Rahul Bakade¹
¹ICAR-National Institute of Secondary Agriculture, Ranchi, Jharkhand, 834010.

Summary

Spent mushroom substrate (SMS) is a major by-product of mushroom cultivation rich in lignocellulosic biomass, nutrients, enzymes, and bioactive compounds. Traditionally considered waste, SMS is now recognized as a valuable renewable resource with applications in agriculture, bioenergy production, bioproduct extraction, and environmental remediation. It can be reused as mushroom cultivation substrate, animal feed, soil conditioner, and compost to improve sustainability and reduce waste generation. SMS also shows strong potential for biogas, bioethanol, activated carbon, and enzyme production due to its partially degraded organic composition. Despite its promising applications, challenges such as variability in composition, economic limitations, and lack of large-scale commercialization still restrict its widespread industrial utilization.

Introduction

Edible mushrooms are widely recognized as nutritious foods because they are rich in proteins, minerals, dietary fiber, and bioactive compounds while remaining low in fat and calories. Along with the rapid growth of the mushroom industry, a substantial amount of agricultural waste is generated during cultivation and processing. Among these wastes, spent mushroom substrate (SMS) represents the major by-product remaining after mushroom harvesting. Approximately 5 kg of SMS is produced for every 1 kg of mushrooms cultivated. SMS mainly consists of residual lignocellulosic materials, fungal mycelia, extracellular enzymes, and partially degraded organic matter. Traditionally, SMS was discarded in open fields or burned, resulting in environmental pollution and loss of valuable biomass resources. However, under the modern circular economy concept, SMS is increasingly recognized as a renewable bioresource with significant potential in agriculture, bioenergy production, bioproduct development, and environmental remediation (Fig. 1).



Fig. 1 Various used of spent mushroom substrate

Features of Spent Mushroom Substrate

SMS possesses several unique structural and biochemical characteristics that distinguish it from conventional lignocellulosic biomass. It generally has a loose and porous structure with fine particle size, making it easy to handle

and process. During mushroom cultivation, fungal enzymes such as cellulase, laccase, and ligninase partially degrade cellulose, hemicellulose, and lignin, reducing crude fiber content and increasing nutrient availability. As a result, SMS contains considerable amounts of crude protein, amino acids, organic acids, minerals, and bioactive compounds.

The substrate also contains essential nutrients including carbon, nitrogen, phosphorus, and potassium. Reduced lignin content improves cellulose accessibility, enhancing the suitability of SMS for enzymatic hydrolysis and bioresource conversion. Moreover, the presence of gypsum or lime helps regulate pH, while abundant surface functional groups provide excellent adsorption properties for heavy metal removal.

Agricultural Applications of SMS

1. Mushroom Cultivation: One of the most important agricultural applications of SMS is its reuse as a second-generation cultivation substrate. After suitable treatment, SMS can support the growth of several mushroom species, particularly *Agaricus* spp. Reusing SMS reduces production costs and minimizes agricultural waste generation. However, excessive reuse may reduce substrate stability due to its loose structure.

2. Animal Feed: SMS has considerable potential as livestock feed because fungal degradation improves the digestibility of lignocellulosic materials. It contains proteins, vitamins, amino acids, and beneficial microorganisms that support animal growth and immunity. Fermentation using yeast and lactic acid bacteria further improves digestibility and nutritional quality. Nevertheless, high fiber content and anti-nutritional compounds still limit its direct feeding efficiency.

3. Soil Amendment and Compost: SMS is widely used as an organic fertilizer and soil conditioner. Its loose structure enhances soil aeration, water retention, and microbial activity. Composting of SMS converts resistant organic matter into stable humus through microbial decomposition. The compost produced is nutrient-rich and provides long-term fertilizer benefits while reducing harmful pathogens through thermophilic composting processes.

4. Bioenergy Production from SMS:

a. Anaerobic Digestion: Anaerobic digestion is an effective biological method for converting SMS into biogas. During this process, anaerobic microorganisms degrade organic matter to produce methane and carbon dioxide. Since fungal pretreatment partially removes lignin, cellulose becomes more accessible for microbial fermentation. However, methane yield from SMS alone is relatively low due to an imbalanced carbon-to-nitrogen ratio; therefore, co-digestion with other organic wastes is commonly recommended.

b. Bioethanol Production: SMS can also be utilized for bioethanol production because fungal degradation increases glucan digestibility. Through enzymatic hydrolysis and fermentation using *Saccharomyces cerevisiae*, high glucose recovery and ethanol yields can be achieved. Studies have reported ethanol production efficiencies reaching nearly 85% of the theoretical maximum from spent *Lentinula edodes* substrate.

c. Supercapacitor Materials: Recent studies have demonstrated that activated carbon derived from SMS can be used as an electrode material for supercapacitors. Pyrolysis of SMS produces high-surface-area carbon materials with excellent electrochemical performance and high capacitance retention, indicating promising applications in sustainable energy storage systems.

5. Bioproducts and Bioremediation Applications: SMS is an important source of valuable bioproducts such as polysaccharides and industrial enzymes. SMS-derived polysaccharides exhibit antioxidant, anti-inflammatory, and hypoglycemic properties. Enzymes including cellulase, laccase, and ligninase can also be recovered from SMS through extraction and purification techniques.

In environmental remediation, SMS shows strong adsorption capacity for heavy metals due to its porous structure and surface functional groups. SMS and SMS-derived biochar are increasingly used for the removal of toxic metals from contaminated water and soil. Furthermore, residual ligninolytic enzymes present in SMS can degrade polycyclic aromatic hydrocarbons (PAHs), making SMS an efficient material for organic pollutant remediation.

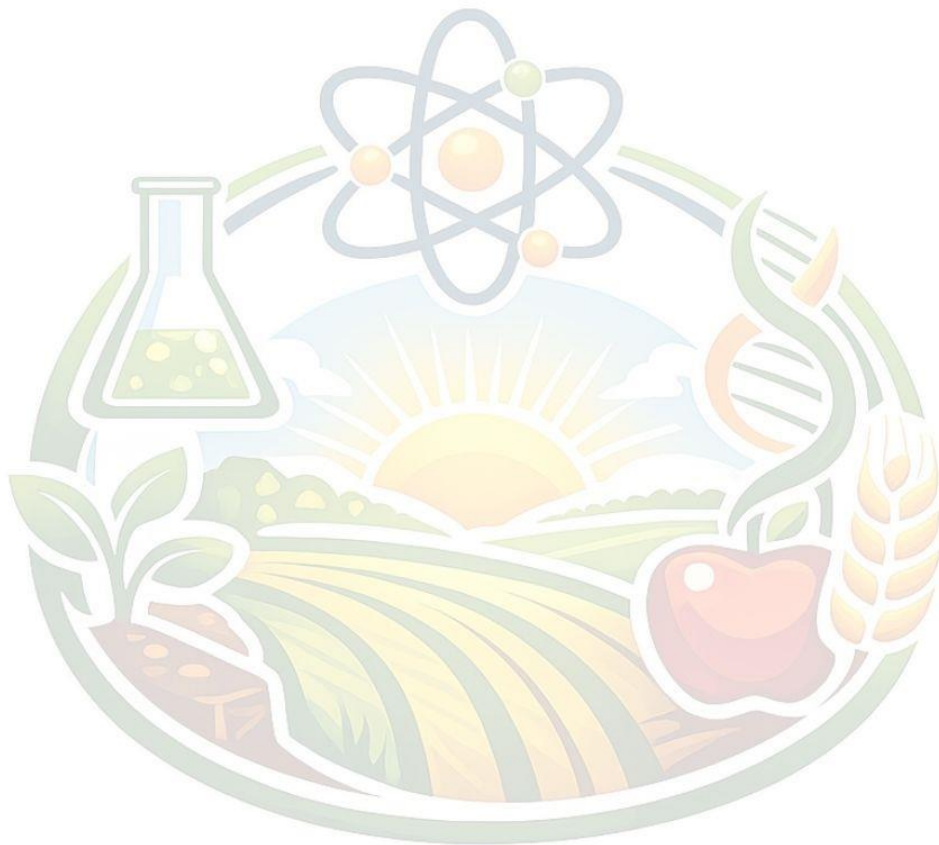
Challenges and Future Perspectives

Despite its enormous potential, several challenges restrict the large-scale utilization of SMS. The physicochemical composition of SMS varies depending on mushroom species and cultivation substrates, making standardization difficult. Competition from other agricultural residues with similar applications also limits commercial adoption. Additionally, many SMS utilization technologies remain economically unfeasible at industrial scale due to high processing and transportation costs. Technical limitations associated with bioenergy conversion, enzyme recovery, and bioproduct extraction further hinder commercialization.

Future research should focus on integrated biorefinery approaches, advanced pretreatment technologies, and development of economically sustainable value-added products. Policy support, industrial collaboration, and circular bioeconomy strategies will play key roles in promoting large-scale utilization of SMS for sustainable environmental management.

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Nutritional Content of Makhana: A Superfood from Wetlands

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 Shivani Jha¹, Dharmender², Vinod Kumar Padala³
¹Young Professional-II, ICAR-National Research Centre for Makhana, Darbhanga, Bihar.

²Scientist, ICAR-National Research Centre for Makhana, Darbhanga, Bihar.

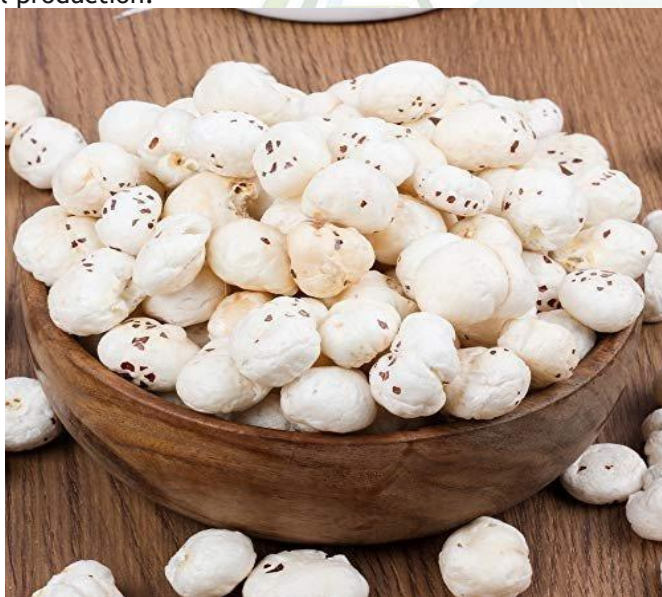
³Scientist, ICAR-National Research Centre for Makhana, Darbhanga, Bihar.

Summary of Article

Makhana, commonly known as fox nut or gorgon nut, is an important aquatic crop valued for its high nutritional and medicinal properties. It is widely cultivated in the wetland regions of Bihar and has gained popularity as a healthy food across the world. Makhana is rich in proteins, carbohydrates, minerals, antioxidants, and dietary fiber while being low in fat and calories. Due to its nutritional richness, it is considered a superfood and is increasingly used in snacks, sweets, breakfast products, and health foods. This article highlights the nutritional composition of makhana, its health benefits, medicinal importance, economic significance, and future prospects in food and nutrition security.

Introduction

Aquatic crops play an important role in ensuring nutritional security and supporting rural livelihoods in wetland ecosystems. Among these crops, makhana (*Euryale ferox*) is one of the most valuable aquatic food crops cultivated mainly in eastern India. Makhana is commonly known as fox nut or lotus seed and is widely consumed as a healthy snack and fasting food. India is the leading producer of makhana, and Bihar contributes nearly 80-90 percent of the country's total production.



Makhana is highly nutritious and contains essential nutrients required for human health. The popped makhana kernels are rich in carbohydrates, proteins, minerals, and antioxidants. They are also low in fat, cholesterol-free, and gluten-free, making them suitable for people of all age groups. According to Jha et. al., (2018), makhana contains high-quality protein and important amino acids that contribute to balanced nutrition.

The nutritional composition of makhana makes it an ideal health food. Makhana contains approximately 9-10 percent protein, 70-77 percent carbohydrates, low fat content, and significant amounts of calcium, phosphorus, potassium, magnesium, and iron. Singh and Kumar (2020) found that makhana possesses strong antioxidant properties due to the presence of flavonoids and phenolic compounds, which help reduce oxidative stress in the body.

Makhana is widely recommended for people suffering from lifestyle-related diseases such as obesity, diabetes, hypertension, and heart disorders. Since it is low in calories and fat, it is considered beneficial for weight management and healthy digestion. The high fiber content of makhana improves digestive health and helps prevent constipation. Its low glycemic index also makes it suitable for diabetic patients.

Nutritional Component	Approximate Value	Importance in Human Health
Energy	347 kcal	Provides energy for daily activities
Carbohydrates	76.9 g	Major source of energy
Protein	9.7 g	Helps in body growth and tissue repair

Fat	0.1-0.5 g	Low fat content suitable for healthy diet
Dietary Fiber	7.6 g	Improves digestion and gut health
Calcium	60 mg	Essential for bones and teeth
Phosphorus	200 mg	Important for energy metabolism
Potassium	500 mg	Helps regulate blood pressure
Iron	1.4 mg	Important for hemoglobin formation
Magnesium	67 mg	Supports muscle and nerve function
Antioxidants	Present	Helps reduce oxidative stress
Gluten	Absent	Suitable for gluten-free diets

(Singh et al 2018)

Makhana is considered an excellent source of plant-based protein and energy. Due to its nutritional quality, it is increasingly included in breakfast cereals, roasted snacks, sweets, and bakery products. The growing demand for healthy and organic foods has increased the popularity of makhana in national and international markets.

According to Mishra et. al., (2021), regular consumption of makhana helps improve kidney function, strengthen bones, and support cardiovascular health. Makhana is also used in traditional Ayurvedic medicine for treating weakness, insomnia, and reproductive disorders.

The crop is processed through a traditional roasting and popping technique. Raw makhana seeds are first dried, roasted at high temperatures, tempered, and then popped manually using wooden hammers. The quality of popping greatly influences the nutritional value and market price of makhana kernels.

Makhana cultivation and processing also provide employment opportunities to rural communities, especially in wetland areas of Bihar. Thousands of farmers, labourers, and processors depend on makhana cultivation for their livelihood. The crop contributes significantly to the rural economy and supports wetland-based farming systems.

In recent years, value addition and product diversification have further increased the commercial importance of makhana. Flavoured roasted makhana, makhana powder, makhana kheer mix, breakfast cereals, and energy bars are becoming popular among health-conscious consumers. Food industries are increasingly using makhana as an ingredient in functional foods and nutraceutical products.

Despite its nutritional and economic importance, makhana cultivation faces several challenges such as labour-intensive processing, lack of mechanization, poor market infrastructure, and limited awareness regarding its nutritional benefits. According to Kumar and Jha (2022), modernization of processing technologies and better marketing strategies are necessary to improve profitability and promote makhana consumption globally.

Research institutions and extension agencies are working to improve makhana production, processing, and value addition technologies. Scientific cultivation practices, mechanized processing systems, and awareness campaigns can further enhance the nutritional and economic value of this aquatic crop.

Personal Opinion Column

In my opinion, makhana has immense potential to become a globally recognized superfood because of its exceptional nutritional and medicinal properties. Greater awareness should be created among consumers regarding the health benefits of makhana. Farmers and processors should also receive training on improved cultivation, processing, packaging, and value addition technologies. Government support, branding, and export promotion can help strengthen the makhana industry and improve rural livelihoods in wetland regions.

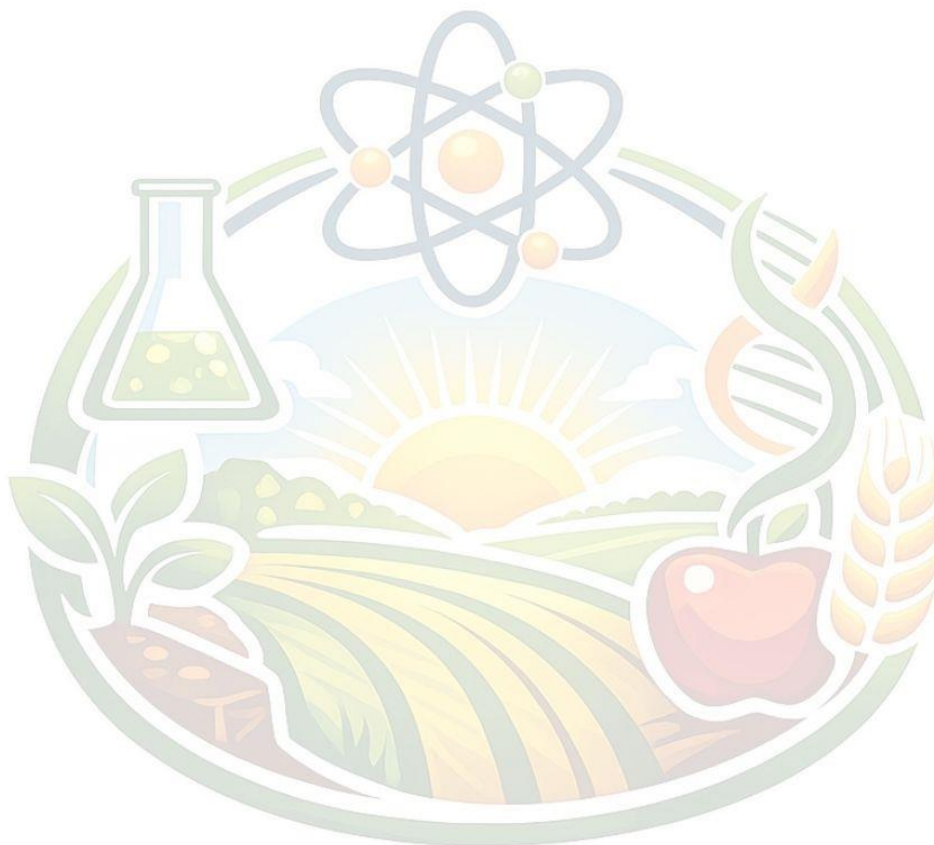
Summary/Conclusion

Makhana is a highly nutritious aquatic crop rich in proteins, carbohydrates, minerals, antioxidants, and dietary fiber. Its low fat and calorie content make it an ideal health food for modern consumers. The crop provides several health benefits, including improved digestion, heart health, weight management, and antioxidant protection. Makhana cultivation and processing also support rural livelihoods and wetland-based farming systems, especially in Bihar. Although challenges such as labour-intensive processing and limited awareness still exist, scientific interventions, value addition, and improved marketing can significantly enhance the future prospects of makhana. With growing global demand for healthy foods, makhana has strong potential to emerge as an important functional food and nutraceutical product.

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Water Chestnut: An Important Aquatic Crop for Nutrition and Rural Livelihood

Article ID: 73764

Shivani Jha¹, Dharmender², Vinod Kumar Padala³

¹Young Professional-II, ICAR-National Research Centre for Makhana, Darbhanga, Bihar.

²Scientist, ICAR-National Research Centre for Makhana, Darbhanga, Bihar.

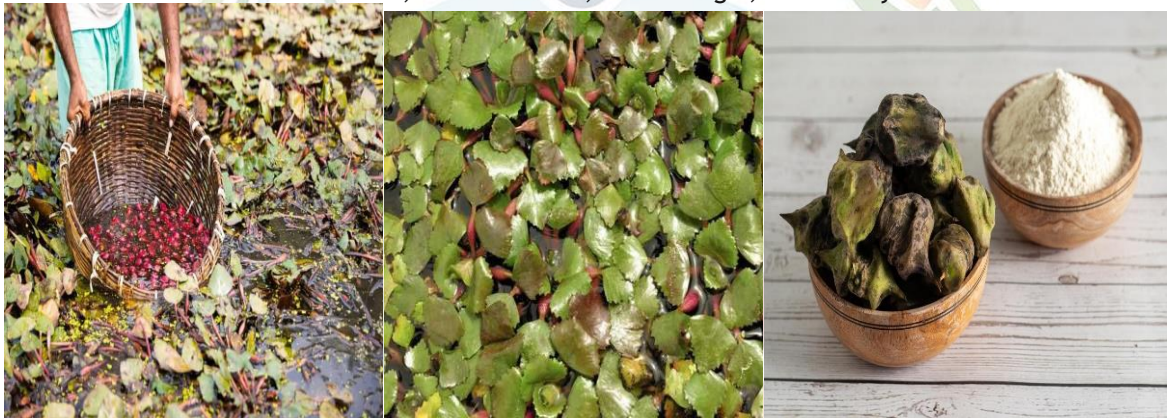
³Scientist, ICAR-National Research Centre for Makhana, Darbhanga, Bihar.

Summary of Article

Water chestnut is an important aquatic crop cultivated in ponds, wetlands, lakes, and waterlogged areas across many parts of Asia. It is valued for its nutritional benefits, medicinal properties, and economic importance for rural communities. The crop is rich in carbohydrates, minerals, vitamins, and antioxidants, making it an important seasonal food. Water chestnut cultivation also provides employment opportunities and contributes to the livelihood of farming communities, especially in wetland regions. This article discusses the importance, cultivation practices, nutritional value, economic significance, challenges, and future prospects of water chestnut cultivation in India.

Introduction

Aquatic crops play a significant role in improving rural livelihoods and ensuring nutritional security in wetland regions. Among these crops, water chestnut is one of the most important aquatic fruits cultivated in ponds, shallow lakes, marshy lands, and waterlogged fields. Water chestnut belongs to the genus *Trapa* and is commonly known as Singhara in India. It is widely cultivated in states such as Bihar, Uttar Pradesh, West Bengal, and Madhya Pradesh.



Water chestnut is an annual floating aquatic plant that grows well in standing freshwater bodies. The crop produces triangular or horn-shaped fruits enclosed within a hard shell. The edible kernel inside the fruit is consumed fresh, boiled, or processed into flour. Singh et. al., (2019) reported that water chestnut cultivation plays an important role in supporting the livelihoods of wetland farmers due to its low input requirement and high market demand.

Water chestnut is highly nutritious and contains carbohydrates, proteins, minerals, vitamins, and dietary fiber. It is also considered beneficial for digestion and overall health. The flour prepared from dried water chestnut fruits is commonly consumed during fasting periods in India. According to Kumar and Mishra (2020), water chestnut flour is gluten-free and rich in essential nutrients, making it suitable for health-conscious consumers.

The crop requires warm climatic conditions and stagnant water for proper growth and development. Water chestnut cultivation generally starts during the summer season when seeds or seedlings are introduced into ponds or shallow water bodies. The plants spread rapidly over the water surface and produce floating leaves. Flowering and fruiting begin during the rainy season, and harvesting is usually carried out from September to November.

Traditional cultivation methods are still commonly practiced in many rural areas. Farmers manually sow seeds, manage weeds, and harvest fruits from ponds. Harvesting is labour-intensive because fruits are collected manually from underwater plants. Despite this, water chestnut cultivation remains profitable due to good market demand and low production costs.

Water chestnut cultivation contributes significantly to rural employment generation. Many landless and small farmers depend on aquatic crop cultivation for seasonal income. In wetland-dominated regions of Bihar, water chestnut farming provides livelihood opportunities for farming communities, labourers, and local traders. Sharma et. al., (2021) found that aquatic crop cultivation improved socio-economic conditions of rural households in wetland ecosystems.

The crop also has medicinal importance. Water chestnut fruits are traditionally used in Ayurvedic preparations for improving digestion, controlling dehydration, and reducing fatigue. The fruits are rich in potassium, calcium, iron, and antioxidants, which help maintain good health. Due to increasing awareness about healthy foods, demand for water chestnut-based products is gradually increasing in urban markets.

Water chestnut cultivation is environmentally beneficial because it utilizes wetlands and waterlogged areas that are often unsuitable for conventional agriculture. The crop supports aquatic biodiversity and helps improve wetland productivity. Integrated farming systems involving fish culture and aquatic crops can further enhance farmers' income and resource utilization efficiency.

However, water chestnut cultivation faces several challenges. Lack of quality planting materials, poor water management, pest infestation, labour shortages, and limited mechanization are major constraints. In many regions, farmers still rely on traditional cultivation techniques and have limited access to scientific knowledge and extension services. According to Verma and Yadav (2022), inadequate research support and poor post-harvest management reduce the profitability of aquatic crops.

Modern technologies and improved extension services can help improve water chestnut production. Scientific pond management, quality seed distribution, integrated nutrient management, and pest control practices can increase yield and profitability. Digital advisory systems and farmer training programs can also support better crop management and marketing.

Water chestnut cultivation also has potential for value addition and agro-processing industries. Products such as water chestnut flour, snacks, sweets, and processed foods have growing market demand. Development of processing units and better marketing infrastructure can create additional income opportunities for farmers and rural entrepreneurs.

Personal Opinion Column

In my opinion, water chestnut cultivation has immense potential for improving rural livelihoods and utilizing wetland resources efficiently. More research attention should be given to aquatic crops because they are highly suitable for regions with abundant water resources. Farmers need training on scientific cultivation practices, post-harvest management, and value addition techniques. Government support, extension services, and market linkages can greatly help promote water chestnut cultivation as a profitable and sustainable farming enterprise.

Summary/Conclusion

Water chestnut is an important aquatic crop with high nutritional, medicinal, and economic value. It plays a significant role in supporting rural livelihoods, especially in wetland regions. The crop requires relatively low inputs and provides good returns to farmers through fresh fruit sales and processed products. Despite its importance, several challenges such as poor mechanization, lack of quality planting materials, and limited scientific support affect its productivity. Adoption of improved cultivation practices, better extension services, value addition, and market development can enhance the profitability and sustainability of water chestnut farming. With increasing demand for nutritious and health-based foods, water chestnut cultivation has strong future potential in India.

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Extreme Weather Events and Their Impact on Agriculture: Evidence Synthesis and Adaptation Priorities

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Aslesha Rath¹

¹Department of Agricultural Meteorology, OUAT, Bhubaneswar, India.

Abstract

Extreme weather events (EWEs), including droughts, heat waves, floods, cyclones, and extreme precipitation events, increasingly threaten agricultural productivity, food security, and rural livelihoods worldwide. This review synthesizes evidence from peer reviewed literature concerning the influence of EWEs on crop production systems, with emphasis on physiological mechanisms, crop stage sensitivity, and climatic risk. Agricultural losses intensify when climatic extremes coincide with critical phenological stages such as flowering and grain filling. Compound stresses, particularly simultaneous heat and drought events, frequently magnify crop damage beyond the impacts of isolated hazards. Existing studies further demonstrate that EWEs substantially increase interannual yield variability, thereby intensifying uncertainty in farm management, agricultural markets, and food systems. Major analytical approaches employed in agrometeorological research, including climatic indices, econometric analysis, crop simulation modelling, and remote sensing applications, are also summarized. Furthermore, adaptation priorities and major research gaps are highlighted to support climate resilient agriculture and strengthen agrometeorological advisory frameworks.

Keywords: extreme weather events, drought, heat stress, floods, crop yield variability, agrometeorology, climate resilience.

Introduction

Agrometeorology examines the interaction between atmospheric processes and agricultural systems, including crops, livestock, soil, and water resources. Extreme weather events are characterized not only by statistical rarity but also by their capacity to exceed ecological tolerance thresholds and disrupt biological and environmental processes within agroecosystems. Such events alter soil moisture dynamics, canopy energy exchange, crop phenology, nutrient cycling, pollination success, and harvesting operations. Wheeler and von Braun (2013) identified climatic extremes as major threats to global food systems because agricultural productivity remains strongly dependent upon seasonal weather conditions.

Agricultural systems exhibit pronounced stage specific sensitivity to environmental stress. Similar climatic anomalies may produce markedly different outcomes depending upon crop species, developmental stage, cultivar characteristics, and management practices. Heat stress during flowering, for instance, may drastically reduce grain formation, whereas comparable stress during vegetative growth often causes comparatively limited damage. Contemporary climate assessments indicate increasing frequency, intensity, and duration of both isolated and compound climatic extremes, especially concurrent heat and drought conditions, thereby amplifying production risks across tropical and temperate agroecosystems (Zampieri *et al.*, 2020).

Extreme weather events additionally destabilize farm income, market supply chains, and rural livelihoods. Developing countries remain particularly vulnerable because substantial populations depend directly upon climate sensitive agriculture for economic security. Limited irrigation infrastructure, inadequate institutional support, and restricted access to climate information further intensify vulnerability among smallholder farming communities. Consequently, understanding the mechanisms, impacts, and adaptation strategies associated with EWEs has become indispensable for achieving sustainable agricultural development and long term food security.

Major Extreme Weather Hazards and Agricultural Impacts

Drought: Drought represents one of the most severe climatic constraints affecting agricultural systems globally. Prolonged precipitation deficits reduce soil moisture availability, impair nutrient uptake, suppress photosynthetic activity, and accelerate leaf senescence. Rainfed agricultural systems are particularly vulnerable because crop productivity depends heavily upon seasonal rainfall variability. BIRTHAL *et al.* (2014) demonstrated that rainfall deficits substantially reduce agricultural productivity and farm income, particularly in semi arid regions of India.

Drought stress becomes especially destructive during reproductive growth stages such as flowering and grain filling because moisture deficits during these phases directly reduce grain development and final yield. Extended drought conditions additionally reduce microbial activity and nutrient mineralization within soils, thereby impairing long term soil fertility and agricultural sustainability. In many developing regions, recurrent drought events contribute to food insecurity, indebtedness, and agrarian distress.

Heat Waves: Heat waves are prolonged episodes of abnormally high temperature that adversely affect crop physiology, reproductive processes, and yield formation. Elevated temperatures increase canopy temperature and vapour pressure deficit, thereby intensifying evapotranspirative demand and plant water stress. Heat stress during anthesis and grain filling frequently induces pollen sterility, shortens grain development duration, and reduces assimilate translocation to reproductive organs. Cereals such as wheat and rice exhibit particularly high sensitivity to elevated temperature stress during reproductive stages (Challinor *et al.*, 2014).

Extreme thermal conditions additionally accelerate crop maturity and reduce biomass accumulation. Severe heat stress impairs photosynthetic efficiency because of enzymatic disruption and membrane instability, ultimately reducing grain quality and market value. Increasing occurrence of heat waves in tropical and subtropical regions therefore constitutes a significant threat to agricultural sustainability and food security.

Floods, Extreme Rainfall, and Cyclones: Extreme rainfall events and floods disrupt agricultural systems through waterlogging, nutrient leaching, soil erosion, and physical crop damage. Flood induced submergence restricts oxygen availability and photosynthetic activity, thereby reducing plant growth and survival. Waterlogging frequently delays sowing and harvesting operations while increasing disease incidence and crop lodging (Porter *et al.*, 2014). Recurrent flooding in low lying and deltaic regions contributes to long term soil degradation and declining agricultural productivity.

Cyclones and severe storms generate additional damage through high velocity winds, intense precipitation, and storm surges. Strong winds cause lodging in cereals and physical destruction of standing crops, while seawater intrusion increases soil salinity in coastal agricultural regions. Salinity accumulation adversely affects soil structure, nutrient availability, and crop productivity over extended periods. Such hazards also damage irrigation infrastructure, transportation systems, and storage facilities, thereby disrupting agricultural operations and market accessibility.

Approaches Used in Agrometeorological Research

Agrometeorological investigations employ diverse analytical approaches to evaluate the impacts of EWEs on agricultural systems. Climatic indices such as the Standardized Precipitation Index (SPI) and Standardized Precipitation Evapotranspiration Index (SPEI) are extensively utilized for drought assessment because they quantify moisture deficits across multiple temporal scales. Heat stress is commonly evaluated using heat degree days and temperature threshold indices, whereas extreme rainfall events are assessed through percentile based precipitation indicators.

Statistical crop climate models, including regression analysis and panel econometric approaches, are widely applied to estimate climatic impacts on agricultural productivity across regional and global scales. Ray *et al.* (2015) demonstrated that climatic variability explains a substantial proportion of interannual crop yield fluctuations worldwide. Such approaches provide valuable insights into historical climate yield relationships and production risk patterns.

Process based crop simulation models such as DSSAT and APSIM are increasingly employed to evaluate crop responses under varying climatic and management scenarios. These models simulate crop growth, water balance, nutrient dynamics, and yield formation under different environmental conditions. Remote sensing technologies additionally provide spatially explicit information regarding vegetation condition, evapotranspiration anomalies, flood inundation, and drought severity. Satellite based observations therefore strengthen early warning systems and climate informed agricultural decision making.

Adaptation Priorities and Conclusion

Adaptation strategies are essential for reducing agricultural vulnerability to EWEs and strengthening long term resilience. Agronomic interventions such as optimized sowing windows, conservation tillage, residue retention, and crop diversification reduce climatic exposure during sensitive growth stages. Development and dissemination of heat tolerant, drought tolerant, salinity tolerant, and submergence tolerant cultivars further enhance adaptive capacity under changing climatic conditions. Efficient water management strategies, including supplemental irrigation and rainwater harvesting, additionally improve drought resilience and water use efficiency.

Risk management instruments such as crop insurance, contingency planning, and climate advisory services contribute to income stabilization under climatic uncertainty. Weather forecasting systems, remote sensing technologies, and seasonal climate outlooks provide valuable support for timely agricultural decision making and disaster preparedness. However, important research gaps remain, particularly regarding compound climatic extremes, horticultural systems, and socioeconomic vulnerability dimensions. Future research should integrate remote sensing datasets, reanalysis products, and process based crop models to strengthen climate resilient agricultural planning.

Extreme weather events increasingly threaten agricultural sustainability through their adverse impacts on crop productivity, production stability, and rural livelihoods. Evidence across diverse agroecological regions demonstrates that crop stage sensitivity and compound climatic hazards largely determine the magnitude of agricultural losses. Strengthening agrometeorological services, promoting climate smart agricultural practices, and improving adaptive crop management will therefore be critical for sustaining future agricultural productivity under intensifying climatic uncertainty.

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An Overview on Plant-Based Meat: Scientific Principles, Manufacturing Process, and Market Scenario in India

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Anushka Singh¹, Dr. D. K. Rana²

¹Research scholar, Department of horticulture, HNB Garhwal University, Srinagar, Uttarakhand.

²Associate Professor, Department of horticulture HNB Garhwal University, Srinagar, Uttarakhand.

Introduction

Plant based meat (PBM) is a product derived from plants that has been designed to resemble the taste, texture and appearance of animal meat through plant proteins, fats and functional additives. Over the past few years, these types of products have moved beyond being vegetarian alternatives to a significant market share of the worldwide protein market, and India is quickly becoming a hotspot for innovation and consumption of plant based meats. The science behind plant-based meats is that during processing, plant proteins are structurally and functionally modified to simulate animal muscle tissue and mimic its chewiness and fibrous consistency.

What is Plant-Based Meat?

1. Definition and Composition: Value added foods are a form of plant-based meat substitutes, which is made with plant ingredients like soy, wheat gluten, peas, mung beans, and other oils and starches that mimic the taste and texture of traditional meat. Typical formulations include:

- a. Plant protein isolates or concentrates (soy, pea, wheat gluten),
- b. Vegetable oils (coconut, sunflower, etc.) to mimic fat,
- c. Starches and fibres for texture and juiciness,
- d. Flavourings, colourants, and fortificants (e.g., vitamin B12, iron).

2. Scientific Classification: For food science, plant based meats are defined as meat analogues or meat mimicking products because they attempt to mimic the way that meats taste, feel and cook (not specifically with respect to protein levels). Unlike vegetarian foods (e.g. tofu or tempeh), they are essentially created to resemble certain cuts or shapes of animal meat such as burgers, nuggets, flavoured keema or sausages, etc.

Scientific Principles Behind Plant-Based Meat Design

1. Protein Structure and Texture Engineering: The main difficulty in plant based meat science is to obtain plant protein that has aligned fibrous bodies in the form of protein that resembles an animal muscle fibre. This can be accomplished through:

- a. **Denaturation and alignment:** Under heat, pressure, and mechanical shear, plant proteins unfold and reorganize into anisotropic networks.
- b. **Crosslinking and hydration:** Using water, salts and gelling agents (such as methylcellulose or starches) will help bind the proteins and keep them moist for juiciness and chewiness.

2. Key Formulation Parameters: Scientists try to improve the taste, consistency and nutritional value of the animal meat:

- a. **Protein blend design** to achieve optimal amino acid profile and function, eg soy-pea, soy-wheat, pulse-mycop.
- b. **Moisture content and temperature-time** on extrusion to regulate fibrousness and springiness.
- c. **Maintain saturated fat** at a relatively low levels with fat level and type to simulate marbling and mouthfeel.

The design features and options enable plant based meats to come close to the water holding, mechanical strength, and sensory properties of traditional meat-based products, given that they are only made from plants.

Manufacturing Process

Overall Process Flow: Many plant based meats (particularly fibrous varieties) are produced industrially through extrusion based texturisation, before flavoring, shaping and packaging. A sequence of events that is scientifically accurate is:

- 1. Raw material selection:** Selection of plant sources (e.g., soybeans, peas, wheat, mung beans) and cleaning.
- 2. Protein isolation and preparation:** Defatting, milling, and protein isolation (such as soy protein isolate and pea protein concentrate).
- 3. Formulation:** Combining protein, water, oils, starches, salts and small quantities of functional ingredients to a usable dough.



- 4. Extrusion (high moisture or low moisture):** The dough is extruded through an extruder where heat and pressure and shear forces cause protein denaturation and fibre formation; products can be continuously extruded as strips or pellets.
- 5. Cutting, shaping and cooling:** The extrudate is then chopped or formed into patties, nuggets, strips or blocks, then cooled to freeze the shape.
- 6. Marination and flavouring:** The products are flavoured with savoury flavour systems, colourants (e.g., beet or heme like compounds), and seasonings to imitate meat flavour and appearance.
- 7. Cooking/finishing and packaging:** Some products are in the “raw like” state and are sold for the purpose of being cooked at home, some are pre-cooked (baked, fried or grilled). Final products are packaged under refrigerated or frozen conditions.

Nutritional and Health Aspects

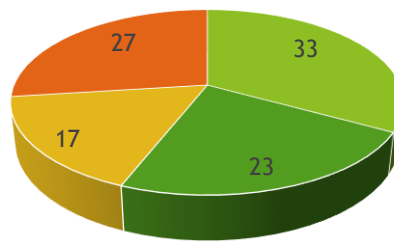
- 1. Macronutrient Profile:** Plant based meats are typically similar to animal meat, but lower in saturated fat and cholesterol free. They are often rich in dietary fibre, whereas most meat products are low in fibre, and can be supplemented with minerals like iron and vitamin B12 to help vegetarian and vegan diets.
- 2. Health Implications:** When combined with a diet rich in whole grains, vegetables and legumes, a replacement of red meat with well formulated plant-based analogues and may help lower LDL cholesterol and some cardiovascular risk markers. Many commercial products, however, are relatively high in sodium, include emulsifiers or flavour enhancers and should be considered as processed plant-based foods, and not as a “health food”.

Reading the labels and combining PBMs with minimally processed plant foods (such as dal, vegetables, whole grains) supports Indian consumers in achieving a balanced consumption of proteins, fibre and micronutrients.

Plant-Based Meat Market in India

- 1. Market Size and Growth:** The sale of plant-based meat in India was estimated to hit around USD 98.6 Million in 2024 and will reach USD 737.9 Million by 2033 at an approximate rate of growth of 22.3% CAGR. It is expected that the trend will continue to grow thanks to increased vegetarians/flexitarians and urban diets, improved affordability and living standards, and the availability of plant-based food on QSR menus and food delivery platforms.
- 2. Product Segmentation:** Indian plant-based meat products are generally sold in the following categories and may also include but not limited to: burger patties, sausages, nuggets and strips, meat for ground meat (keema), meatballs and additives for Indian cuisine - including biryani ‘meat’ and kebabs. Soy & wheat-based proteins currently are the predominant proteins, with pea & mixed pulse-based proteins rising in popularity.
- 3. Pie-Chart Data: Product-Type Share (Approximate):** This pie chart represents the approximate percentages, based on recent market reports on India’s plant-based meat segment.

Approximate Share (%)

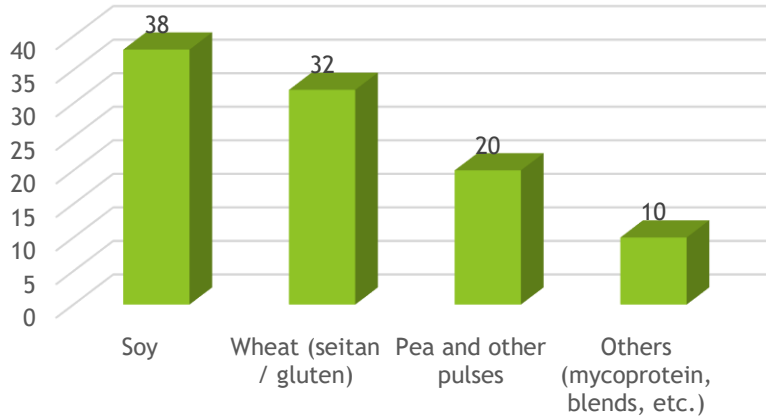


- Burger patties and sausages
- Nuggets and strips
- Ground meat and meatballs
- Other formats (kebabs, biryani proteins, etc.)

Ken Research. “India Plant-Based Meats Market Outlook 2030.” 2024.kenresearch

4. Protein-Source Breakdown (Illustrative Bar Graph Data): Indian plant-based meat products rely mainly on soy and wheat, with growing shares of pea and various pulse-based proteins. The following bar graph provides the approximate shares:

Approximate Share (%)



Food Processing Sector Profile (MoFPI). “Plant-based Proteins.” Government of India, revised 2020s.mofpi

Environmental and Ethical Dimensions

1. Environmental Impact: Plant based meats are typically lower in land, water, and energy use per protein pound, and result in lower GHG emissions, compared to beef and poultry. Lifecycle assessment studies indicate that the carbon footprint of soy and pea based PBM can be lowered by approximately 60-90% when compared to the beef carbon footprint as a function of the agriculture and processing.

Responsible sourcing and agricultural practices are essential for the environmental benefits, but intensive cultivation of soy or other feed crops can still cause problems like deforestation or soil degradation if done in an unsustainable way.

2. Ethical and Cultural Fit: In India, plant-based meats fit in with the popular vegetarian culture and rising animal welfare consciousness, that provide reduced or no animal slaughter. They also provide a route for the diversification of protein sources for a nation experiencing increased demand for animal vs. vegetable protein and related environmental issues.

Challenges and Future Directions

1. Current Challenges: Major hurdles to the use of plant-based meat in India are:

- a. **Flavor and texture:** PBMs continue to be perceived as “artificial” or different from real meat.
- b. **Price sensitivity:** Lower income segments may not consume plant-based products as they are more expensive than conventional meat.

c. **Clarification and regulation of labels:** Labelling needs to be clearer (e.g. “plant-based meat” vs “vegetarian meat”) and there is a need for uniformity in safety standards.

2. Scientific and Technological Trends: Research is ongoing in the following areas:

- Optimization of protein blends with amino acid completeness and textural authenticity.
- Reduced sodium, cleaner label ingredients and shelf stability and taste.
- Creating a recipe of the traditional Indian dishes like keema, biryani “meat” and grilled kebabs.

The development in high moisture extrusion, fermentation and 3D food printing technologies are anticipated to improve the sensory profile and nutritional profile of plant-based meats towards animal meat, meeting India's long term sustainable and safe protein supply.

Conclusion

Plant-based meat offers a promising solution to mitigate environmental impacts associated with meat production, the public-health hazards of overindulgence in processed animal-based foods, and the challenge of diversifying India's food systems while satisfying cultural dietary preferences. Although sensory and nutritional properties have been enhanced due to advanced ingredient functionality and processing, further research is required to maximize ingredient protein quality, micronutrient bioavailability and clean-label ingredients for regional cuisines. Scaling production in an affordable and equitable manner will require policy support, transparent labelling and investments in local supply chains. If India transitions to a plant-based diet with careful policy, science and industry coordination, plant-based meat can be a complementary part of a sustainable and healthful diet without displacing livelihoods.

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Circular Bioeconomy: Turning Waste into Wealth for a Sustainable Future

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 Abhilash¹
¹Ph.D. Scholar, College of Agriculture, University of Agricultural Sciences, Dharwad.

Summary of Article

The circular bioeconomy is an approach that integrates renewable biological resources with circular economic principles to create a sustainable system that minimizes waste and maximizes resource efficiency. It offers benefits such as reduced pollution, climate change mitigation, and economic growth. While challenges like high costs and technological limitations exist, strong policies and innovation can help unlock its full potential, making it a key strategy for sustainable development.

Introduction

As the world faces growing environmental challenges such as climate change, resource depletion, and waste generation, the concept of a *circular bioeconomy* has emerged as a promising solution. It combines the principles of the circular economy—reducing, reusing, and recycling—with the use of renewable biological resources to create a sustainable and efficient economic system.

What is Circular Bioeconomy?

A circular bioeconomy refers to an economic system where biological resources such as crops, forests, animals, and microorganisms are used sustainably to produce food, energy, and materials, while minimizing waste and environmental impact. Unlike the traditional “take-make-dispose” model, it focuses on closing resource loops by reusing and recycling biological materials (European Commission, 2021).

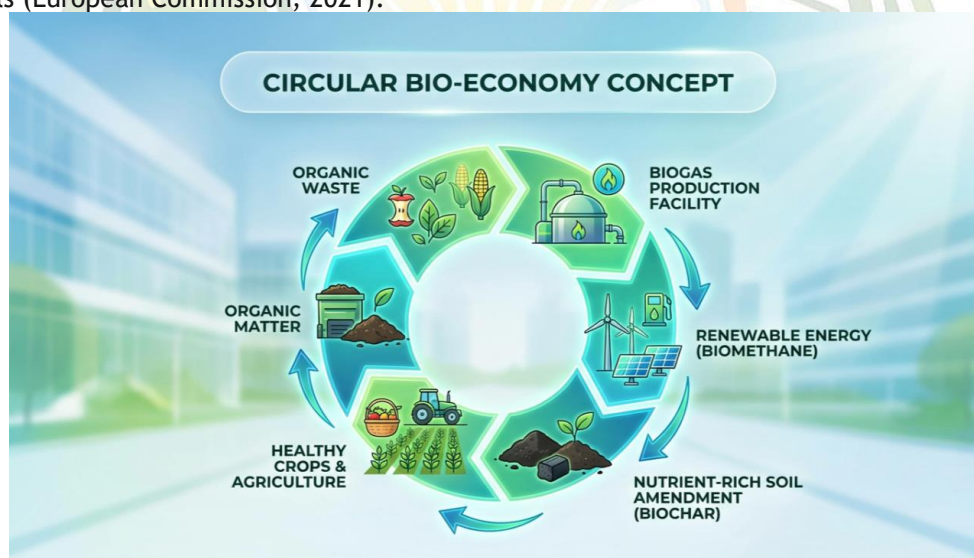


Figure: Circular Bio-economy flow

For example, agricultural waste can be converted into bioenergy, bioplastics, or organic fertilizers, ensuring that resources are continuously reused rather than discarded.

Key Components of Circular Bioeconomy

The circular bioeconomy is built on three main pillars:

1. **Renewable Biological Resources:** Use of biomass such as plants, algae, and organic waste.
2. **Circular Processes:** Recycling, composting, and reusing biological materials.
3. **Sustainable Production:** Minimizing environmental damage while maximizing resource efficiency (OECD, 2020).

Benefits of Circular Bioeconomy

This approach offers multiple economic, environmental, and social benefits:

1. **Waste Reduction:** Converts waste into valuable products, reducing landfill and pollution (UNEP, 2022).
2. **Climate Change Mitigation:** Lowers greenhouse gas emissions by replacing fossil-based products.

3. **Resource Efficiency:** Promotes optimal use of natural resources.
4. **Economic Growth:** Creates new industries and job opportunities in bio-based sectors (World Bank, 2023).
5. **Energy Security:** Encourages the use of renewable energy sources such as biofuels.

Real-World Applications

Circular bioeconomy practices are already being implemented worldwide:

1. Conversion of agricultural residues into biofuels
2. Production of biodegradable plastics from plant materials
3. Composting of food waste into organic fertilizers
4. Use of algae for bioenergy and wastewater treatment

These applications demonstrate how waste can be transformed into valuable resources.

Challenges and Limitations

Despite its potential, the circular bioeconomy faces several challenges:

1. **Technological Barriers:** Advanced technologies are required for efficient biomass conversion.
2. **High Initial Costs:** Infrastructure and research investments can be expensive.
3. **Policy Gaps:** Lack of supportive regulations and incentives in some regions.
4. **Sustainability Concerns:** Overuse of biomass may lead to ecological imbalance if not managed properly (OECD, 2020).

The Way Forward

To promote the circular bioeconomy, governments and stakeholders must focus on:

1. Strengthening policies and regulatory frameworks
2. Investing in research and innovation
3. Encouraging public-private partnerships
4. Raising awareness about sustainable consumption

With coordinated efforts, the circular bioeconomy can significantly contribute to achieving global sustainability goals.

Summary

The circular bioeconomy is an approach that integrates renewable biological resources with circular economic principles to create a sustainable system that minimizes waste and maximizes resource efficiency. It offers benefits such as reduced pollution, climate change mitigation, and economic growth. While challenges like high costs and technological limitations exist, strong policies and innovation can help unlock its full potential, making it a key strategy for sustainable development.

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Water Pricing and Groundwater Markets: Managing a Scarce Resource

Article ID: 73768

Abhilash¹

¹Ph.D. Scholar, College of Agriculture, University of Agricultural Sciences, Dharwad.

Summary of Article

Water pricing and groundwater markets are important tools for managing scarce water resources efficiently. Water pricing assigns value to water use, encouraging conservation, while groundwater markets allow users to trade water, improving access and allocation. Although these systems promote efficiency, innovation, and sustainability, they also pose challenges such as over-extraction, inequality, and implementation difficulties. With appropriate regulation and monitoring, they can significantly contribute to sustainable water management.

Introduction

Water is one of the most essential yet increasingly scarce natural resources in the world. With rising population, urbanization, and climate change, the pressure on freshwater resources—especially groundwater—has intensified. In this context, *water pricing and groundwater markets* have emerged as important tools for promoting efficient and sustainable water use.



Figure: Ground water management in agriculture

Understanding Water Pricing

Water pricing refers to the practice of assigning a monetary value to water usage. Traditionally, water has often been underpriced or even provided for free, especially in agriculture. However, this has led to overuse and depletion of water resources. By pricing water appropriately, governments aim to encourage conservation, reduce wastage, and allocate water to its most productive uses (World Bank, 2023).

There are different approaches to water pricing, such as:

1. **Flat rates:** Users pay a fixed amount regardless of consumption.
2. **Volumetric pricing:** Charges are based on the quantity of water used.
3. **Increasing block tariffs:** Higher rates are applied as consumption increases.

Among these, volumetric pricing is considered more efficient as it directly links cost with usage (OECD, 2021).

Groundwater Markets: How They Work

Groundwater markets develop when individuals or farmers who have access to groundwater (through wells or borewells) sell water to others. These markets are particularly common in rural areas where formal water distribution systems are weak.

In such markets, water is traded either:

1. **Per unit of water**, or
2. **Per hour of pump usage**

Groundwater markets can improve access to water for small farmers who cannot afford their own wells. They also enable more efficient distribution of water resources (Shah, 2009).

Benefits of Water Pricing and Groundwater Markets

These mechanisms offer several advantages:

1. **Efficient Resource Use:** Pricing discourages wasteful consumption and promotes conservation (World Bank, 2023).
2. **Equity in Access:** Groundwater markets allow those without direct access to obtain water (Shah, 2009).
3. **Incentive for Investment:** Proper pricing encourages investment in water-saving technologies such as drip irrigation (OECD, 2021).
4. **Sustainability:** Helps in reducing over-extraction of groundwater resources (UNESCO, 2022).

Challenges and Concerns

Despite their benefits, these systems face several challenges:

1. **Over-Exploitation:** Markets may lead to excessive extraction if not regulated (UNESCO, 2022).
2. **Inequality:** Wealthier farmers may dominate water access, marginalizing small users (Shah, 2009).
3. **Measurement Issues:** Accurate monitoring of groundwater use is difficult.
4. **Political Resistance:** Raising water prices is often unpopular and difficult to implement.

The Way Forward

To ensure sustainability, water pricing and groundwater markets must be supported by strong institutions and regulations. Policies should focus on:

1. Metering and monitoring groundwater use
2. Protecting small farmers' access
3. Promoting efficient irrigation technologies
4. Raising awareness about water conservation

With proper governance, these tools can play a critical role in addressing global water scarcity.

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AGRICULTURE & FOOD

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Vertical and Urban Farming: Growing Food in the Cities of Tomorrow

Article ID: 73769

Abhilash¹

¹Ph.D. Scholar, College of Agriculture, University of Agricultural Sciences, Dharwad.

Summary of Article

Vertical and urban farming are innovative agricultural practices that enable food production within cities using advanced technologies and limited space. Vertical farming uses stacked layers and controlled environments, while urban farming includes community and rooftop agriculture. These methods improve food security, conserve resources, and reduce environmental impact. However, challenges such as high costs and energy use remain. With technological progress and policy support, these systems have strong potential to shape the future of sustainable food production.

Introduction

As cities expand and arable land becomes scarce, feeding the growing global population is an increasing challenge. In response, innovative agricultural practices such as *vertical farming* and *urban farming* are transforming how and where food is produced. These methods bring agriculture closer to consumers, making food systems more sustainable, efficient, and resilient.

What is Vertical Farming?

Vertical farming is the practice of growing crops in vertically stacked layers, often within controlled indoor environments such as warehouses or skyscrapers. It relies on advanced technologies like hydroponics (growing plants in nutrient-rich water), aeroponics (growing plants in air with mist), and artificial lighting systems.



Figure: Vertical Farming

This method allows year-round production, independent of weather conditions, and uses significantly less land and water compared to traditional farming (FAO, 2022). Additionally, vertical farms can be located in urban areas, reducing transportation costs and carbon emissions.

What is Urban Farming?

Urban farming refers to the cultivation of crops and raising of animals within cities and towns. It includes community gardens, rooftop farms, backyard cultivation, and small-scale commercial farms.



Figure: Urban Farming

Urban farming improves access to fresh and nutritious food, especially in densely populated areas. It also promotes community engagement, reduces food miles, and supports local economies (UN-Habitat, 2021).

Benefits of Vertical and Urban Farming

These modern farming systems offer several advantages:

1. **Efficient Land Use:** Vertical farming maximizes production per unit area by growing crops in layers (FAO, 2022).
2. **Water Conservation:** Uses up to 90% less water than traditional farming methods.
3. **Reduced Transportation:** Producing food within cities cuts down on transportation costs and emissions (UN-Habitat, 2021).
4. **Year-Round Production:** Controlled environments ensure consistent crop yields regardless of climate.
5. **Food Security:** Enhances access to fresh produce in urban areas (World Bank, 2023).

Challenges and Limitations

Despite their potential, these systems face several challenges:

1. **High Initial Costs:** Setting up vertical farms requires significant investment in technology and infrastructure.
2. **Energy Consumption:** Artificial lighting and climate control can lead to high energy use (IEA, 2023).
3. **Limited Crop Variety:** Currently, only certain crops like leafy greens are economically viable.
4. **Technical Expertise:** Requires skilled labor and knowledge of advanced farming systems.

The Future of Urban Agriculture

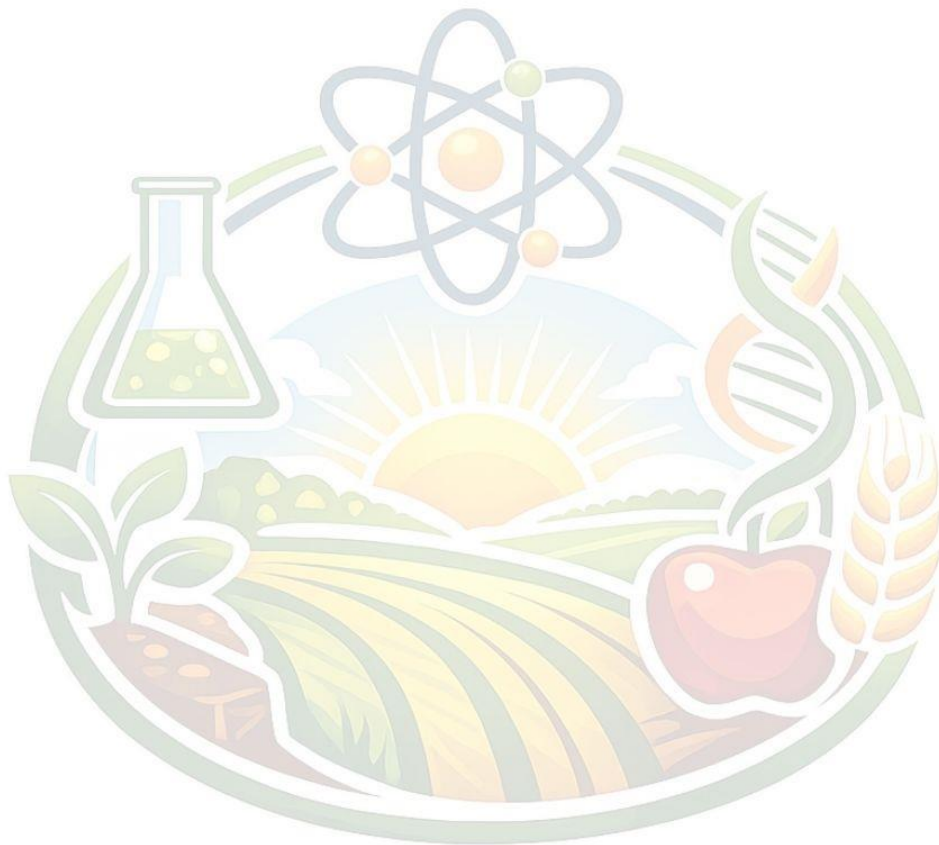
With advancements in renewable energy, automation, and smart technologies, vertical and urban farming are expected to become more efficient and affordable. Governments and private investors are increasingly supporting these innovations as part of sustainable urban development strategies.

As cities continue to grow, integrating agriculture into urban spaces will be crucial for ensuring food security and environmental sustainability.

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Thalinomics: Understanding Food Inflation Through the Common Plate

Article ID: 73770

Abhilash¹

¹Ph.D. Scholar, College of Agriculture, University of Agricultural Sciences, Dharwad.

Summary of Article

Thalinomics is an approach that measures food inflation by analyzing the cost of a typical Indian meal or thali. It provides a practical and relatable way to understand price changes in essential food items. Food inflation is driven by factors such as supply constraints, rising input costs, and global price fluctuations. Thalinomics highlights trends in affordability, price volatility, and regional differences, helping policymakers and the public better understand economic conditions. Despite some limitations, it is an effective tool for assessing food security and inflation.

Introduction

Food is a basic necessity, and its affordability is a key indicator of economic well-being. In India, the concept of *Thalinomics*—popularized in the Economic Survey—offers a simple yet powerful way to understand food inflation by analyzing the cost of a typical meal or “thali.” This approach connects macroeconomic trends with everyday experiences, making inflation more relatable to the common person.



Figure: Food Inflation

What is Thalinomics?

Thalinomics refers to the study of the cost of preparing a standard Indian meal (vegetarian and non-vegetarian thali) over time. Instead of abstract price indices, it focuses on the actual expenses incurred by households for basic food consumption (Government of India, 2020).

COST OF VEG AND NON-VEG THALIS UP 24% AND 13%, RESPECTIVELY, ON-YEAR IN AUG; RISE SOFTENS TO 10% AND 6% IN THE LAST WEEK DUE TO A SHARP DECLINE IN TOMATO PRICE

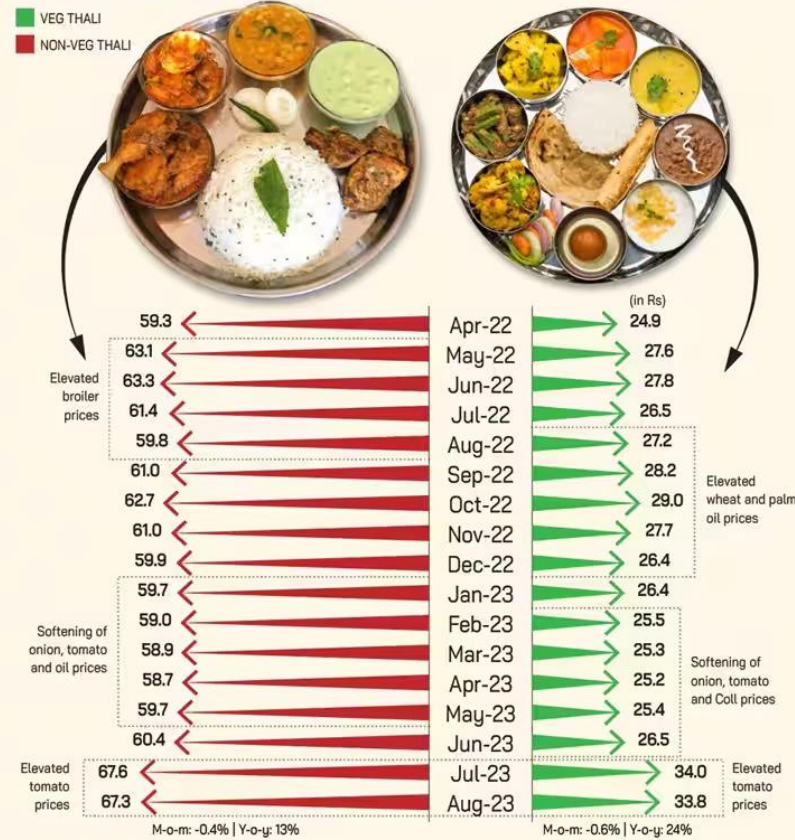


Figure: Veg & Non-Veg Thalies Inflation

By tracking the cost of ingredients such as cereals, pulses, vegetables, and cooking oil, Thalonomics provides a practical measure of food affordability and inflation trends.

Food Inflation and Its Drivers

Food inflation refers to the rise in prices of food items over time. Several factors contribute to food inflation:

- 1. Supply-Side Constraints:** Poor harvests due to droughts or floods can reduce supply and increase prices (FAO, 2022).
- 2. Rising Input Costs:** Increases in fuel, fertilizers, and transportation costs raise food prices.
- 3. Demand-Supply Imbalance:** Growing population and income levels increase demand for food.
- 4. Global Price Shocks:** International market fluctuations affect domestic food prices (World Bank, 2023).

Thalonomics helps capture these changes by reflecting how the cost of a daily meal evolves with these factors.

Insights from Thalonomics

Thalonomics has revealed several important insights:

- 1. Improved Affordability Over Time:** In certain periods, the cost of a thali has decreased relative to income, indicating improved purchasing power (Government of India, 2020).
- 2. Volatility in Food Prices:** Prices of key items like onions, tomatoes, and pulses can fluctuate significantly, impacting overall meal costs.
- 3. Regional Variations:** Food costs vary across states due to differences in production, distribution, and consumption patterns.

Importance of Thalonomics

Thalonomics is valuable for both policymakers and the public:

1. **Simplifies Inflation Measurement:** Makes complex inflation data easy to understand.
2. **Policy Guidance:** Helps governments design targeted food and subsidy policies.
3. **Focus on Nutrition:** Encourages consideration of balanced and affordable diets.
4. **Public Awareness:** Connects economic indicators with everyday life.

Challenges and Limitations

Despite its usefulness, Thalonomics has some limitations:

1. **Standardization Issues:** The composition of a “thali” may vary across regions.
2. **Exclusion of Non-Food Costs:** Does not account for other essential expenditures.
3. **Data Limitations:** Accurate and timely price data may not always be available.

Conclusion

Thalonomics offers a unique and relatable way to understand food inflation by focusing on the cost of a common meal. It bridges the gap between economic theory and real-life experiences, highlighting how inflation affects daily living. While it is not a comprehensive measure, it serves as a powerful tool for analyzing food affordability and guiding policy decisions in an increasingly uncertain economic environment.

Summary

Thalonomics is an approach that measures food inflation by analyzing the cost of a typical Indian meal or thali. It provides a practical and relatable way to understand price changes in essential food items. Food inflation is driven by factors such as supply constraints, rising input costs, and global price fluctuations. Thalonomics highlights trends in affordability, price volatility, and regional differences, helping policymakers and the public better understand economic conditions. Despite some limitations, it is an effective tool for assessing food security and inflation.

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Camouflage and Mimicry in Insects

Article ID: 73771

Gopu Sushma¹, Repaka Harika², Kota Sahithi Chowdary²

¹Ph. D Scholar, Professor Jayashankar Telangana Agricultural University, Hyderabad.

²Ph. D Scholar, Indira Gandhi Krishi Vishwavidyalaya, Raipur.

Introduction

Insects are among the most successful organisms on Earth because of their remarkable survival strategies. Among these, camouflage and mimicry are fascinating adaptations that help insects avoid predators, capture prey and survive in changing environments. Many insects blend perfectly with leaves, bark, flowers or even bird droppings, while others imitate dangerous species to deceive enemies. These natural defense mechanisms demonstrate the incredible creativity of evolution in the insect world.

Warning Coloration

Animals that are toxic to predators or use other chemical defenses often possess warning colors. Some animals living in the same habitats with inedible species sometimes evolve a coloration that mimics the warning coloration of the toxic species. Mimicry and camouflage is vital for many species to survive and prevent from becoming extinct. Thus this ensures longer survival for the animal and a higher chance of it being able to reproduce.

Camouflage

A survival technique in which an otherwise visible organism may be unseen or indiscernible from its surrounding environment. Prey species have evolved numerous defense mechanisms. Cryptic coloration includes colors and patterns that allow prey to blend into the background. A walking stick bug looks like the branch of a tree or a stick that has fallen off a tree.

Some animals are protectively colored, blending into the background of their normal environment. Object resemblance is common among insects. Some species appear to have conspicuous coloration when they are not in the proper surroundings. For example, among the brilliant butterflies of the forest, the magnificent electric blue Morpho, has iridescent blue upper wings. However, because the under wings are dark, when the Morpho flies through the flickering light of the forest or even out in broad daylight, it seems to disappear. Further it also helps the insects to hide from predators, to catch prey and to protect to young ones or eggs.

Examples:

- Stick insects resemble twigs.
- Leaf insects look exactly like leaves.
- Grasshoppers blend with green vegetation.
- Some moths resemble tree bark.



Mimicry

Mimicry is resemblance/similarity in appearance and/or behavior between a mimic and a model that provides a selective advantage to the mimic because it affects the behavior of a receiver causing it to misidentify the mimic and that evolved (or is maintained by selection) because of those effects.

Types of Mimicry

Batesian Mimicry: Batesian mimicry is named for Henry Walter Bates, a scientist who studied mimicry in Amazonian butterflies. Batesian mimicry refers to two or more species that are similar in appearance, but only one of which is dangerous. Example: Hoverflies resemble stinging bees or wasps.



Müllerian Mimicry: Müllerian mimicry is named for Fritz Mueller, a zoologist who worked in the Amazon after Bates. This form of mimicry refers to two not pleasant tasting species that are mimics of each other with conspicuous warning coloration. Thus all mimics share the benefits of the coloration since the predator will recognize the coloration of a group after a few bad experiences is unpalatable or toxic, not just one model species. Example: Certain monarch and viceroy butterflies share similar warning colors.



Self Mimicry: Self-mimicry is a misleading term for animals that have one body part that mimics another to increase survival during an attack or helps predators appear innocuous. For example, countless moth, butterfly and freshwater fish species have "eye-spots", large dark markings that when flashed may momentarily startle a predator and allow the prey extra seconds to escape.



Aggressive Mimicry: Aggressive mimicry is a type of mimicry that a predator will mimic a prey to catch another predator. For example, a snapping turtle's tongue mimics a worm so fish will come close to try to eat it and then the fish will be eaten by the snapping turtle.

Importance in Nature

1. Protects insects from predators.
2. Increases survival and reproduction.
3. Maintains ecological balance.
4. Shows the role of evolution and adaptation.

Importance in Agriculture

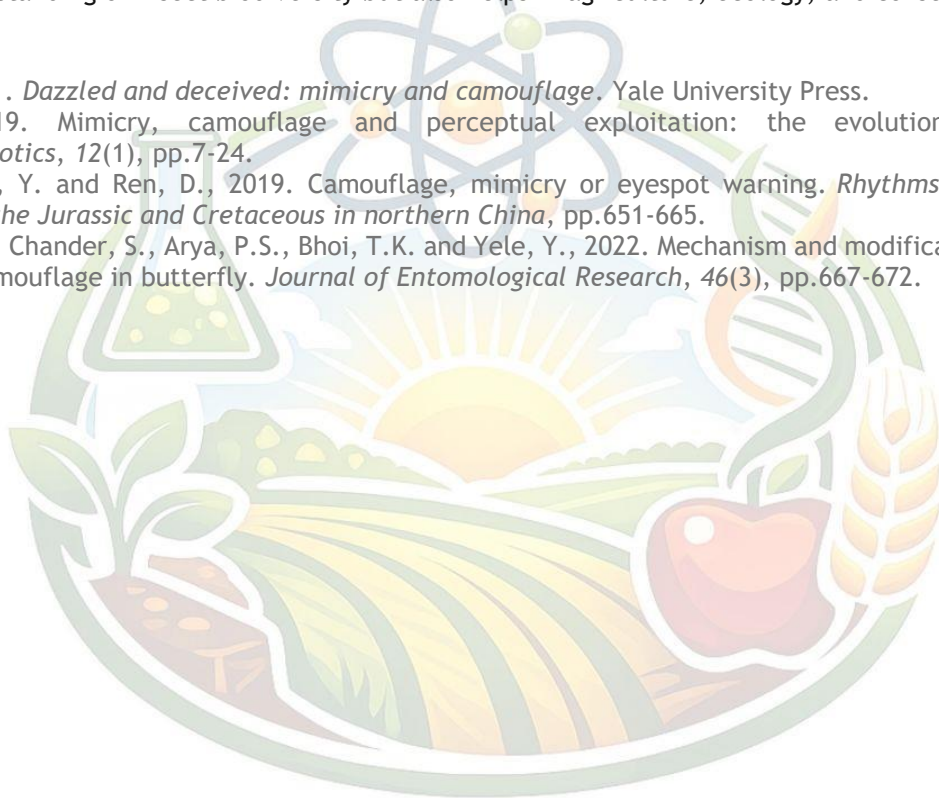
1. Some pest insects use camouflage to escape detection.
2. Beneficial insects also use mimicry for protection.
3. Understanding these adaptations helps in pest identification and management.

Conclusion

Camouflage and mimicry are extraordinary survival strategies that highlight the intelligence of nature. These adaptations allow insects to survive against predators and environmental challenges. Studying such fascinating mechanisms not only increases our understanding of insect biodiversity but also helps in agriculture, ecology, and conservation.

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Bio-Inspiration: Insect Inspired Technology

Article ID: 73772

Lipsa Dash¹, Ipsita Das², Pragyan Paramita Rout³

¹Assistant Professor, College of Horticulture, Odisha University of Agriculture and Technology, Odisha.

^{2,3}Assistant Professor, College of Agriculture, Odisha University of Agriculture and Technology, Odisha.

Introduction

Insect-inspired technology, also known as entomological biomimetics, is an emerging interdisciplinary field where biological principles derived from insects are applied to engineering, robotics, artificial intelligence, architecture, and sustainable systems. Insects represent the most diverse group of organisms on Earth and have evolved over millions of years to efficiently solve problems related to movement, communication, survival, and resource utilization.

Unlike human-made systems that often rely on heavy energy inputs and centralized control, insects achieve remarkable efficiency with minimal resources. This makes them ideal models for designing sustainable and adaptive technologies. From swarm intelligence to advanced materials, insect-based innovations are revolutionizing modern science and engineering. This article explores the major areas where insect-inspired technologies are shaping the future and highlights their relevance in addressing global challenges such as climate change, food security, and environmental sustainability.

Swarm Intelligence

Swarm intelligence refers to the collective behavior of decentralized systems, commonly observed in ants, bees, termites, and other social insects. Individual insects follow simple rules, yet their interactions lead to complex and efficient outcomes.

Ant colony optimization algorithms are inspired by the pheromone trail-following behavior of ants. These algorithms are widely used in logistics, network routing, and scheduling problems. Similarly, honeybee decision-making processes have inspired optimization techniques in computing and management sciences.

Swarm robotics is another application where multiple small robots coordinate to perform tasks such as search and rescue, environmental monitoring, and agricultural operations. These systems are robust, scalable, and flexible, making them suitable for dynamic environments.

Insect-Inspired Robotics

Robotics has greatly benefited from studying insect locomotion and flight. Hexapod robots, inspired by insects like ants and cockroaches, exhibit superior stability and mobility compared to wheeled robots. They can navigate uneven terrains and confined spaces, making them ideal for disaster management.

Micro aerial vehicles (MAVs) mimic the flapping wing mechanisms of flies and dragonflies. These drones are lightweight, energy-efficient, and capable of hovering and agile flight. They have applications in surveillance, pollination, and environmental monitoring.

Cockroach-inspired robots can compress their bodies to move through narrow gaps, which is particularly useful in rescue operations in collapsed structures.

Architecture and Termite Inspiration

Termite mounds are natural examples of efficient climate control systems. Despite extreme external temperature fluctuations, the internal environment of termite mounds remains stable due to their sophisticated ventilation systems.

Architects have adopted these principles to design energy-efficient buildings with passive cooling mechanisms. Such buildings significantly reduce the need for air conditioning, thereby lowering energy consumption and carbon emissions. This approach is especially relevant in tropical regions.

Materials Science

Insects possess unique structural materials such as chitin, which provides strength, flexibility, and lightweight properties. These characteristics have inspired the development of advanced composite materials used in aerospace, defense, and sports equipment.

Butterfly wings and insect eyes have nanostructures that reduce reflection and enhance optical properties. These features are being used to improve solar panel efficiency and create anti-reflective coatings.

Self-cleaning surfaces inspired by insect wings are also being developed for applications in construction and healthcare.

Artificial Intelligence

Insects demonstrate complex behaviors such as navigation, learning, and pattern recognition despite having small brains. This has inspired the development of efficient artificial intelligence systems and neuromorphic computing.

Insect vision systems, particularly compound eyes, provide a wide field of view and excellent motion detection. These features are being replicated in cameras for autonomous vehicles and surveillance systems.

Agricultural Applications

In agriculture, insect-inspired technologies are helping improve productivity and sustainability. Robotic pollinators are being developed to supplement natural pollination in areas where bee populations are declining. Smart pest management systems use principles of insect behavior, such as pheromone communication, to monitor and control pest populations. These systems reduce the reliance on chemical pesticides and promote eco-friendly farming.

Environmental Applications

Insect-inspired drones and sensors are being used for environmental monitoring. These systems can collect data on temperature, humidity, and pollution levels in remote or hazardous locations. Swarm-based monitoring systems allow large-scale data collection, which is essential for studying climate change and ecosystem dynamics.

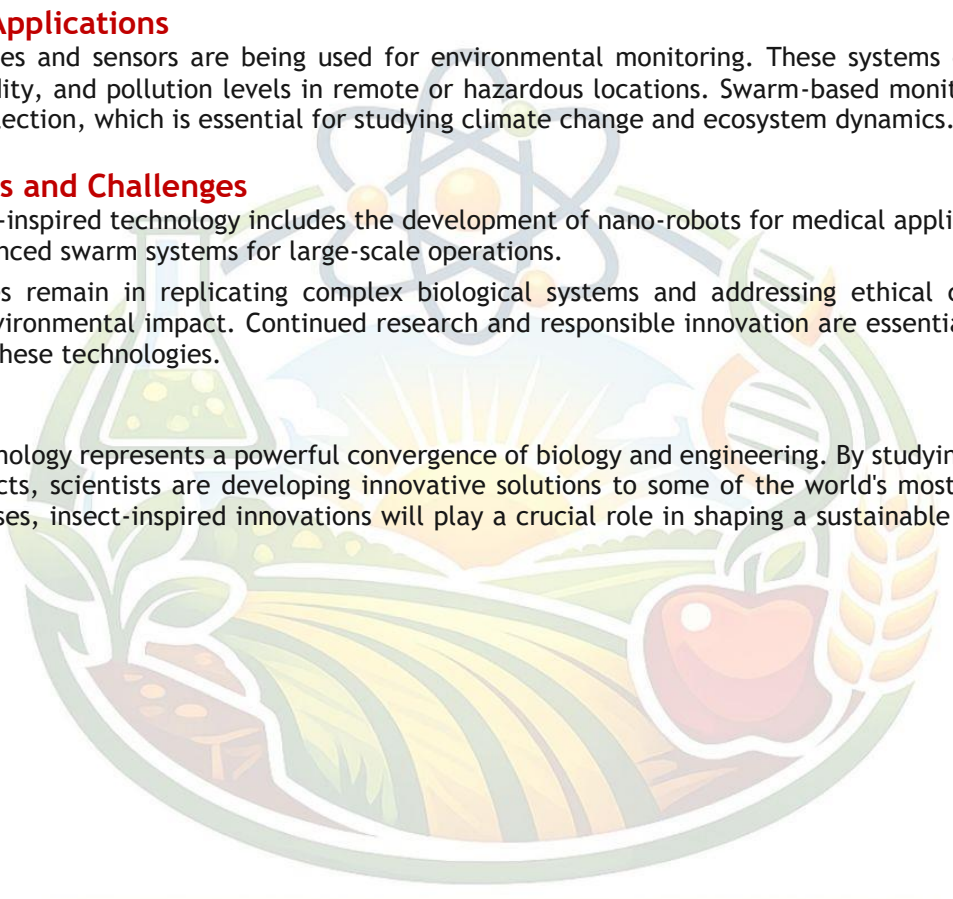
Future Prospects and Challenges

The future of insect-inspired technology includes the development of nano-robots for medical applications, self-healing materials, and advanced swarm systems for large-scale operations.

However, challenges remain in replicating complex biological systems and addressing ethical concerns related to surveillance and environmental impact. Continued research and responsible innovation are essential for the successful implementation of these technologies.

Conclusion

Insect-inspired technology represents a powerful convergence of biology and engineering. By studying the efficiency and adaptability of insects, scientists are developing innovative solutions to some of the world's most pressing problems. As research progresses, insect-inspired innovations will play a crucial role in shaping a sustainable and technologically advanced future.

A large, circular logo featuring a stylized landscape with a sun, mountains, and a field. A red apple is prominently placed on the right side of the field. The entire scene is enclosed within a circular border.
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Biofortification: Fighting Hidden Hunger Through Agriculture

Article ID: 73773

 Gopu Sushma¹, Kota Sahithi Chowdary², Repaka Harika²
¹Ph. D Scholar, Professor Jayashankar Telangana Agricultural University, Hyderabad.

²Ph. D Scholar, Indira Gandhi Krishi Vishwavidyalaya, Raipur.

Abstract

Biofortification is a sustainable approach to improving the nutritional quality of food crops by increasing their micronutrient content through conventional and transgenic breeding methods. Several nutrient rich crop varieties have already been developed, while many more are under improvement. Research studies and successful field level adoption indicate that biofortification is an effective strategy to reduce hidden hunger, although challenges still exist in the large scale delivery and acceptance of biofortified crops.

Introduction

Food is essential not only for satisfying hunger but also for maintaining good health. Millions of people around the world consume enough calories every day, yet they suffer from a lack of essential vitamins and minerals. This condition is known as “hidden hunger.” Deficiency of nutrients such as iron, zinc, vitamin A, and iodine can lead to anemia, weak immunity, poor growth, and several health problems, especially among children and pregnant women. To address this challenge, scientists and agricultural experts have introduced an innovative and sustainable solution called biofortification.

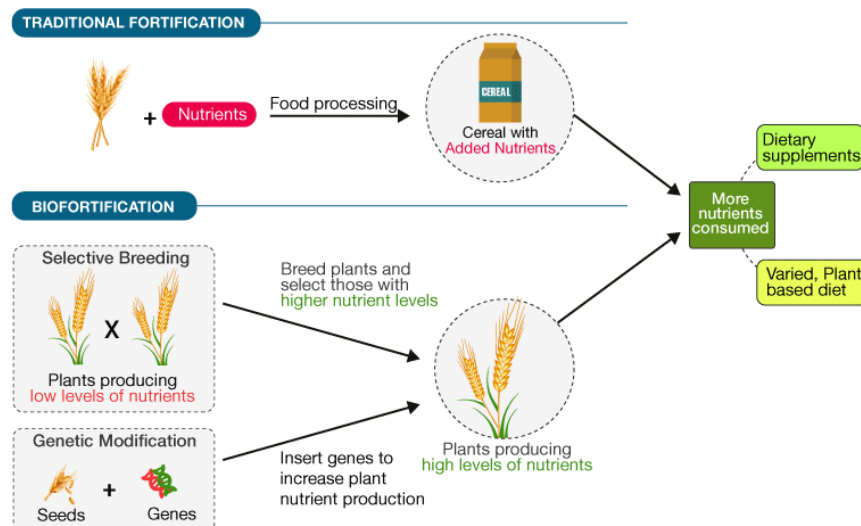
Biofortification

Biofortification is the process of increasing the nutritional value of food crops by enhancing their content of essential vitamins and minerals (Saltzman *et al.*, 2013; Singh *et al.*, 2016)). Unlike food fortification, where nutrients are added during food processing, biofortification improves the nutrient content while the crop is growing in the field.

This can be achieved through:

- Conventional plant breeding
- Modern biotechnology
- Agronomic practices such as micronutrient fertilization

The main aim of biofortification is to provide nutrient rich food to people through their daily diet.



Importance of Biofortification

In many developing countries, people depend mainly on staple crops such as rice, wheat, maize and cassava. These crops provide energy but often contain low levels of important micronutrients (Nestel *et al.*, 2006). As a result, malnutrition remains a serious public health issue.

Biofortification offers several advantages:

- Improves nutritional security
- Reduces micronutrient deficiencies

- c. Benefits rural populations with limited access to supplements
- d. Provides a cost-effective and long term solution
- e. Supports sustainable agriculture.

Types of Biofortification

1. Conventional Breeding: This conventional approach involves crossbreeding naturally nutrient-rich crops with high yielding varieties to develop improved hybrids. Nutritionists closely evaluate these varieties to ensure that the enhanced nutrient content is beneficial to consumers and remains stable during storage, processing, and cooking.

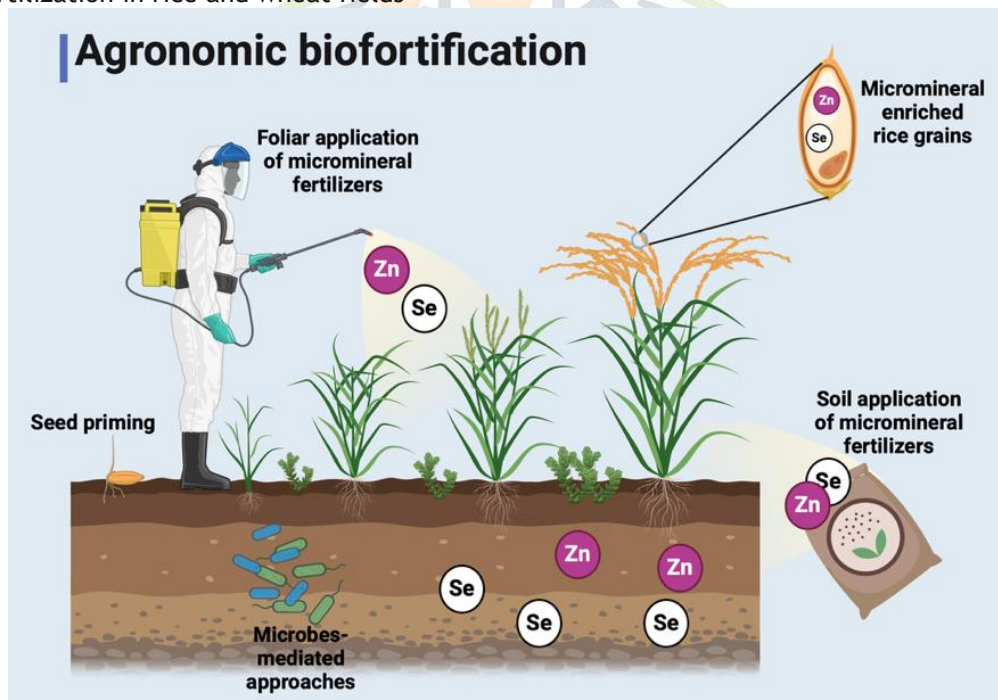
Example:

- a. Iron-rich pearl millet
- b. Zinc-rich rice and wheat

2. Genetic Engineering: Genetic modification involves changing the genetic composition of crops by introducing genes from wild relatives or other species to enhance nutrient content or improve disease resistance. Multiple nutrient related genes can also be combined in a single crop to increase its nutritional quality. A well known example is Golden Rice, which is enriched with beta-carotene, a precursor of Vitamin A.

3. Agronomic Biofortification: Application of mineral fertilizers to soil or leaves helps increase nutrient concentration in crops.

Example: Zinc fertilization in rice and wheat fields



Examples of Biofortified Crops: Several biofortified crops are now cultivated worldwide:

- a. Golden Rice rich in vitamin A
- b. Iron rich beans
- c. Zinc rich wheat and rice
- d. Orange fleshed sweet potato rich in beta carotene
- e. Iron rich pearl millet

These crops help improve human health without changing food habits significantly.

Role of Biofortification in India

India faces a high burden of malnutrition and anemia. To combat this problem, agricultural institutions and scientists are developing nutrient rich crop varieties suitable for Indian conditions. The Indian Council of Agricultural Research (ICAR) has released several biofortified varieties of Rice, wheat, maize pearl millet and lentils. These varieties not only improve nutrition but also maintain good yield and adaptability.

Challenges of Biofortification

Although biofortification has many benefits, some challenges remain:

1. Limited awareness among farmers and consumers

2. Acceptance issues due to color or taste changes
3. Need for proper distribution systems
4. High research and development costs in biotechnology based approaches

Despite these limitations, continuous research and government support are helping expand biofortification programs.

Future Prospects

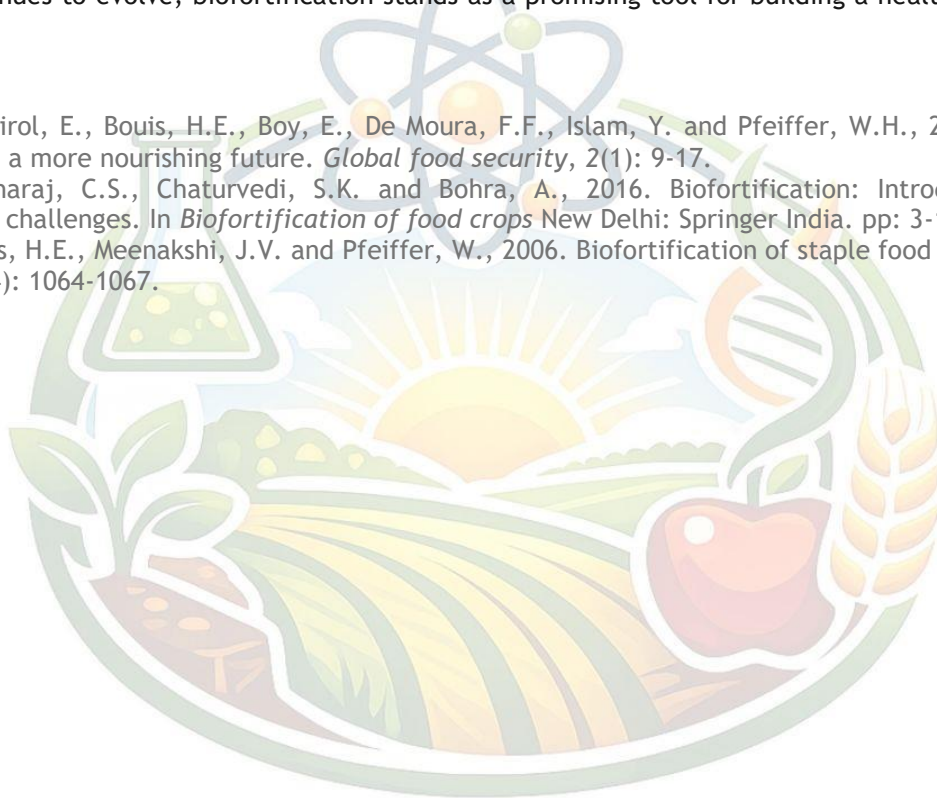
Biofortification has great potential to improve global nutrition and food security. With advancements in genetics, molecular breeding and biotechnology, scientists can develop crops with multiple nutrient enhancements and better resistance to pests, diseases and climate stress. Combining agriculture and nutrition through biofortification can play a major role in achieving sustainable development and healthier societies.

Conclusion

Biofortification is an effective and sustainable approach to fight hidden hunger and malnutrition. By enriching staple food crops with essential nutrients, it helps improve the health of millions of people, especially in developing countries. As agriculture continues to evolve, biofortification stands as a promising tool for building a healthier and nutritionally secure future.

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Seaweeds: The Fuel Source of Future Generations

Article ID: 73774

Biya Mary Mathai¹, Ashish Khandelwal¹

¹Bioprospecting Section, Marine Biotechnology, Fish Nutrition and Health Division, ICAR-Central Marine Fisheries Research Institute, Kochi-18.

Abstract

The seaweeds are one of the potential and sustainable raw materials for third-generation biofuel production that can be used as an alternative to fossil fuels and conventional biofuels. Biofuels derived from seaweed, can be grown in ocean. They grow fast, have a low lignin content and high carbohydrate content, making them perfect for bioethanol production. The fermentable sugars can be extracted from seaweeds using various pretreatment methods, such as acid, alkali, microwave, and enzymatic hydrolysis, then fermented with microorganisms like *Saccharomyces cerevisiae* and *Zymomonas mobilis* to produce bioethanol. Even though challenges like cultivation of seaweeds, salt inhibition and pretreatment by-products remain, new research is enhancing the efficiency of production. Favourable coastal conditions and supportive biofuel policies of India indicate the future potential of algal-based biofuels for a cleaner and safer energy system.

Introduction

Ever wondered if those slimy, colourful organisms that float with the ocean currents could be more than just beach decor? If you think that they might be useful, you are absolutely right. Seaweeds, as they are called, have a wide range of uses. From food to medicine, agriculture and even in cosmetics, they are valuable. But using seaweed as a biofuel is an emerging field that proves to be both sustainable and eco-friendly. When the world itself is suffering from global warming, the production and use of biofuels would provide a great relief.

TYPES OF SEaweeds

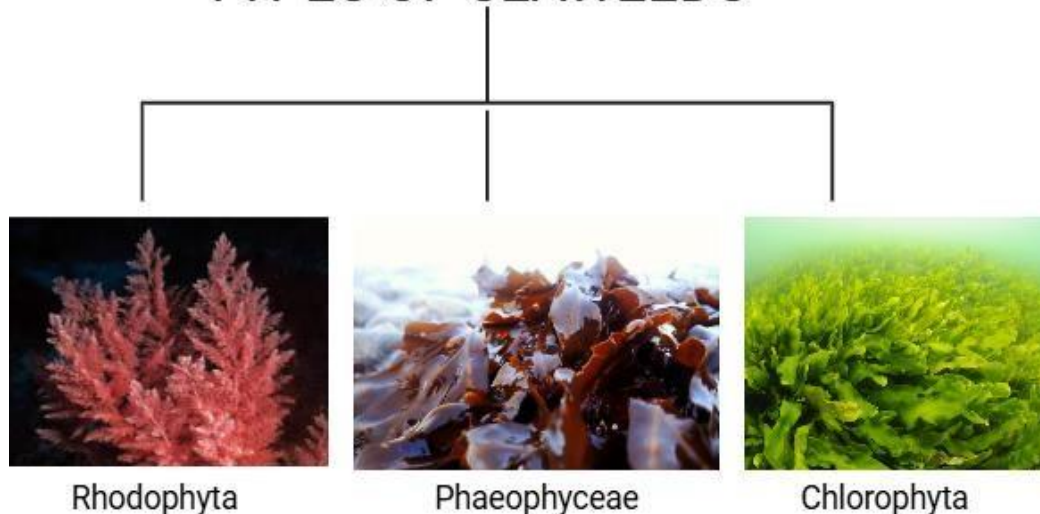


Figure 1: Commonly found different types of seaweeds in marine system

Generations of Bio-Fuels

The term "biofuel" is not new or unheard of. The brilliance of science has been proven through the development of various biofuel sources, thus largely reducing dependence on fossil fuels. Based on the source, biofuels are classified into first, second and third generation. According to Nanda S. et al., (2018), the first generation used edible starch-rich materials like corn, wheat and sugarcane for biofuel production. But the use of food for fuel production was an issue. This was dealt with the production of a second - generation biofuels using non-edible lignocellulosic biomass. These increased production costs, energy consumption and processing time made things difficult. Thus comes the third-generation biofuel, which is mainly made from microalgae and seaweeds.

Why Seaweeds are Better?

There are a few reasons why marine algae is better at this job than the other two sources. Zhao *et al.*, (2022) points out the greater potential of seaweeds over other sources. One of the strongest arguments they state is that seaweeds don't

need special agricultural land for their production, unlike the first-generation source, which is produced in arable land. This has several advantages, including no deforestation to produce cultivation land, no freshwater irrigation needed. Another important factor is that since they grow in the ocean, large-scale production is possible. This would indirectly point out that the increasing energy demand can be met easily.

Their high carbohydrate content and rapid growth rate make them an easy target. The papers repeated emphasis on high carbohydrate content and low levels of lignin makes seaweed highly efficient for biofuel production. Lignin is a complex organic polymer, and its absence in seaweed makes it easier to hydrolyse and more fermentable in a less energy-intensive process. The paper also highlights that the cultivation of 1 ton of dry seaweed can remove approximately 961 kg of carbon dioxide. This suggests that seaweed can also be used to mitigate climate change.

Another benefit of them is that most seaweeds are cosmopolitan, ranging from tropical to temperate to polar regions. This ensures continuous biomass availability supporting large-scale global biofuel production. Another major advantage of seaweeds over land crops is that they are not seasonal and can be found throughout the year.

Global Biofuel Market and Future Demand

Currently, the global biofuel market is valued at around \$ 268 billion and is said to increase to \$497 billion by 2032. But only about 4% of the total global transport energy demand is met by biofuels, highlighting a major gap between production and energy requirements. More over 90% of present biofuel production happens from first-generation feedstocks. All the technological advancements have helped developed countries to produce most of the biofuels, even though several studies claim that developing countries possess significant potential for better biofuel production due to favourable climatic conditions and larger availability of resources. This highlights that the developing countries may play crucial role in higher fuel production in the near future. (Matt Johnston *et al* 2011).

India's Progress in Biofuel Production

In terms of biofuel production, India has created milestones in the last decade. India's flagship program, the Ethanol Blending Program, which blends ethanol into petrol to reduce dependence on crude oil, has seen much progress, reaching 20% blending rate in March 2025, which was originally a 2030 target. The current ethanol production capacity of India is about 16 billion litres, which is largely produced from 1G feedstock such as sugarcane and grain-based sources.

India's first commercial second-generation ethanol biorefinery was commissioned in Panipat by indian oil cooperation, which uses crop residue like rice straw for bioethanol production. But compared to the first generation, the use of 2G is limited mainly due to high processing cost and pretreatment challenges.

Potential of Seaweed Biofuel in India

India has a coastline of around 11000 km that supports the growth of marine algae to a large extent. Favourable tropical conditions and abundant marine biodiversity also support algal growth. India currently has minimal commercial-scale third-generation biofuel production. Even though the contributions are negligible at present, the impact the marine algae is going to have in the near future is huge.

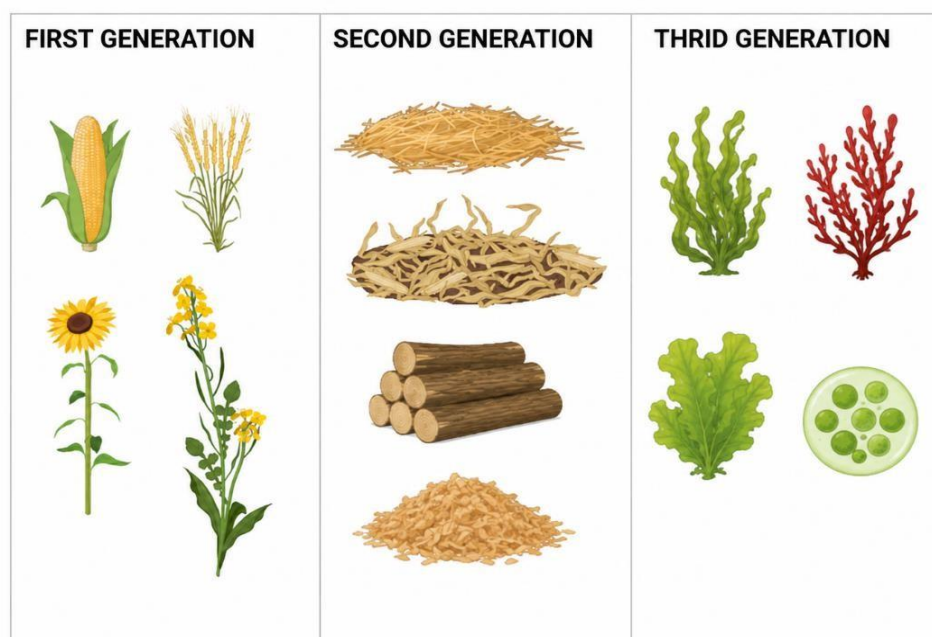


Figure 2: first, second and third generation sources of biofuel production

Bioethanol Production from Seaweeds

There are many biofuels that are currently produced all around the world. These include bioethanol, biodiesel, biobutanol, bio- oil, etc. Among all this, bioethanol is easier to produce because seaweeds have a high amount of carbohydrates like laminarin, mannitol, and carrageenan that can be easily converted into fermentable sugars. The pretreatment is an essential step that helps in breaking down the complex structure and thus makes the fermentable sugars readily available. These can be done in various ways. These include acid, alkali, microwave and enzymatic pretreatment.



Figure 3.0: Hydrolysable seaweeds before (a) and (b) after treatment

The sugars alone are useless if not fermented to produce ethanol. Microorganisms use sugars and convert them into ethanol (called fermentation) in an anaerobic condition. Microbes ferment the sugars derived from seaweeds. Fungi like yeast *Saccharomyces cerevisiae* and bacteria like *Zymomonas mobilis* are used for this fermentation process. These easy steps if done correctly, would result in the production of a large amount of bioethanol. The ethanol produced can be separated by distillation.

Challenges in Seaweed-Based Biofuel Production

Even though it sounds easy, there are several challenges and limitations to this process. Since seaweed is a marine organism, the pretreated hydrolysate would have salt content that can act as an inhibitor for microbial growth and pretreatment doesn't release the sugars alone, they can break down other compounds like HMF and furfural that also act as inhibitors. Moreover, oceans have high currents that make the cultivation of seaweeds difficult.

This underexplored area is becoming a field of rapid research, and scientists are studying different seaweed species for higher yield. They are finding ways to reduce these inhibitors to maximise bioethanol production. Even the microbes are being genetically modified. This trend has encouraged countries with large coastlines to invest in seaweed cultivation and bioethanol production.

Government Policies and Support

India has implemented several policies and schemes to promote biofuel production. Initially, most initiatives were for the first generation, which included food-based livestock. Through the national policy on biofuels, the government of India has encouraged ethanol blending in petrol. These efforts have seen success and have strengthened the conventional biofuel sector. Later, the second generation gained popularity, which utilised crop residues and agricultural waste. A major initiative in this regard is the Pradhan Mantri JI-Van Yojana, which supports the establishment of advanced bioethanol refineries through financial support. This aims to convert agricultural waste into ethanol while directly addressing environmental issues.

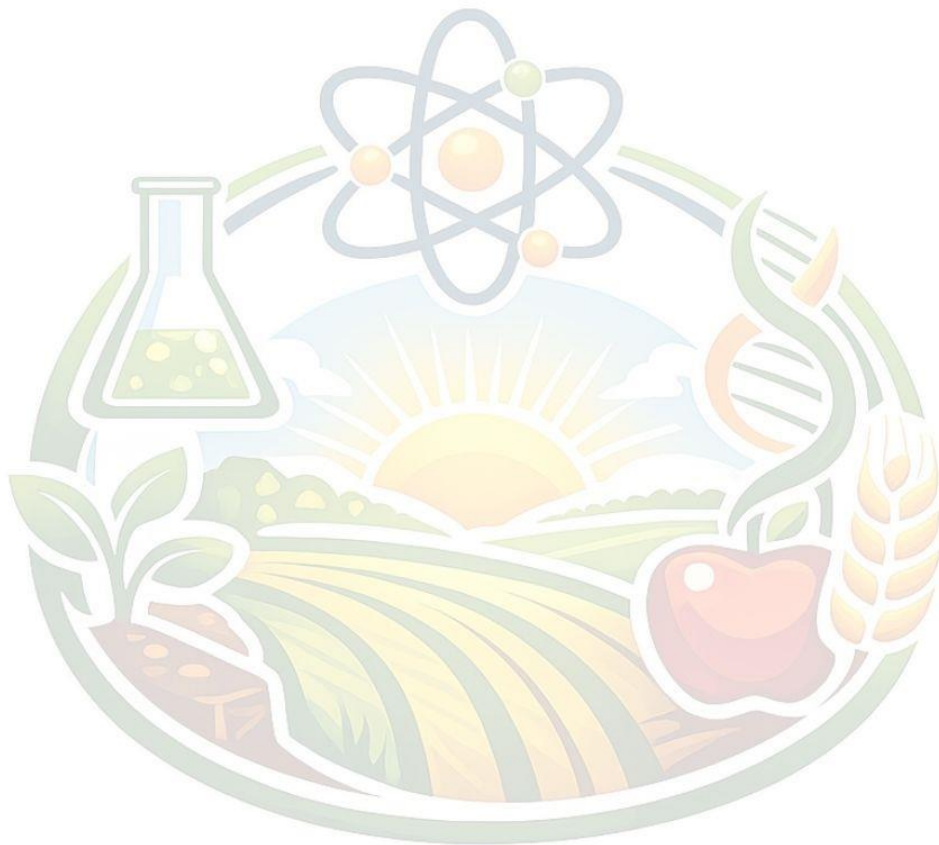
Now a greater focus is provided to the third generation particularly those derived for, microalgae and seaweeds due to their potential to address the limitations set by the earlier generations although currently India doesn't have a dedicated national scheme that exclusively focuses on third generation biofuels, existing frameworks such as the nations policy on biofuels, the national bioenergy program and government supported marine biotechnology initiatives provide indirect support for research. Agencies like the Department of Biotechnology (DBT), Department of Science & Technology (DST) and the Ministry of New and Renewable Energy have funded projects related to algal and marine biomass utilisation.

Conclusion

These slimy, shiny marine organisms are a safe zone that could fuel cars and industries in the near future. Though challenges remain, they stay as an indicator that progress can be made and perfection can be attained with further scientific advancements. An end to the fossil fuels era would mean a start to an era which is cleaner, greener and better.

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Genome-Wide Association Studies (GWAS): A Powerful Tool for Understanding Complex Traits

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A. Anisha¹

¹Ph.D. scholar, Professor Jayashankar Telangana State Agricultural University, Telangana.

Abstract

Genome-Wide Association Studies (GWAS) have emerged as a powerful genomic approach for identifying genetic variants associated with complex traits in plants, animals, and humans. Unlike traditional linkage mapping methods, GWAS utilizes natural populations and high-density molecular markers to explore genome-wide associations with high resolution. The technique is primarily based on linkage disequilibrium, enabling the detection of significant relationships between single nucleotide polymorphisms (SNPs) and phenotypic traits. GWAS has gained immense importance in crop improvement programs for identifying quantitative trait loci (QTLs) and candidate genes controlling yield, stress tolerance, disease resistance, and quality traits. In crops such as rice, wheat, maize, and sorghum, GWAS has accelerated the discovery of favorable alleles and facilitated marker-assisted breeding. The approach also plays a significant role in human disease genetics and livestock improvement. Despite challenges such as population structure, false-positive associations, and environmental influences, advances in sequencing technologies, bioinformatics, and statistical models have greatly improved the efficiency and accuracy of GWAS. Furthermore, the integration of GWAS with genomic selection, transcriptomics, and gene-editing technologies offers promising opportunities for future genetic research and precision breeding. Overall, GWAS has revolutionized modern genomics by providing deeper insights into the genetic architecture of complex traits and contributing significantly to sustainable agriculture, functional genomics, and human health research.

Introduction

The rapid advancement of molecular genetics and high-throughput sequencing technologies has transformed modern biological research. Among the most influential genomic approaches developed in recent decades is the Genome-Wide Association Study (GWAS). GWAS is a statistical method used to identify associations between genetic variations and phenotypic traits across the entire genome. Unlike traditional linkage mapping, which relies on biparental populations, GWAS utilizes natural populations or diverse germplasm collections, thereby capturing a broader range of genetic diversity and recombination events. This approach has become an essential tool in human genetics, plant breeding, animal improvement, and evolutionary biology.

Complex traits such as yield, drought tolerance, disease resistance, plant height, obesity, diabetes, and cardiovascular diseases are controlled by multiple genes and are strongly influenced by environmental factors. Conventional genetic approaches often fail to dissect these polygenic traits accurately. GWAS overcomes these limitations by scanning thousands to millions of single nucleotide polymorphisms (SNPs) distributed across the genome and identifying genomic regions associated with the trait of interest. Due to its high resolution and ability to exploit historical recombination, GWAS has emerged as a revolutionary technique for gene discovery and marker-assisted breeding.

Principle and Methodology of GWAS

The fundamental principle of GWAS is based on linkage disequilibrium (LD), which refers to the non-random association of alleles at different loci. When a genetic marker and a causative gene are inherited together more frequently than expected by chance, they exhibit linkage disequilibrium. GWAS detects these associations by statistically correlating phenotypic variation with genome-wide marker data.

The general workflow of GWAS involves several steps. First, a genetically diverse population is selected and phenotyped accurately for the target traits under multiple environments or replications. Precise phenotyping is critical because the reliability of GWAS results depends heavily on the quality of phenotypic data. Second, individuals are genotyped using high-density molecular markers such as SNPs generated through sequencing or SNP arrays. Third, quality control measures are applied to remove markers with low minor allele frequency, missing data, or poor quality.

After data preparation, population structure and kinship analyses are conducted to avoid false-positive associations caused by relatedness or stratification within the population. Statistical models such as the General Linear Model (GLM) and Mixed Linear Model (MLM) are commonly used for association analysis. The MLM is widely preferred because it accounts for both population structure and familial relationships. Significant marker-trait associations are then identified using stringent statistical thresholds.

The results of GWAS are usually visualized through Manhattan plots and Quantile-Quantile (Q-Q) plots. In a Manhattan plot, each point represents a SNP marker, and significant peaks indicate genomic regions associated with the trait. Q-Q

plots help assess whether the observed associations deviate from expected distributions, thereby indicating the reliability of the analysis.

Applications of GWAS in Crop Improvement

GWAS has become an indispensable tool in modern crop breeding programs. In crops such as rice, wheat, maize, sorghum, and soybean, GWAS has successfully identified quantitative trait loci (QTLs) and candidate genes associated with important agronomic traits. These include grain yield, flowering time, plant architecture, drought tolerance, salinity resistance, nutrient efficiency, and disease resistance.

In rice, GWAS has identified several genomic regions controlling yield-related traits such as panicle length, grain weight, grains per panicle, and number of tillers. Multi-parent populations such as MAGIC (Multi-parent Advanced Generation Intercross) populations have further enhanced the efficiency of GWAS by increasing allelic diversity and recombination frequency. Similarly, in sorghum, GWAS has been used to study traits related to stay-green characteristics, fertility restoration, grain quality, and adaptation to post-rainy environments.

One of the major advantages of GWAS in plant breeding is its ability to identify favorable alleles present in landraces and wild relatives. These alleles can subsequently be incorporated into elite breeding lines through marker-assisted selection or genomic selection. Furthermore, GWAS accelerates the identification of candidate genes, enabling breeders to develop climate-resilient and high-yielding crop varieties.

Beyond plants, GWAS has also revolutionized human medicine by identifying genes associated with diseases such as cancer, diabetes, Alzheimer's disease, and hypertension. In livestock, GWAS contributes to the improvement of milk production, meat quality, reproductive efficiency, and disease resistance.

Advantages of GWAS

GWAS possesses several advantages over conventional mapping approaches. One of its primary strengths is high mapping resolution due to the utilization of historical recombination events accumulated over many generations. Unlike biparental mapping populations, GWAS can analyze large and diverse populations, thereby capturing extensive genetic variation.

Another important advantage is that GWAS does not require the development of specialized mapping populations, saving both time and resources. It is particularly effective for dissecting complex quantitative traits controlled by multiple genes with small effects. Additionally, GWAS enables simultaneous evaluation of thousands of markers across the genome, facilitating the discovery of novel genes and pathways.

The integration of GWAS with advanced genomic tools such as transcriptomics, metabolomics, and genomic prediction has further strengthened its utility in functional genomics and precision breeding.

Limitations and Challenges

Despite its immense potential, GWAS also has certain limitations. Population structure and cryptic relatedness can produce false-positive associations if not properly controlled. Similarly, rare alleles with low frequency are often difficult to detect because of limited statistical power. Environmental influences and genotype-by-environment interactions may also affect the accuracy of phenotypic data.

Another challenge is that significant SNP markers identified through GWAS may not necessarily represent the actual causative genes. Instead, they may simply be linked to nearby genomic regions. Therefore, further validation through fine mapping, gene expression studies, or functional characterization is necessary.

Additionally, GWAS requires large sample sizes and high-density genotyping platforms, which can be expensive and computationally demanding. The interpretation of massive genomic datasets also requires expertise in bioinformatics and statistical genetics.

Conclusion

Genome-Wide Association Studies have revolutionized the field of genetics by enabling the identification of genomic regions associated with complex traits. Through the analysis of natural genetic diversity and high-density molecular markers, GWAS provides a powerful framework for understanding the genetic basis of economically important traits in plants, animals, and humans. Its applications in crop improvement, disease research, and functional genomics continue to expand rapidly.

Although challenges such as population structure, rare allele detection, and environmental interactions remain, continuous advancements in genomics and computational biology are overcoming these limitations. As a result, GWAS is expected to remain one of the most valuable tools in modern biology and breeding research, contributing significantly to food security, sustainable agriculture, and human health.

Contribution of Food Processing Industries in Rural Development: A Comprehensive Review

Article ID: 73776

Jeevita J Pujari¹, Dr. Shashekala S.G², Shreya N Biradar³

¹M.Tech Food Processing Technology.

²Assistant Professor of Agriculture Extension.

Abstract

The food processing industry has emerged as a key driver of economic growth and rural development by establishing strong linkages between agriculture and industry. This review examines the contribution of food processing industries to rural development, with a focus on employment generation, income enhancement, reduction of post-harvest losses, infrastructure development, and promotion of agro-based entrepreneurship. In countries like India, where a significant proportion of the population depends on agriculture, the expansion of food processing activities plays a crucial role in improving rural livelihoods and ensuring sustainable development. The sector facilitates value addition to agricultural produce, enhances market access, and supports food security and nutritional outcomes.

The review also highlights the role of government initiatives led by the Ministry of Food Processing Industries in strengthening infrastructure, promoting small and medium enterprises, and encouraging investment in the sector. Despite its potential, the industry faces several challenges, including inadequate infrastructure, limited access to finance, technological constraints, and supply chain inefficiencies. However, emerging opportunities such as increasing demand for processed and functional foods, technological advancements, and expansion of global markets provide significant scope for future growth.

Overall, the food processing industry has the potential to act as a catalyst for rural transformation by generating employment, enhancing income levels, and promoting inclusive and sustainable development. Strengthening this sector through effective policies, innovation, and capacity building will be essential to fully realize its role in rural development.

Introduction

The food processing industry has emerged as a vital sector in transforming agricultural economies into diversified and value-driven systems. It involves the conversion of raw agricultural produce into consumable, safe, and value-added food products through various physical, chemical, and biological processes. In a country like India, where agriculture remains the primary source of livelihood for a large proportion of the population, the integration of food processing industries plays a crucial role in enhancing economic growth and rural development. According to recent estimates, nearly 68% of India's population resides in rural areas, with agriculture being their main occupation, highlighting the need for strong agro-based industries to support rural livelihoods.

The food processing sector acts as a critical link between agriculture and industry by facilitating value addition, reducing post-harvest losses, and improving the shelf life of perishable commodities. It contributes significantly to the national economy by accounting for around 8-9% of Gross Value Added (GVA) in both agriculture and manufacturing sectors and plays an important role in exports and industrial investment. Furthermore, the sector supports over 7 million jobs across the value chain, both directly and indirectly, thereby contributing substantially to employment generation and rural industrialization.

Rural development is a multidimensional concept encompassing economic growth, employment generation, infrastructure development, and improvement in the quality of life of rural populations. Agro-based industries, particularly food processing units, serve as an effective tool for achieving these objectives by creating income opportunities, promoting entrepreneurship, and reducing migration from rural to urban areas. The availability of abundant raw materials, diverse agro-climatic conditions, and increasing demand for processed foods further strengthen the potential of this sector in rural transformation.

In recent years, the Government of India, through initiatives led by the Ministry of Food Processing Industries, has emphasized the development of food processing infrastructure, value chains, and rural enterprises to achieve inclusive growth. These efforts aim not only to enhance farmers' income but also to promote sustainable and equitable rural development. Therefore, understanding the contribution of food processing industries to rural development is essential for framing effective policies and strategies.

Overview of Food Processing Industries

The food processing industry is a significant component of the agro-based industrial sector, involving the transformation of raw agricultural commodities into edible, safe, and value-added food products. It encompasses a wide range of

activities such as cleaning, grading, sorting, preservation, packaging, and distribution. This sector not only enhances the shelf life of perishable commodities but also improves their quality, safety, and marketability.

Food processing industries can be broadly classified into **primary and secondary processing sectors**. Primary processing includes basic operations such as milling, dehulling, and extraction, which prepare raw materials for further use. Secondary processing involves the conversion of these raw materials into ready-to-eat or ready-to-cook products, such as bakery items, dairy products, beverages, and packaged foods. These processes contribute significantly to value addition and diversification of food products, thereby increasing their economic value.

Based on scale and investment, food processing industries are categorized into **small-scale, medium-scale, and large-scale enterprises**. Small-scale industries are predominantly located in rural areas and play a crucial role in utilizing locally available raw materials, generating employment, and supporting rural livelihoods. Medium and large-scale industries, on the other hand, contribute to technological advancement, large-scale production, and export growth.

In India, the food processing sector has experienced substantial growth over the past decade, driven by rising consumer demand, urbanization, changing dietary patterns, and government support. The sector contributes significantly to the economy by accounting for a considerable share of Gross Value Added (GVA) in agriculture and manufacturing. It also plays a vital role in reducing post-harvest losses, which are estimated to be substantial due to inadequate storage and processing facilities.

The industry covers diverse segments, including **dairy, fruits and vegetables processing, grains and cereals, meat and poultry, fisheries, and packaged foods**. Among these, the dairy sector is one of the largest contributors, followed by grain processing and fruit and vegetable processing. The increasing demand for convenience foods and functional foods has further accelerated the growth of the sector.

Moreover, the expansion of food processing industries has led to the development of supply chains, cold storage facilities, and transportation networks, thereby strengthening the linkage between agriculture and industry. This integration is particularly important for rural development, as it creates opportunities for farmers, entrepreneurs, and small-scale processors to participate in value-added activities.

Overall, the food processing industry serves as a bridge between agricultural production and industrial development, contributing to economic growth, food security, and rural transformation.

Concept of Rural Development

Rural development is a comprehensive and multidimensional process aimed at improving the economic, social, and infrastructural conditions of rural areas. It focuses on enhancing the quality of life of rural populations by increasing income levels, generating employment opportunities, reducing poverty, and ensuring sustainable use of natural resources. In developing countries like India, rural development is particularly significant as a large proportion of the population depends on agriculture and allied activities for their livelihood.

The concept of rural development extends beyond agricultural growth and includes the overall transformation of rural society through improved access to education, healthcare, housing, sanitation, and infrastructure. It emphasizes inclusive growth by ensuring that the benefits of development reach marginalized and weaker sections of society, including small and marginal farmers, landless laborers, and rural women. Thus, rural development is not only about economic progress but also about social equity and empowerment.

Key indicators of rural development include **employment generation, income enhancement, poverty alleviation, infrastructure development, and livelihood security**. Employment generation is a critical component, as rural areas often face issues of underemployment and seasonal unemployment. The promotion of agro-based industries, particularly food processing units, plays a vital role in creating both direct and indirect employment opportunities. Similarly, increasing farmers' income through value addition and better market access is essential for improving rural livelihoods.

Infrastructure development is another important aspect, involving the establishment of roads, irrigation systems, storage facilities, electricity, and communication networks. These facilities are crucial for supporting agricultural activities and enabling the growth of rural industries. Additionally, access to institutional credit, market linkages, and technological advancements contributes significantly to rural development.

Sustainable rural development also emphasizes environmental protection and efficient resource utilization. Practices such as sustainable agriculture, waste management, and eco-friendly processing methods help in maintaining ecological balance while supporting economic growth. Furthermore, the development of rural entrepreneurship, self-help groups (SHGs), and cooperatives has strengthened community participation and local economic development.

In recent years, various government initiatives have focused on promoting rural development through integrated approaches that combine agriculture, industry, and services. The role of agro-based industries, especially food processing, has gained prominence as they provide opportunities for value addition, reduce post-harvest losses, and support rural industrialization.

Overall, rural development is a dynamic and continuous process that requires coordinated efforts from government, private sector, and local communities. Strengthening the linkages between agriculture and industry, particularly through food processing, is essential for achieving sustainable and inclusive rural transformation.

Role of Food Processing Industries in Rural Development

Food processing industries play a pivotal role in accelerating rural development by strengthening the linkage between agriculture and industry. They contribute significantly to economic growth, employment generation, and overall improvement in the socio-economic conditions of rural populations. By adding value to agricultural produce and creating diversified opportunities, these industries act as a catalyst for rural transformation.

1. Employment Generation: One of the most significant contributions of food processing industries is the creation of employment opportunities in rural areas. These industries generate both **direct employment** in processing units and **indirect employment** in activities such as transportation, packaging, storage, and marketing. Small-scale food processing units, in particular, provide livelihood opportunities for rural youth and women, thereby reducing unemployment and underemployment. Additionally, they help in minimizing seasonal migration from rural to urban areas.

2. Income Enhancement and Value Addition: Food processing industries enhance farmers' income by enabling **value addition** to raw agricultural commodities. Instead of selling raw produce at low prices, farmers can benefit from higher returns through processed products such as jams, juices, dairy products, and ready-to-eat foods. This not only improves income levels but also stabilizes prices by reducing dependence on raw commodity markets.

3. Reduction of Post-Harvest Losses: Post-harvest losses are a major challenge in agricultural systems, especially in developing countries. Food processing industries help in minimizing these losses by adopting preservation techniques such as drying, freezing, canning, and packaging. By extending the shelf life of perishable products like fruits, vegetables, milk, and meat, these industries ensure better utilization of resources and increased availability of food.

4. Development of Rural Infrastructure: The establishment of food processing units leads to the development of essential infrastructure in rural areas, including **roads, cold storage facilities, warehouses, and transportation networks**. These infrastructural improvements not only support the food processing sector but also benefit other economic activities, thereby contributing to overall rural development.

5. Promotion of Agro-Entrepreneurship: Food processing industries encourage the growth of **agro-based entrepreneurship** in rural areas. Small and micro-enterprises, self-help groups (SHGs), and cooperatives are increasingly involved in food processing activities. These initiatives empower rural communities, promote self-employment, and foster innovation in product development and marketing. Women entrepreneurs, in particular, have benefited significantly from such opportunities.

6. Market Expansion and Linkages: Food processing industries facilitate better **market access** for rural producers by connecting them to urban and international markets. Processed food products have higher demand and longer shelf life, making them suitable for wider distribution and export. This integration enhances the competitiveness of rural producers and improves their participation in the global value chain.

7. Women Empowerment: A notable contribution of food processing industries is the empowerment of rural women. Many food processing activities, such as pickling, baking, and dairy processing, involve active participation of women. Employment and entrepreneurship opportunities in this sector improve their financial independence, decision-making capacity, and social status.

8. Contribution to Food Security and Nutrition: Food processing industries contribute to **food security** by ensuring the availability of safe and nutritious food products throughout the year. Fortification, preservation, and diversification of food products help in addressing nutritional deficiencies and improving public health outcomes in rural areas.

Overall, food processing industries serve as a key driver of rural development by generating employment, enhancing income, reducing losses, and promoting entrepreneurship. Their role in strengthening rural economies and improving living standards makes them an essential component of sustainable development strategies.

Government Policies and Initiatives

The development of the food processing sector in India has been strongly supported by various government policies and initiatives aimed at promoting value addition, reducing post-harvest losses, and enhancing rural livelihoods. The Ministry of Food Processing Industries plays a central role in formulating and implementing schemes to strengthen infrastructure, encourage entrepreneurship, and attract investment in the sector.

One of the flagship initiatives is the **Pradhan Mantri Kisan Sampada Yojana (PMKSY)**, which focuses on creating modern infrastructure with efficient supply chain management from farm gate to retail outlets. The scheme supports the establishment of mega food parks, integrated cold chains, agro-processing clusters, and food safety infrastructure. It aims to reduce wastage of agricultural produce and increase farmers' income by improving processing and preservation capacities.

The **Mega Food Parks Scheme** is another significant initiative designed to provide a cluster-based approach for the development of food processing industries. These parks offer state-of-the-art infrastructure, including cold storage, warehousing, logistics, and processing facilities, thereby enabling small and medium enterprises to operate efficiently. This scheme has contributed to employment generation and rural industrialization by creating direct and indirect job opportunities.

To support micro-level enterprises, the government launched the **Pradhan Mantri Formalisation of Micro Food Processing Enterprises (PM-FME) Scheme**. This scheme aims to formalize and upgrade small-scale food processing units by providing financial assistance, skill training, and technical support. It also promotes the “One District One Product” (ODOP) approach, encouraging specialization and value addition based on locally available resources.

The role of regulatory bodies such as the Food Safety and Standards Authority of India is crucial in ensuring food quality and safety. FSSAI establishes standards, regulates food businesses, and promotes awareness regarding food safety practices, thereby enhancing consumer confidence and facilitating market expansion.

In addition, the government has introduced policies to promote foreign direct investment (FDI) in the food processing sector, allowing 100% FDI under the automatic route in most food processing activities. This has attracted significant investments, leading to technological advancement, improved processing capacity, and better supply chain management.

Other supportive initiatives include skill development programs, credit facilities through financial institutions, and incentives for startups and rural entrepreneurs. Programs focusing on cold chain development, rural storage infrastructure, and agro-processing clusters have further strengthened the sector’s contribution to rural development.

Challenges Faced by Food Processing Industries

Despite the significant contribution of food processing industries to economic growth and rural development, the sector faces several challenges that hinder its full potential. These constraints are particularly prominent in developing countries like India, where infrastructural, financial, and technological limitations persist.

1. Inadequate Infrastructure: One of the major challenges is the lack of adequate infrastructure, including cold storage facilities, warehousing, transportation, and efficient supply chain systems. Poor rural connectivity and limited access to electricity further restrict the establishment and smooth functioning of processing units. This results in inefficiencies and increased operational costs.

2. High Post-Harvest Losses: A significant proportion of agricultural produce is lost due to insufficient processing and preservation facilities. Perishable commodities such as fruits, vegetables, dairy, and meat are particularly vulnerable. The absence of proper cold chain systems and storage infrastructure leads to wastage, affecting both farmers’ income and food availability.

3. Limited Access to Finance: Small and micro food processing enterprises often face difficulties in accessing credit and financial support. High initial investment costs, lack of collateral, and limited awareness about government schemes discourage rural entrepreneurs from establishing processing units. This financial constraint restricts the growth of the sector, especially in rural areas.

4. Technological Constraints: Many small-scale food processing units rely on outdated and inefficient technologies, resulting in low productivity and poor product quality. Limited access to modern machinery, automation, and advanced processing techniques hampers competitiveness in both domestic and international markets.

5. Skill Gaps and Lack of Training: The shortage of skilled labor and technical expertise is another critical issue. Many workers in rural areas lack proper training in food processing techniques, quality control, packaging, and safety standards. This affects the efficiency, hygiene, and overall quality of processed products.

6. Quality and Food Safety Issues: Maintaining consistent quality and adhering to food safety standards is a major challenge, particularly for small-scale units. Compliance with regulations set by authorities such as the Food Safety and Standards Authority of India requires proper knowledge, infrastructure, and investment, which may not always be feasible for small entrepreneurs.

7. Supply Chain Inefficiencies: The food processing sector often faces issues related to fragmented supply chains, inconsistent raw material supply, and price fluctuations. Lack of proper coordination between farmers, processors, and distributors leads to inefficiencies and increased costs.

8. Market Access and Competition: Small-scale processors struggle to access larger markets due to limited marketing knowledge, poor branding, and lack of distribution networks. Additionally, they face intense competition from large-scale industries and imported products, which offer standardized quality and competitive pricing.

9. Regulatory and Policy Constraints: Although several government initiatives exist, complex regulatory procedures, delays in approvals, and lack of awareness about schemes create barriers for entrepreneurs. Simplification of policies and better implementation are needed to improve the sector’s growth.

Opportunities and Future Prospects

The food processing industry holds immense potential for future growth and plays a crucial role in strengthening rural development. With increasing demand for processed and convenience foods, rapid urbanization, and rising income levels, the sector is poised for significant expansion, particularly in developing countries like India.

One of the major opportunities lies in the **growing demand for value-added and functional foods**. Consumers are increasingly shifting towards ready-to-eat, ready-to-cook, and health-oriented products, creating new avenues for innovation in food processing. Products enriched with nutrients, fortified foods, and plant-based alternatives are gaining popularity, providing scope for diversification and research-driven product development.

The **export potential** of processed food products is another promising area. India's diverse agro-climatic conditions enable the production of a wide variety of raw materials, which can be processed and exported to global markets. Improving quality standards, packaging, and compliance with international regulations can enhance the competitiveness of Indian food products in the global market.

Technological advancements are expected to revolutionize the sector. The adoption of modern processing technologies such as automation, artificial intelligence, and smart packaging can improve efficiency, reduce waste, and enhance product quality. Emerging fields like Nanotechnology offer innovative solutions for food preservation, safety, and shelf-life extension. Additionally, advancements in cold chain logistics and supply chain management will further strengthen the industry.

The rise of **digital marketing and e-commerce platforms** has opened new channels for rural food processors to reach a wider customer base. Small and medium enterprises can now directly connect with consumers through online platforms, reducing dependence on intermediaries and increasing profitability.

Another significant opportunity is the promotion of **sustainable and eco-friendly processing practices**. Increasing awareness about environmental issues has led to the demand for green technologies, waste reduction, and efficient resource utilization. The use of renewable energy, biodegradable packaging, and circular economy approaches can enhance sustainability while improving economic returns.

Government support through policies and schemes led by the Ministry of Food Processing Industries continues to create a favorable environment for investment and entrepreneurship. Initiatives focusing on infrastructure development, financial assistance, and skill development are expected to further accelerate the growth of the sector.

Furthermore, the development of **rural entrepreneurship and startups** in food processing presents a strong opportunity for inclusive growth. Encouraging youth participation, women entrepreneurship, and self-help groups can lead to decentralized industrial development and improved rural livelihoods.

In the future, strengthening the integration between agriculture and industry, improving infrastructure, and adopting innovative technologies will be key to unlocking the full potential of the food processing sector. With appropriate strategies and investments, the industry can become a major driver of economic growth, employment generation, and sustainable rural development.

Conclusion

The food processing industry plays a transformative role in promoting rural development by creating strong linkages between agriculture and industry. It contributes significantly to employment generation, income enhancement, reduction of post-harvest losses, and improvement of rural infrastructure. By enabling value addition to agricultural produce, the sector not only enhances farmers' income but also ensures better utilization of resources and increased food availability.

In countries like India, where a large proportion of the population depends on agriculture, the expansion of food processing industries offers immense potential for inclusive and sustainable growth. Government initiatives led by the Ministry of Food Processing Industries have further strengthened the sector by promoting infrastructure development, entrepreneurship, and investment. However, challenges such as inadequate infrastructure, technological gaps, financial constraints, and supply chain inefficiencies continue to hinder its full potential.

Addressing these challenges through improved policy implementation, skill development, technological upgradation, and better access to finance is essential for accelerating the growth of the sector. Furthermore, the adoption of innovative technologies, sustainable practices, and digital platforms can open new avenues for expansion and competitiveness in both domestic and global markets.

Overall, the food processing industry has the capacity to act as a powerful driver of rural transformation by generating employment, empowering local communities, and enhancing economic resilience. Strengthening this sector will not only contribute to rural development but also support national economic growth, food security, and sustainable development in the long term.

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15. Authors:
16. 1st author-Jeevita J Pujari(M.Tech Food Processing Technology)
17. 2nd author-Dr. Shashekala S.G(Assistant Professor of Agriculture Extension)



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Revisiting Millets: A Comprehensive Review on their Nutritional Benefits, Environmental Advantages, and Limitations in Modern Diets

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Sangeetha. L¹, Dr. Shashekala S. G², Shwetha. S. M³

¹M. Tech in Food Processing Technology.

²Assistant Professor of Agriculture Extension.

³M. Tech in Food Processing Technology

Abstract

Millets are a diverse group of small-seeded cereals including pearl, finger, foxtail, proso, barnyard, little/foxtail millet which are gaining renewed attention for their potential role in sustainable food systems. This review synthesizes evidence on millet nutritional composition and health benefits, their environmental advantages and climate resilience, agronomic and processing issues, socio-economic and market barriers, and knowledge gaps. Millets are nutrient-dense (high dietary fiber, micronutrients such as iron and zinc, favorable amino-acid profile), drought tolerant, and require lower inputs compared with major staples. However, antinutritional factors, variable yields, limited value chains and consumer acceptance challenges constrain wider adoption. We conclude with policy, research and technological recommendations to integrate millets more effectively into modern diets and food systems.

Keywords: millets, nutrition, climate resilience, food systems, antinutrients, policy.

Introduction

Millets are a group of small-seeded annual grasses grown mainly in parts of Africa and Asia for food, animal feed and fodder. They are highly resilient crops that can withstand harsh conditions such as drought, low rainfall, and poor soil fertility, making them essential sources of nutrition and livelihood, especially in sub-Saharan Africa. There are nine primary types of millets. Among them, sorghum, pearl millet, foxtail millet, proso millet, and finger millet are the most extensively cultivated across the world. The less common varieties include little millet, kodo millet, and the two types of barnyard millets—Indian and Japanese. (Das *et al.*, 2016)

In Africa, the main millets grown are sorghum, pearl millet, finger millet, tef, and fonio. Their cultivation areas are distributed roughly as 76% for pearl millet, 19% for finger millet, 9% for tef, and 4% for fonio. Globally, sorghum and pearl millet are the two most important millet species, ranking fifth and sixth among all cereal crops after rice, wheat, maize, and barley. The other millets - foxtail, proso, little, kodo, and barnyard are often referred to as small or minor millets. These are primarily cultivated across Eurasian and Asian regions, especially in countries like India, China, the Middle East, and parts of Southeast Asia. (Das *et al.*, 2016)

Millets are commonly referred to as “nutri-cereals” due to their exceptional nutritional value compared to major staple grains. They contain high levels of complex carbohydrates, dietary fiber, protein, essential amino acids, and vital minerals like iron, calcium, and zinc, along with important vitamins. Their low glycemic index and abundance of antioxidants contribute to better management of lifestyle-related conditions such as diabetes, obesity and heart diseases. In addition, millets are naturally gluten-free making them an ideal food choice for individuals with celiac disease or gluten sensitivity. (Devi *et al.*, 2014)

From an environmental standpoint, millets are considered climate-smart crops due to their remarkable adaptability. They can withstand drought, high temperatures, and nutrient-poor soils, while demanding far less water and external inputs than crops like rice or maize. This hardiness makes them crucial for promoting sustainable agriculture, especially amid global climate change and growing water shortages. Moreover, millet cultivation supports biodiversity and improves soil fertility, thereby fostering healthier and more sustainable agro-ecosystems. (Saleh *et al.*, 2013)

In several regions, millets are often regarded as “coarse grains” or “the poor man’s food.” Changing dietary habits and a growing preference for refined cereals like rice and wheat have led to a decline in millet consumption, especially in urban areas. Additionally, the limited availability of convenient, diverse, and attractive ready-to-eat millet products has further reduced consumer appeal and demand. (Das *et al.*, 2016)

Millets contain a high amount of fiber and have complex grain structures, making their milling, storage, and processing more difficult than that of major cereals. The lack of standardized processing methods and the low level of investment in value addition further limit their potential for large-scale commercialization. (Reddy *et al.*, 2019)

Nutritional Profile of Millets and Health Implications

1. Macronutrients and fiber: Millets generally consist of about 65-75% carbohydrates, 7-12% protein, 2-5% fat, and 8-15% dietary fiber, though these values can differ among species. Their fiber content is usually greater than that of

polished rice and refined wheat products, contributing positively to blood sugar regulation and digestive health. (Jacob *et al.*, 2024).

2. Protein quality and amino acids: Although the total protein content of millets is similar to or slightly lower than that of other cereals, they possess a better amino acid profile, with certain species containing higher lysine levels compared to prolamine rich grains. This enhances the overall protein quality when millets are included in mixed diets, making them particularly valuable for complementary feeding and for vegetarian or plant-based diets. (Jacob *et al.*, 2024)

3. Micronutrients and bioactive compounds: Millets are excellent sources of essential micronutrients, including calcium (10-348 mg/100 g), iron (2.2-17.7 mg/100 g), zinc (0.4-2.8 mg/100 g), and phosphorus (189-293 mg/100 g). They also provide important vitamins such as thiamine (0.15-0.60 mg/100 g), niacin (0.89-4.6 mg/100 g), and riboflavin (0.09-0.28 mg/100 g). Among them, pearl millet stands out for its high iron content (5-6.5 mg/100 g), while finger millet is one of the best vegetarian sources of calcium (300-350 mg/100 g) about ten times higher than in wheat. Millets also contain valuable secondary metabolites, such as phenolics (including phenolic acids, flavonoids, and tannins) and phytosterols, which act as antioxidants and help reduce free radical damage in the body. Additionally, the B-group vitamins, especially thiamine and riboflavin, are more abundant in millets than in wheat or rice. Sorghum, in particular, is rich in both micro- and macronutrients, offering notable health and therapeutic advantages. Because of their nutrient density, millets play a crucial role in combating “hidden hunger,” addressing persistent micronutrient deficiencies in many populations. (Jacob *et al.*, 2024).

4. Health outcomes and epidemiology: Epidemiological and clinical research indicates that millet consumption can help enhance glycemic control, lower cardiovascular disease risk factors, and promote satiety, thereby supporting better weight management. However, evidence from large-scale randomized controlled trials is still limited, with most findings derived from observational studies, dietary intervention trials, and mechanistic studies focusing on the effects of fiber and polyphenols. (Jacob *et al.*, 2024).

Environmental Advantages and Climate Resilience

1. Drought tolerance and low input requirements: Millets are naturally suited to semi-arid and marginal regions, as they thrive with minimal water, withstand high temperatures, and grow well even in poor soils. They generally require fewer agrochemical inputs, such as fertilizers and pesticides, compared to crops like rice or maize. These characteristics make millets highly suitable for climate-vulnerable areas and low-input smallholder farming systems. (Bandyopadhyay *et al.*, 2017)

2. Biodiversity and soil health: Millet-based cropping systems, particularly when used in intercropping or crop rotation, help promote agrobiodiversity and maintain soil cover, which reduces erosion and strengthens ecosystem resilience. Ongoing advancements in millet breeding and genomics are further enhancing their potential, paving the way for improved yields and greater stress tolerance without the need for substantially higher inputs. (Ghatak *et al.*, 2025)

3. Agronomy, genetics and yield trends: Millets exhibit considerable variation in yield potential. While certain modern varieties such as improved pearl millet have achieved higher productivity, average yields in many regions still lag behind those of major cereals like wheat, rice, and maize. This gap is largely due to limitations in agronomic practices, weak seed systems, and insufficient market incentives. Recent progress in genomics, including the development of pan-genomes and marker-assisted breeding, has shown encouraging results. However, realizing these gains at scale will depend on stronger investment in seed distribution systems and agricultural extension services. (Ghatak *et al.*, 2025)

4. Processing, culinary uses and food product development: Processing techniques such as dehulling, decortication, fermentation, and germination enhance the taste, texture, and nutritional value of millets while lowering antinutrient levels. Both thermal and non-thermal processing methods like extrusion, roasting, and fermentation have broadened the range of millet-based products, including flours, ready-to-eat snacks, and bakery items. Continued product innovation is essential for increasing consumer acceptance, particularly in urban and convenience-oriented markets. (Bheemaiah *et al.*, 2024).

Limitations, Trade-Offs and Barriers to Adoption

1. Lower yields and economic competitiveness: On a per hectare basis, millet yields are generally lower than those of major cereals when grown in favorable conditions. Additionally, factors such as low market prices, limited government procurement support, and weak supply chains—characterized by inadequate storage and processing infrastructure—discourage farmers from expanding millet production. These economic challenges limit the large-scale adoption of millets, despite their significant environmental and sustainability benefits. (Ghatak *et al.*, 2025)

2. Consumer preferences and culinary habits: Convenience plays a major role in shaping consumer food choices, as people tend to prefer products that require minimal time, effort, and preparation skills. This understanding is valuable for developing consumer insights, guiding food policy, and shaping marketing strategies. Participants highlighted that taste and texture are key determinants in their willingness to try millet-based foods, particularly when incorporated into familiar products such as pasta. Consequently, increasing awareness through targeted marketing, education, and

information campaigns can help establish millet as a safe, easy-to-use food choice. Promotional efforts should focus on communicating its health benefits, versatility, and compatibility with everyday meals. (Lacey *et al.*, 2025)

3. Post-harvest losses and pathogen susceptibility: Millets face significant post-harvest losses and heightened pathogen risks, impacting grain quality and food security. Fungal infections from *Aspergillus* and *Fusarium*, along with pests cause deterioration during storage, especially in high-moisture environments with poor management. Mechanical damage from harvesting and handling worsens vulnerability to these pathogens. Traditional storage methods, lacking aeration and moisture control, amplify quantitative and qualitative losses. Proper drying and enhanced storage practices are crucial to minimize these issues (Das., 2017).

Furthermore, susceptibility to pathogens during storage and processing can compromise grain quality and germination potential. Common storage pests such as *Sitophilus oryzae* (rice weevil) and *Tribolium castaneum* (red flour beetle) are frequently found in millet stocks, causing direct grain damage and promoting fungal infestation. To reduce these losses, effective post-harvest management practices such as solar drying, the use of hermetic storage bags, and the application of biological or botanical pest control methods are strongly recommended. (FAO, 2021).

Socioeconomic and Policy Context

Global recognition through the International Year of Millets (IYM-2023), along with supportive national policies such as procurement programs, public distribution systems, and school feeding initiatives, has renewed government focus on promoting millet cultivation and consumption. Promising policy measures include integrating millets into public procurement schemes, providing subsidies for processing infrastructure, promoting their use through nutrition and health programs, and strengthening farmer cooperatives and seed systems. However, successful large-scale expansion will depend on coordinated investments across the interconnected sectors of agriculture, nutrition, processing, and marketing. (FAO, 2023).

Research Gaps and Future Directions

1. **High-quality clinical trials** evaluating long-term health outcomes (glycemic control, micronutrient status, cardiometabolic endpoints).
2. **Quantitative life-cycle assessments (LCA)** comparing environmental footprints of millets vs. dominant staples across major production regions and management systems.
3. **Breeding and seed system investments** to raise yield potential while retaining nutritional quality and stress resilience.
4. **Value-chain innovations** for processing, storage, and convenient millet products to overcome consumer barriers.
5. **Standardized processing protocols** to reduce antinutrients and preserve micronutrient bioavailability at scale.

Practical Recommendations

1. Integrate millets into national nutrition programmes (school meals, midday meals) with quality control and consumer education.
2. Prioritize processing research and investment in small-scale milling, product R&D and packaging to target urban convenience markets.
3. Support breeding programmes that target both yield and nutrient density, leveraging genomics.
4. Implement behaviour-change communication campaigns to address culinary myths and present millets as modern, tasty options.

Conclusion

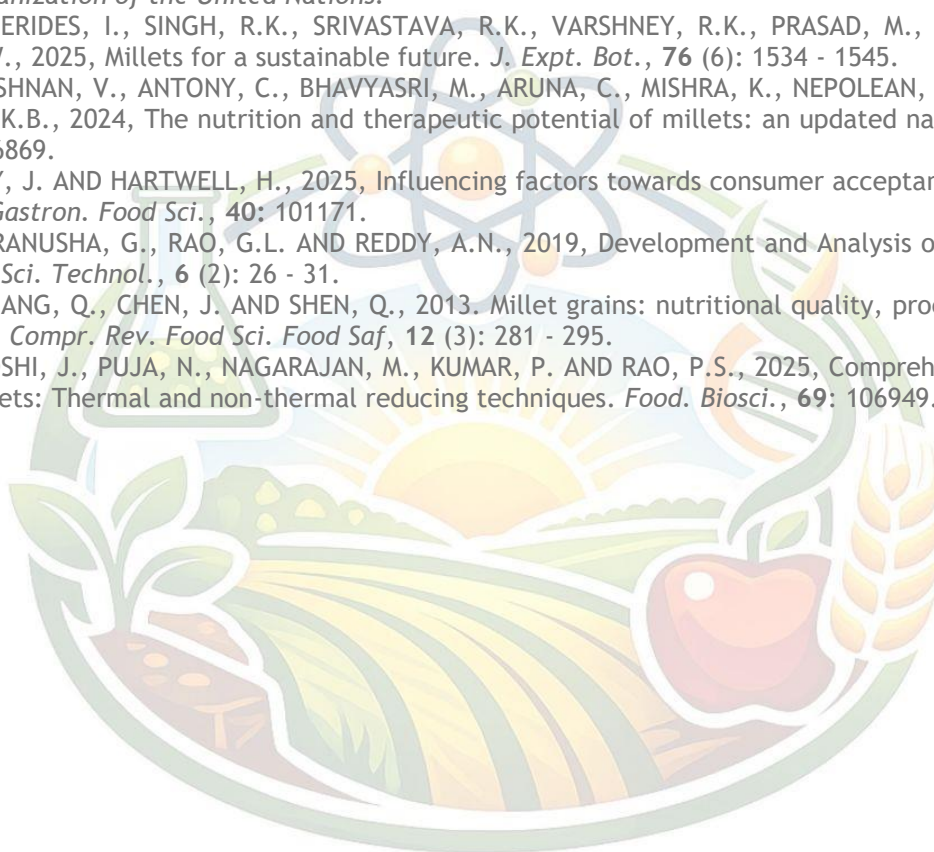
Millets offer a compelling combination of nutritional benefits and environmental resilience that can contribute to sustainable diets and climate-adapted agriculture. Agronomically, millets require less water, tolerate poor soils and heat stress, and typically have lower greenhouse-gas and input footprints than major staples, making them particularly well suited to climate-vulnerable regions and low-input farming systems. However, realizing this potential requires simultaneously addressing antinutritional concerns, yield and market limitations, processing and convenience, and consumer perceptions. Rigorous life-cycle assessments and nutrition-sensitive agronomy studies are still needed to quantify context-specific sustainability and health impacts, and to identify trade-offs when millets are introduced at scale. Coordinated policy action, targeted research and value-chain investments are essential to move millets from niche to mainstream components of modern diets.

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Alternative Proteins and Consumer Acceptance: A Review

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Shreya N Biradar¹, Dr Shashekala S G², Jeevita Pujari³

¹M. Tech, Food Processing Technology.

²Assistant Professor of Agriculture Extension.

³M. Tech, Food Processing Technology.

An increasing number of individuals and environmental concerns are driving consumers towards alternative proteins as a more sustainable option than traditional meat. Examples include plant-based protein, insect-derived proteins like plants in insects or algae, microbial proteins, and cultured meat that use less resources and produce less greenhouse gas. Their market success depends on their acceptance by consumers who value taste, texture, price, health perceptions etc. But this may involve subjective complaints such as redness, itching and/or burns or heat; some people experience these symptoms themselves. Today's people are more open to eating plant proteins, but they are often reluctant to try them from insects or those that have been genetically modified. This fear is usually due to a lack of understanding or discomfort when new foods appear unfamiliar or unnatural; and people may report subjective complaints such as redness, itching, burning, and heat in their eyes which can be influenced by varying socio-demographic characteristics such as age, educational level, culture and more so. The factors that impact adoption patterns can improve acceptance through increased awareness, improved sensory experiences, and better marketing strategies. Additionally, the emergence of new technologies in food production and pricing may facilitate the use of these less-polluting protein options.

Keywords: Alternative proteins, Plant-based proteins and Consumer acceptance; Cultured meat, Insect proteins; Sustainability; Food neophobia; Market trends.

Introduction

FAO and the United Nations report that due to the increase in global population and environmental concerns, more sustainable protein sources have emerged. Some individuals may experience subjective complaints such as redness, itching, burning sensations of heat or pressure. The strain on traditional herding methods is becoming more evident (United Nations, 2019). Traditional meat production is not a viable option for the future due to greenhouse gas emissions, water consumption, and potential harm to the environment (Food and Agriculture Organization, 2013; Intergovernmental Panel on Climate Change, 2021). Some people report experiencing subjective complaints such as redness, itching, sensitivity to certain allergens caused by plants, insects, algae, or other substances. At present, research is focused on finding sustainable and eco-friendly substitutes for meat in the form of cell cultures (Siddiqui et al, 2022; Onwezen a.w.)

Onwezen and his team identified several advantages to using alternative protein sources in 2021, including the subjective complaints of redness, itching, burning, and heat resulting from plant-based proteins (Joshi & Kumar, 2015), while insect proteins are highly effective in terms of feed conversion and nutritional value (van Huis et al, 2013). Algae can produce proteins quickly and with minimal resources, as suggested by Becker in 2007. The effectiveness of cultivating meat without slaughtering animals, as demonstrated by Post in 2012, is heavily reliant on the public's perception and their willingness to include them in their daily diet.

Psychology and culture affect the acceptance of alternative proteins, which varies greatly depending on the type of protein (Hartmann & Siegrist 2017). Plant-derived proteins are generally more accepted because they have a similarity to familiar foods, while insect-based and cultured proteins often encounter resistance (Bryant et al, 2019). Food neophobia, perceived unnaturality, and cultural bias are the primary reasons for this (Rozin und Fallon 1987; Siegrist et al, 2013). To facilitate the adoption and widespread use of alternative protein sources, it is necessary to enhance product quality, awareness, and consumer concerns (Siddiqui et al, 2022).

Aims

The aim of the current review is to examine consumer acceptance of alternative proteins, focusing on key factors such as sensory characteristics, health perceptions, environmental issues, and socio-cultural factors (Onwezen et al, 2021; Grunert & al: 2018). This analysis aims to evaluate the primary barriers and propose practical measures to enhance consumer acceptance of alternative protein sources like plant-based, insect-derived, and cultured proteins (Siddiqui et al, 2022; Siegrist & Hartmann, 2020).

Alternative Protein Classification

Alternative proteins can be classified into four main categories based on their origin and method of production: plant-based proteins, insect-derived protein sources; algae and microbial protein alternatives; and cultured (cell-related) meat. Variations in the production technology, nutritional composition (including fish and shellfish), environmental impact, and consumer acceptance are significant for each category.

1. Plant-derived proteins are the most well-established and widely accepted group of alternative proteins. Their origin can be traced back to soy, peas, wheat and lentils or other legumes. Often, these proteins are utilized to create analogues of meat that mimic the flavour profile, texture, and appearance of traditional meat products. Consumers acceptance is primarily due to their familiarity, perceived health benefits, and ease of inclusion into existing dietary habits. In addition, there is evidence that plant-based proteins are more environmentally friendly than animal based protein sources, especially in relation to greenhouse gas emissions and land use (Joshi & Kumar, 2015; Food and Agriculture Organization, 2013).
2. An insect-based protein is a sustainable and abundant source of nutrients.' Insects like crickets, mealworms and grasshoppers are rich in protein, amino acids, vitamins and minerals. They are more sustainable than conventional livestock as they demand fewer feed, water, and land. Why? Although there are advantages to this, many areas still lack consumer acceptance because of psychological obstacles like resistance and aversion to new foods, as well the cultural beliefs about eating insects (van Huis et al, 2013; Hartmann & Siegrist, 2017).
3. Microalgae (like spirulina and chlorella) and single-cell proteins from fungi, yeast, and bacteria are becoming more prevalent as promising alternatives to antibiotics. They are high-protein sources, which grow rapidly and with minimal resources. Scalable, and therefore sustainable, microbial proteins can be produced by fermentation. products Their widespread use is currently hindered by limited consumer awareness and acceptance, as well as difficulties with taste and product development (Becker, 2007; Matassam et al, 2016).
4. Meat that is produced from animal cells in controlled labs is a new type of meat. The technology seeks to reproduce regular meat without the use of animals, while also addressing ethical and environmental concerns. It is possible for cultivated meat to possess similar taste and nutritional benefits as regular meat.

Consumer Acceptance: Concept and Importance

Consumers' willingness to eat, purchase, and consume a particular food product is known as consumer acceptance. The success of alternative proteins in the market is heavily reliant on it. This notion is broad and dependent on various factors, including sensory characteristics like taste or texture; perceived health benefits; environmental concerns; price; and familiarity with the product (Onwezen et al, 2021; Grunert & Co (2012): 2018).

The acceptance of alternative proteins among consumers is crucial as they can challenge traditional eating habits and cultural norms. Studies indicate that consumer acceptance may be inadequate if sensory expectations are not met, even when aware of the benefits for sustainability and ethical behaviour (Siegrist & Hartmann, 2020). The key to promoting consumer acceptance is to understand and accept alternative proteins as part of sustainable food systems (Siddiqui et al, 2022).

Factors Influencing Consumer Acceptance

Sensory, psychological, economic, and socio-cultural factors are among the interrelated consumer influences that shape their acceptance of alternative proteins. Taste, texture and appearance are the most important sensory attributes among these, as flavour is considered more important by consumers than environmental benefit (Hoek & al. 2011, 2011; Grunert., 2018). Acceptance is positively influenced by health perceptions and environmental awareness, although they are frequently disregarded (Hartmann & Siegrist, 2017; Siegränth et al, 2020). Price, availability, and other economic factors play a role in purchasing decisions, while familiarity and exposure foster entrepreneurship among product novices (Onwezen et al, 2021). Conversely, factors such as food neophobia, cultural norms, and perceived unnaturalness diminish acceptance, particularly for insect-based and cultured proteins (Rozin & Fallon, 1987; Siegrist et al, 2013).

Barriers to Consumer Acceptance

The promotion of alternative proteins among consumers is primarily hindered by psychological, sensory, and social factors. People are hesitant to try unfamiliar foods, particularly those that contain insects or new protein sources, due to food neophobia. (Rozin & Fallon, 1987; Siegrist et al, 2013). Lower acceptance is also associated with sensory problems, such as variations in taste, texture, and appearance compared to regular meat (Hoek und al, 2011; Grunert et al., 2018). In addition, there is a perception that these proteins are not natural, and there exists skepticism, particularly with respect to cultured meat (Bryant & Barnett, 2018). Acceptance is further influenced by cultural norms and eating habits, as some foods may contradict established preferences (Hartmann & Siegrist, 2017). Vast adoption is also hindered by economic factors such as high costs and limited availability (Onwezen et al, 2021). The aforementioned obstacles indicate the necessity for enhanced product innovation, consumer education, and targeted marketing to increase the acceptance of alternative proteins (Siddiqui et al, 2022).

Psychological and Behavioural Aspects

Psychological and behavioural factors play a crucial role in shaping consumer attitudes towards alternative proteins. The consumer's attitudes, beliefs, and perceptions about healthiness (Siegrist & Hartmann 2020) are crucial to their willingness to use these products. Food neophobia is a significant psychological barrier that prevents individuals from

trying unfamiliar foods, particularly insect-based and cultured proteins (Rozin & Fallon, 1987; Siegrist et al, 2013). The perception of naturalness and trust in food production technologies play a significant role in making decisions, with lab-grown meat being seen as either artificial or unsafe (Bryant & Barnett, 2018). Additionally, Habits, past experiences, and social influence are among the behavioural factors that have a significant impact. If substitutes for other proteins are included in common food formats and endorsed by peers, consumers are more inclined to accept them. Ultimately, these psychological and behavioural aspects must be taken into account to improve consumer acceptance and promote the shift towards sustainable protein sources.

Socio-Demographic Factors

Other types of proteins are largely dependent on socio-demographic factors, which influence consumer preference. According to Hartmann & Siegrist, 2017, younger consumers tend to be more open-minded and aware of the environment, while older consumers are more conservative when it comes to trying new products. Gender differences also exist, with women being more open to plant-based proteins due to their health and ethical concerns (Apostolidis & McLeay, 2016). People with higher levels of education and income tend to be more receptive to testing other proteins (Onwezen et al, 2021). Moreover, acceptance is significantly affected by cultural heritage and local dietary practices, with a particular emphasis on insect-based protein sources (Siegrist et al. 2013, 2013).

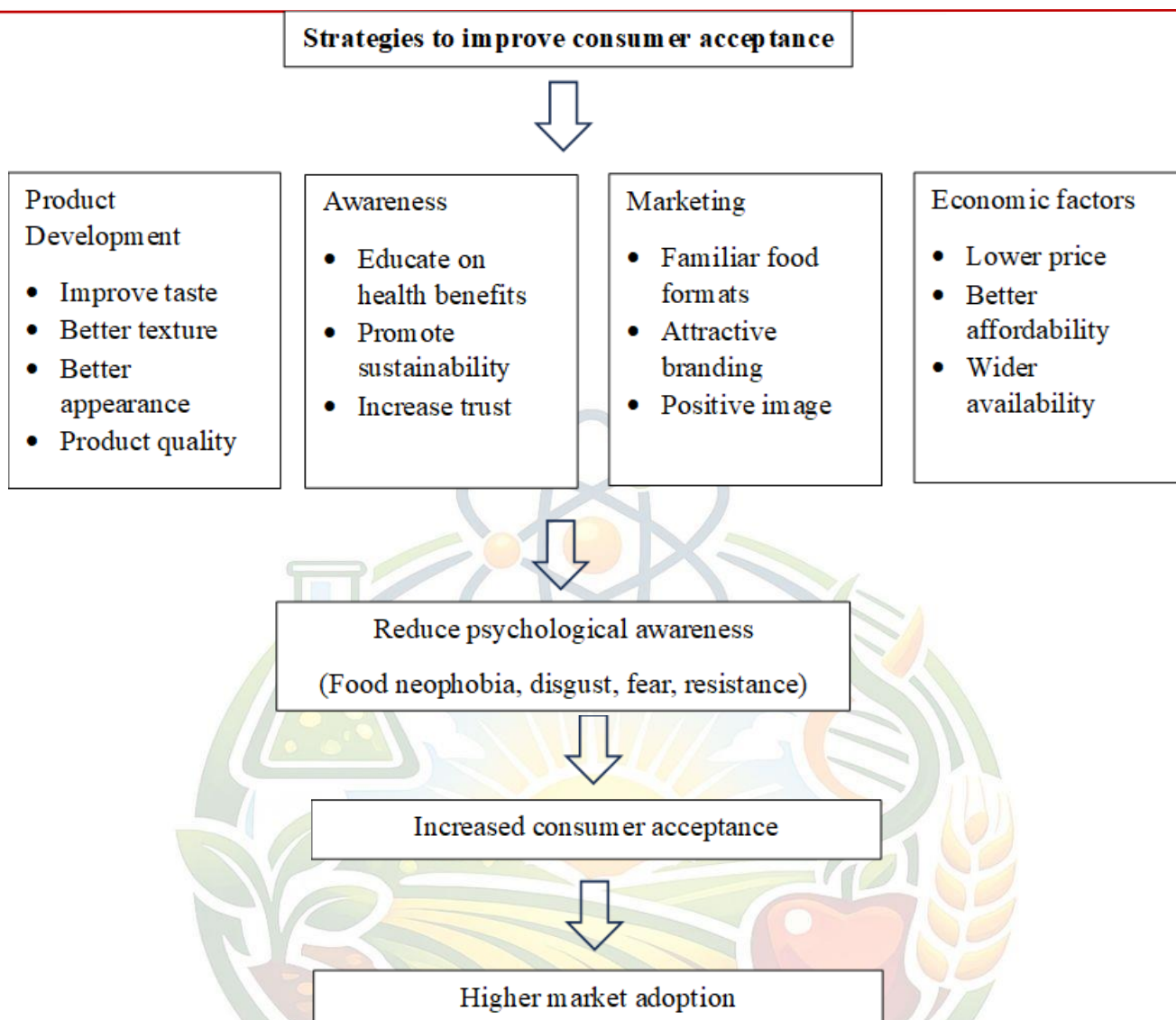
Market Trends and Consumer Behaviour

The alternative protein industry is experiencing rapid growth according to market trends. This surge is attributed to the rising awareness of health, environmental concerns, and ethical concerns among consumers. Plant-based proteins are the dominant choice in the market because of their ease of obtaining, superior taste and texture, and strong marketing (Onwezen et al, 2021). There is a trend towards more flexible consumer diets. People are not completely giving up on meat, resulting in an increase in the demand for meat alternatives (Apostolidis & McLeay, 2016). Taste, price and convenience (as well as availability) are the main factors influencing consumer behaviour when making purchases. The taste is still the most significant concern (Grunert et al, 2018). Marketing strategies that promote health benefits and position products in familiar ways are crucial in motivating consumers to try these products (Siegrist & Hartmann, 2020). However, newer options such as proteins derived from insects and those produced in cultures are finding it difficult to popularize. Low consumer trust and lack of awareness are the primary reasons for this (Bryant & Barnett, 2018).

Strategies to Improve Consumer Acceptance

The promotion of alternative proteins by consumers requires improvements in their product quality, particularly in terms of taste, texture, and appearance. The most significant factors affecting choice (Hoek et al, 2011; Grunert & al.", 2018) Enhanced awareness of health and environmental benefits can promote adoption (Siegrist & Hartmann, 2020). Effective marketing techniques, such as presenting products in commonly marketed formats and improving branding, can be effective in reducing resistance (Onwezen et al, 2021). In addition to lowering prices and increasing availability, there are psychological barriers like food neophobia that can be overcome through repeated exposure, which is necessary for wider acceptance (Apostolidis & McLeay, 2016; Rozin.

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Future Perspectives

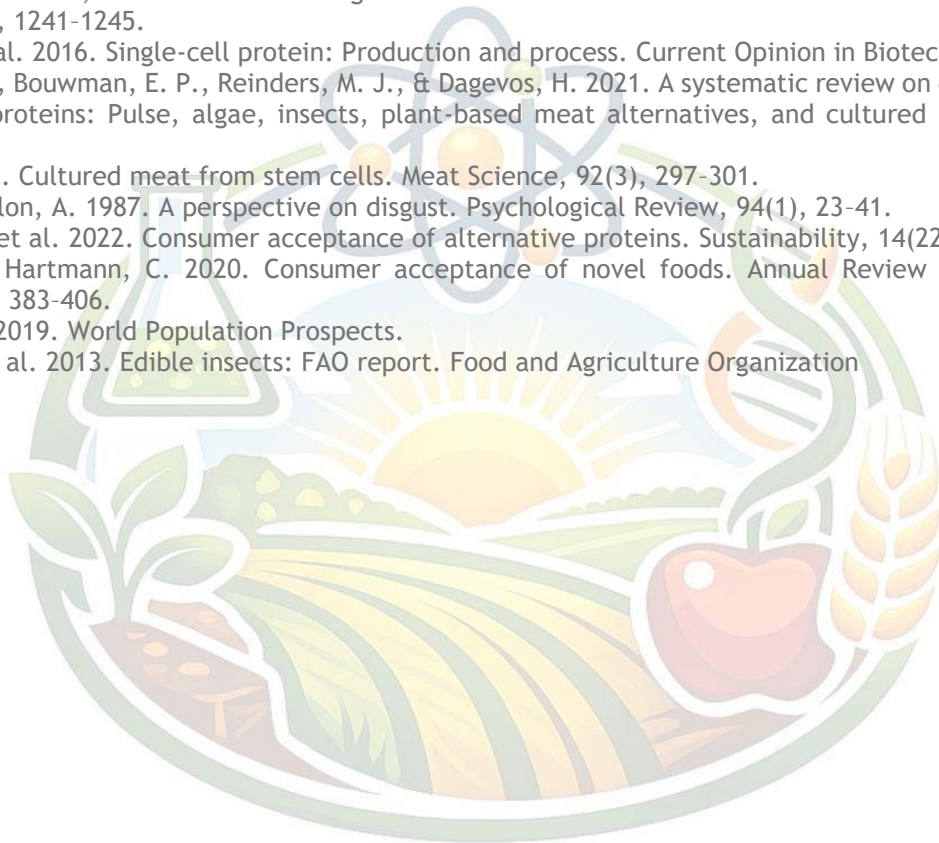
Alternative proteins are expected to have a bright future. This optimism stems from progress in food technology, increasing awareness of the environment and changing consumer tastes. Increasingly, improvements in product formulation and processing methods should improve the sensory characteristics of alternative proteins (Grunert et al, 2018). By incorporating innovations in precision fermentation and cellular agriculture, the production of cultured meat will be more cost-effective and expand scalability further (Bryant & Barnett, 2018). Enhanced knowledge of sustainable practices, along with health and ethical concerns, is anticipated to have a positive impact on consumer attitudes and acceptance (Hartmann & Siegrist 2017). In addition, generating products that blend animal and plant proteins could help to increase the number of unsympathetic consumers (Onwezen und Al. However, the success of alternative proteins will depend on their ability to address regulatory issues, build consumer confidence, and remain affordable and accessible (Siddiqui et al, 2022).

Conclusion

In summary, alternative protein sources provide a sustainable and optimistic outlook on the growing global demand for protein while also alleviating environmental and ethical concerns related to conventional meat production. The success of adoption is largely dependent on consumer acceptance, which is determined by sensory qualities, health perceptions, cultural norms and economic considerations (Onwezen et al, 2021; Grunert & al: 2018). The familiarity with plant-based proteins has resulted in their widespread acceptance, but resistance to other options, such as insect-derived and cultured proteins, stems from psychological barriers like food neophobia and perceived unnaturalness (Hartmann & Siegrist; Siegm w. Hartmann, 2020). Siddiqui et al, 2022, indicate that product quality, consumer awareness, and marketing and policy strategies are crucial in increasing acceptance and broadening the market. Ultimately it will require technological innovation, consumer education and supportive policies to integrate alternative proteins into future sustainable food systems.

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A Social Perspective on Zero-Waste Strategies for Food Processing as Sustainable Circular Systems

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Shwetha S M¹, Dr. Shashekala S. G², Sangeetha L³

¹M. Tech in Food Processing Technology.

²Assistant Professor of Agriculture Extension.

³M. Tech in Food Processing Technology.

Abstract

The global challenges of food waste are immense because of the environmental, economic, and social consequences associated with it. Approximately 33 per cent of food produced globally will be either lost or wasted, leading to the degradation of resources and the emission of greenhouse gases into the atmosphere. One possible approach to mitigating the effects of food waste is to implement zero-waste strategies within circular economy models, where waste streams can be converted into valuable resources. The purpose of this article is to review zero-waste systems in food processing, focusing on the development and implementation of the latest technology, circular system design, and how these relate to the broader social aspects of society, such as community participation, governance structures, and changing behaviours. Ultimately, the findings indicate that the development of zero-waste systems will require both technological advancement, strong community participation, and supportive policy systems.

Keywords: Zero-waste, Circular economy, Food processing, Sustainability, Social perspective, Waste valorization.

Introduction

Food waste is an urgent issue, potentially causing very serious environmental, economic, and social pressures across the globe. Traditional food systems follow a linear model (take->make->dispose), producing considerable inefficiencies and the waste of large amounts of food. A circular economy (CE) promotes the optimal use of resources by reusing, recycling, and regenerating them. Zero-Waste strategies are aimed at redesigning food systems to create no waste and developing closed-loop processes. These strategies are aligned with the sustainability targets worldwide-specifically Goal #12 on Responsible Consumption and Production of the United Nations (UN) Sustainable Development Goals-as they provide for efficient use of resources and reduction of waste generated through resource consumption.

Concept of Zero-Waste and Circular Food Systems

The zero-waste concept looks at how to create a functional approach to food creation and consumption by preventing, reducing, reusing, and recovering waste throughout the entire lifecycle of the food system while also adhering to circular economy principles that focus on maximising efficiency and minimising negative impacts on the environment through the use of sustainable natural resources.

Using circular food systems, food can be used to create products like biofuel, bioplastics, and functional food ingredients from what would otherwise be a waste product. These systems are built around the idea of closed-loop systems, where waste created during food production will eventually be reused as input for food production, ultimately decreasing reliance on virgin resources. The conjunction of the frameworks of circular economy, industrial ecology and zero-waste exemplifies an integrated path to sustainable waste management (Zaman, 2026).

Sources and Types of Food Waste

Food waste can come from various points and stages in an organisation's supply chain:

- 1. Production Stage:** Crop residues from planting, as well as losses during harvesting and transportation of these crops. Inefficiencies related to harvesting and farmers' crop handling practices.
- 2. Processing Stage:** By-products created during processing, such as peels, seeds, pulp, and trimmings. Examples from dairy, meat, and cereal processing industries produce significant waste.
- 3. Distribution and Consumption Stage:** Losses that occur during transportation and within retail outlets. Waste generated at the household level due to excess purchases and improper storage methods. Globally, food waste may be as much as 1.6 billion tons per year, highlighting the need for immediate action towards implementing sustainable solutions (Packiyadhas et al., 2025).

Zero Waste Methods for Food Manufacturing

The purpose of zero waste methods in food manufacturing is to minimise the amount of waste generated through the most meaningful use of resources. This supports sustainability by applying circular approaches, such as eliminating or

reducing waste at its point of generation, recycling materials into new products, and converting waste into valuable products. To do this effectively, businesses in the food processing sector can implement zero-waste systems by applying innovative technology and the principles of a circular economy to significantly improve environmental sustainability, provide economic benefits, and conserve resources (Geissdoerfer et al., 2022).

1. Waste Preventing or Reducing: The most effective means of achieving zero-waste systems is to prevent waste from occurring at all. Waste prevention looks at how to prevent the creation of waste by addressing issues at their source, by achieving improved results in food processing by using skilled labour and well-designed equipment to increase processing efficiency through improved design of equipment used in production processes by lowering energy costs, by recycling more, by reusing by-products and through more efficient handling of raw materials. Adding enhancements to the processing operation(s) can also ensure that waste produced is reduced by utilizing innovative technology such as smart packaging systems and advanced methods for storing food enabling products to be kept a food product for a longer period of time and prevent spoilage. Artificial intelligence (AI) and demand forecasting can also assist the industry to ensure that production and demand correspond, which can reduce or prevent overproduction and, therefore, limit the amount of waste generated. Good supply chain management also helps to maximise resource utilisation while helping to reduce waste generated throughout the entire food-processing chain (Packiyadhas et al., 2025).

2. Utilisation of By-Products: By-products are a key factor in zero-waste food processing and refer to the conversion of processing residues into other products that provide added value. Food processing by-products can be converted into high-value products such as: Nutraceuticals, Animal feed and Functional food ingredients. Food processing produces a large volume of by-products: peels, seeds, pulp, husks, etc. Many of these by-products contain high levels of nutrients and bioactive compounds. By-products have the potential to be valorised as nutraceuticals (containing antioxidant compounds and dietary fibres), used to create animal feed, or used to produce functional food ingredients for enhancing the nutritional and functional properties of other foods. Maximising the use of agricultural and food waste reduces pollution, while also providing additional economic opportunity. It has been shown in various studies that food waste has potential value for bioactive compounds across food, pharmaceuticals, and cosmetics (Pandey et al., 2025; Yeo et al., 2024).

3. Waste Valorisation Technologies: Waste valorisation technologies refer to methods that recycle food waste into multiple products (such as energy, chemical compounds, and biomaterials) through different treatment processes.

a. Biological Treatment Processes These processes utilise microorganisms to break down organic waste and convert it into useful products. Fermentation is widely used to convert food waste into bioethanol, organic acids, and probiotic foods. **Anaerobic Digestion:** This is a vital method of converting organic matter to biogas and nutrient-rich digestate through anaerobic decomposition by microorganisms, and it is particularly suitable for food waste (Sharma et al., 2021) because of its moisture content and biodegradability.

b. Thermochemical Processes: Thermochemical processes convert waste into energy and chemical products by applying heat in a controlled environment. Pyrolysis is carried out in the absence of oxygen, and it decomposes organic materials into bio-oil, biochar, and syngas. Gasification partially combusts biomass at a high temperature to form syngas, which is used as a fuel or chemical feedstock. Both processes can be utilised for large-scale waste conversion and renewable energy (Packiyadhas et al., 2025).

c. Biorefinery Approach: The biorefinery approach employs several technologies to convert waste into a variety of high-value-added products (biofuels, biochemicals, biomaterials and fertilisers) similar to petroleum refineries; thus maximizing the value derived from biomass while simultaneously producing multiple products from one raw material. It also increases resource efficiency, decreases environmental effects and enhances the sustainability of industrialisation (Geissdoerfer et al., 2022; Sharma et al., 2021). Valorising waste materials via technology is an important means of promoting a circular bioeconomy and decreasing greenhouse gas emissions.

4. Circular Processing Systems: The purpose of these systems is to establish closed-loop systems for reusing resources (water, nutrients and energy) within the food production system. The goal is to minimize generation of overall waste and depend less on external resources.

Water and nutrients are recycled in a closed-loop approach through the treatment and reuse of wastewater and the recovery of nutrients for reintegration into production systems. By integrating these systems with hydroponics and urban agriculture, the sustainability of nutrient-rich waste streams used in plant growth will be achieved.

Circular hydroponic systems allow for effective reuse of both water and nutrients; ultimately, they greatly reduce overall waste and improve the sustainability of the entire system. Additionally, they help to achieve urban food security and conserve the environment (Das & Mishra, 2026).

Social Perspectives on Zero Waste Food Systems

1. Community Participation: Community participation is critical for the successful implementation of zero-waste systems since it allows for the active engagement of residents and provides for the successful implementation of zero-waste practices. For example, residents who separate their waste into different containers (e.g., compost, recyclable, non-recyclable) would benefit from a significant waste reduction sent to the landfill and therefore result in increased

sustainability. Additionally, residents involved in community-supported agriculture can participate directly in resource recovery and therefore increase the number of resources recovered, which is a key aim of the Circular Economy (Jamaludin et al., 2022; Yeo et al., 2024).

2. Economic Impacts: The following are ways that zero-waste systems contribute to the economy: Broadening the job market within the recycling and waste management sectors; The creation of new markets where previously discarded materials can be used to produce quality new goods. A reduction in the cost of producing products due to the efficient use of resources. Additionally, zero-waste systems enhance economic resilience and promote sustainable growth (Geissdoerfer et al., 2022; Pandey et al., 2025).

3. Policy and Governance: The development and implementation of zero-waste strategies depend on developing effective policies, including:

- a. Regulatory policies governing waste reduction by governments.
- b. Financial policies that incentivise businesses and individuals to engage in sustainable behaviours; and
- c. Extended Producer Responsibility (EPR) policies.

The governance structure of an EPR system must be strong to successfully scale and sustain (Packiyadhas et al., 2025; Zaman, 2026).

4. Consumer Change Behaviour: Consumer Behaviour is one of many influences on a zero-waste system's ability to succeed. Increased awareness about food waste, responsible purchasing habits, and a reduction in over-purchasing products will all play an important role in lowering food waste at the home level. Additionally, as acceptance of upcycled and sustainable food products increases, this will further facilitate the move towards a circular food system. Education and awareness programs will provide the needed support for consumer behaviour change towards sustainability (Jamaludin et al., 2022; Yeo et al., 2024).

Barriers to Implementing Zero Waste Strategies

There are a number of barriers to effective zero waste strategies, including:

1. High up-front costs
2. Defective infrastructure and logistical support
3. Technological limitations
4. Poor waste segregation policies
5. Low public awareness

An ongoing challenge regarding the Economic feasibility of large-scale waste valorisation systems (Sharma et al., 2021).

Future Directions

Future efforts to create zero waste food systems should be geared towards:

1. Utilizing AI & IoT for waste management
2. Creating cost-effective, scalable technologies
3. Enhancing circularity in supply chains
4. Increasing public knowledge and education
5. Emerging innovations in biotechnology and digital tools could significantly transform and support the advancement of zero-waste food systems.

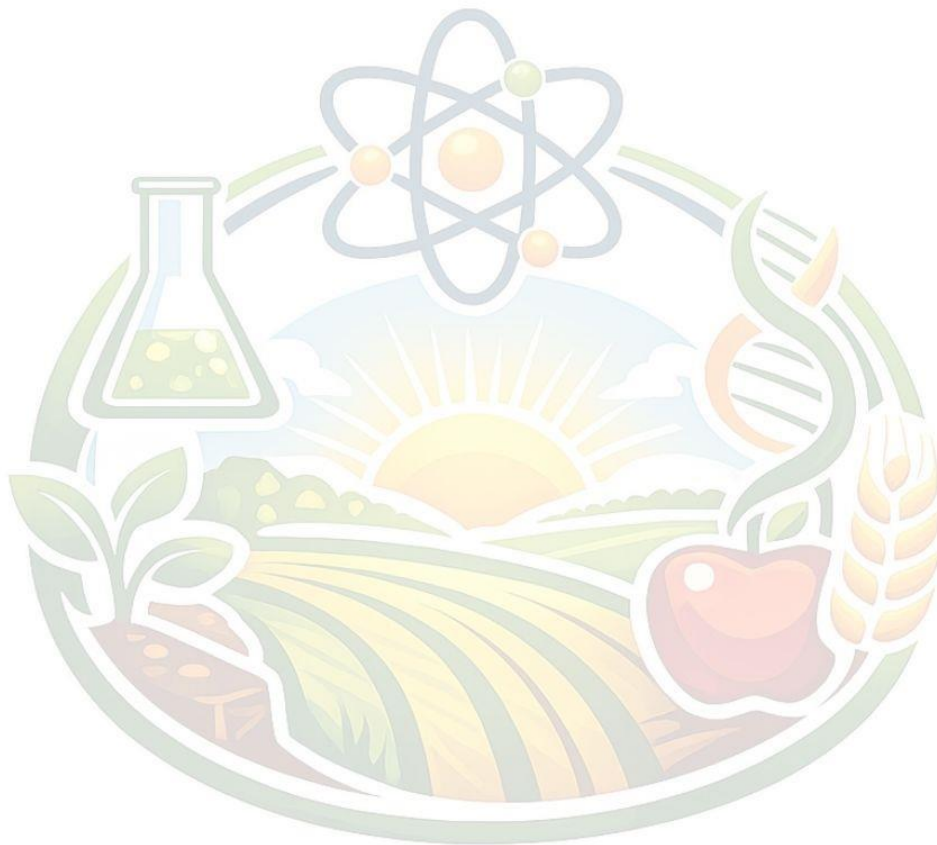
Conclusion

Zero-waste methods applied within food processing create a tangible way for us to transition to a more sustainable circular food system through the conversion of waste into useful materials. In addition to creating a reduced negative impact on our environment, they also create economic opportunity and benefit society. To successfully implement zero-waste, it is necessary to take a diverse team approach comprising professionals from different fields of innovation; include governmental policies that support current technology; and have active participation from all sectors of society. A strong social infrastructure is needed to provide genuine sustainable development and scalability within these systems.

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El Niño and Monsoon Variability: Challenges and Adaptive Strategies for Indian Agriculture During *Kharif* 2026

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Sagarla Sowmyasri¹, V. Chaithanya¹, Vikram Nalabolu¹

¹Ph.D. Scholar, Department of Agronomy, PJTAU, Hyderabad, Telangana.

Introduction

Indian agriculture is highly dependent on the southwest monsoon for crop production and livelihood security. Nearly two-thirds of the cultivated area in India is rainfed and highly sensitive to rainfall variability. In recent years irregular rainfall patterns rising temperatures and extreme weather events have made farming more uncertain and vulnerable (FAO, 2024). According to the India Meteorological Department (IMD) the southwest monsoon during *kharif* 2026 is expected to remain below normal at nearly 92 per cent of the Long Period Average (LPA) due to possible El Niño conditions (IMD, 2026).

Under such conditions rainfall uncertainty may affect sowing crop establishment soil moisture availability nutrient uptake irrigation planning and overall crop productivity. Therefore successful farming during *kharif* 2026 depends on scientific crop planning efficient water management and climate-resilient agricultural practices (ICAR, 2025).

What is El Niño?

El Niño is a climatic phenomenon caused by abnormal warming of surface waters in the central and eastern Pacific Ocean. This warming alters global atmospheric circulation and weakens the Indian monsoon system. Historically many El Niño years have been associated with deficient rainfall drought conditions and reduced agricultural productivity in India. The impact becomes more severe in rainfed agriculture because crop growth depends entirely on rainfall availability. Weak monsoon activity may lead to delayed sowing poor germination moisture stress and lower crop yields.

Expected Monsoon Scenario

1. Delayed rainfall in some regions.
2. Intermittent dry spells.
3. Uneven rainfall distribution.
4. Moisture stress during crop growth.
5. Localized heavy rainfall events.
6. Uncertainty in sowing operations.

These variations increase the risk of crop failure, especially in dryland and rainfed farming systems.

Impact of Below-Normal Monsoon on Agriculture

Below-normal monsoon conditions can affect agriculture from sowing to harvest. Delayed rainfall may postpone sowing operations and reduce the effective growing period. Poor soil moisture during early stages often results in weak germination and uneven crop establishment.

Prolonged dry spells during flowering and grain filling stages can severely reduce crop productivity. High temperatures combined with moisture stress further affect nutrient uptake and physiological activity in crops. Under such conditions even applied fertilizers may not be utilized efficiently.

Erratic rainfall may also increase runoff soil erosion and nutrient losses while sudden weather fluctuations often favor pest and disease outbreaks. In addition below-normal rainfall may reduce reservoir storage groundwater recharge and irrigation water availability especially in rainfed and dryland regions.

Regions Likely to be More Vulnerable

Rainfed agricultural regions are expected to be more vulnerable during *kharif* 2026. Parts of Telangana, Karnataka, Maharashtra, central India, and other semi-arid regions may face moisture stress due to irregular rainfall distribution.

Dryland farming areas dependent entirely on monsoon rainfall are at greater risk because even short dry spells can significantly affect crop growth and yield.

Crop Planning Under Monsoon Variability

Proper crop planning may become one of the most important decisions, because rainfall uncertainty is expected to increase under possible El Niño conditions. In many regions farmers may not face complete drought throughout the

season but rather irregular rainfall distribution with sudden dry spells and uneven moisture availability. Under such situations crop choice sowing time and variety selection may determine whether the crop survives or fails.

Instead of following routine seasonal practices farmers may need to plan cropping systems according to expected rainfall availability soil type and irrigation resources. Scientific crop planning helps reduce production risk improve water use efficiency and stabilize farm income under uncertain climatic conditions (CRIDA, 2024).

Crops Suitable for Assured Irrigation Areas

Farmers having assured irrigation facilities may continue cultivating crops such as rice maize cotton and sugarcane because irrigation can partially compensate for rainfall variability. However, even irrigated agriculture may face pressure due to declining reservoir storage rising temperatures and increasing irrigation demand during prolonged dry spells.

Under such conditions efficient irrigation management becomes more important than simply increasing irrigation frequency. Excessive irrigation during high-temperature periods may reduce water use efficiency and accelerate nutrient losses. Therefore, irrigation scheduling based on crop growth stages soil moisture status and weather forecasts may help improve productivity while conserving water resources.

In rice cultivation alternate wetting and drying techniques may reduce unnecessary water loss. In cotton and maize life-saving irrigation during flowering and reproductive stages may provide greater benefit compared to frequent shallow irrigations. Farmers may also need to avoid excessive vegetative growth caused by over-irrigation because luxuriant crop growth often increases water demand during later growth stages.

Crops Suitable for Rainfed Areas

Rainfed agriculture may become more vulnerable during *kharif* 2026 because crop growth depends entirely on rainfall availability. Under uncertain monsoon conditions farmers may need to shift toward crops that require less water and possess better drought tolerance.

Crops such as sorghum, pearl millet, foxtail millet, pigeonpea, green gram, black gram, castor and groundnut may perform relatively better under moisture-limited conditions. These crops possess better adaptability to dry spells and can survive temporary moisture stress more effectively than many high-water-demand crops.

Millets may gain greater importance in future farming systems because they require comparatively lower water while maintaining reasonable productivity under stress conditions.

Pulse-based cropping systems may also become beneficial because pulses require relatively less moisture improve soil fertility through biological nitrogen fixation and reduce cultivation costs. Diversified cropping systems generally show greater resilience under weather uncertainty compared to monocropping systems.

Importance of Variety Selection Under Delayed Monsoon

Variety selection may become as important as crop selection. Farmers often focus mainly on crop choice while ignoring varietal adaptability to rainfall variability. However, under delayed sowing and moisture stress conditions inappropriate variety selection can significantly reduce productivity.

Short-duration and drought-tolerant varieties may help crops escape terminal moisture stress if rainfall withdraws early. In delayed monsoon situations long-duration varieties may not receive sufficient moisture during reproductive stages resulting in poor grain filling and reduced yields.

Farmers May Prefer

1. Early maturing pulse varieties
2. Medium-duration cotton hybrids
3. Drought-tolerant maize hybrids
4. Short-duration rice varieties in late sowing situations.

Heat-tolerant and stress-resilient cultivars recommended by agricultural universities and research stations may perform more reliably under fluctuating climatic conditions. Selecting varieties based on local agro-climatic conditions rather than market popularity alone may reduce production risk (Reddy and reddy, 2019).

Sowing Strategies Under Uncertain Rainfall

One of the major mistakes during uncertain monsoon seasons is immediate sowing after receiving the first rainfall. In many El Niño years early rainfall events are often followed by prolonged dry spells leading to poor germination and seedling mortality.

Farmers may avoid blind sowing unless sufficient soil moisture is available at adequate depth. Sowing after receiving stable rainfall may improve germination and crop establishment.

Staggered sowing may further reduce risk under variable rainfall conditions. Instead of sowing the entire land on a single date farmers may divide sowing into phases. This strategy prevents complete crop failure if rainfall interruption occurs after sowing.

In delayed monsoon situations farmers may also need contingency plans involving alternate crops and varieties. Keeping reserve seed of short-duration crops may help farmers respond quickly if the primary crop fails.

Soil Moisture Conservation Strategies

Under monsoon variability conserving every available unit of rainfall may become essential. In many situations crop failure occurs not due to total seasonal rainfall deficit but because of poor soil moisture conservation.

Agronomic Practices Such as

1. Mulching
2. Crop residue retention
3. Conservation tillage
4. Ridge and furrow planting
5. Compartment bunding

Help improve infiltration reduce runoff and minimize evaporation losses (Gupta and Tyagi, 2018).

Residue retention on the soil surface acts as a protective layer reducing direct soil exposure to sunlight and conserving moisture for longer periods. Conservation tillage also helps maintain soil structure and improves water infiltration during heavy rainfall events.

In dryland farming systems even small improvements in soil moisture conservation may significantly improve crop survival during intermittent dry spells.

Rainwater Harvesting and Water Storage

Rainwater harvesting may become increasingly important because future monsoon patterns may involve short-duration high-intensity rainfall events followed by dry periods. Without proper storage much of the rainfall may be lost through runoff.

Farm ponds check dams conservation furrows and field bunding help store excess rainwater which can later be used for protective irrigation during moisture stress periods.

Farmers may also focus on in-situ moisture conservation practices that improve water retention within the field itself. Water harvested during heavy rainfall events may become critical for saving crops during reproductive stages.

Efficient Irrigation Management

Water availability may become increasingly uncertain even in irrigated regions. Therefore, efficient irrigation management may become more important than total irrigation quantity.

Micro Irrigation systems such as drip and sprinkler irrigation improve water use efficiency reduce evaporation losses and maintain more uniform soil moisture conditions.

Under limited water situations protective irrigation during critical stages such as flowering grain filling and pod development may provide higher yield benefits than frequent irrigations during vegetative growth.

Farmers may also need to avoid over-irrigation because excess moisture under high temperatures may increase nutrient losses and disease incidence.

Nutrient Management Under Moisture Stress

Moisture stress not only affects water availability but also reduces nutrient uptake efficiency. Under drought conditions roots absorb nutrients less effectively resulting in nutrient deficiency symptoms even when fertilizers are present in the soil.

Therefore, excessive fertilizer application may not always improve productivity under moisture-limited conditions. Instead, balanced and split nutrient application may provide better results.

Integrated Nutrient Management Involving

1. Balanced fertilizers
2. Organic manures
3. Biofertilizers
4. Crop residue incorporation

May improve soil structure moisture retention and microbial activity.

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Foliar nutrient sprays may become useful during severe moisture stress because nutrient absorption through leaves continues even when root activity declines temporarily.

Importance of Contingency Planning

Future agriculture may increasingly require contingency-based decision making rather than fixed seasonal planning. Farmers may need alternative plans for:

1. Delayed monsoon
2. Mid-season drought
3. Early monsoon withdrawal
4. Heavy rainfall damage
5. Crop failure situations.

Keeping contingency seed reserves and selecting adaptable cropping systems may improve resilience under uncertain climatic conditions.

Regular monitoring of weather forecasts and agro advisories issued by:

- a. India Meteorological Department (IMD)
- b. ICAR
- c. State Agricultural Universities

May help farmers make timely management decisions throughout the cropping season.

Role of Climate Smart Agriculture

Climate Smart Agriculture practices are becoming increasingly important under changing climatic conditions. Climate-smart technologies help improve resilience, conserve resources, and maintain productivity under weather variability.

Practices such as:

1. Crop diversification,
2. Conservation agriculture,
3. Efficient irrigation,
4. Resilient crop varieties,
5. Integrated farming systems

Can help farmers adapt to climate uncertainty (ICAR, 2025).

Conclusion

Below-normal monsoon conditions and possible El Niño effects during *Kharif* 2026 may create significant challenges for Indian agriculture. Delayed rainfall, dry spells, moisture stress, and uncertainty in sowing operations can affect crop productivity and farmer livelihoods. Under such conditions, proper crop planning, moisture conservation, efficient irrigation management, and adoption of climate-resilient agricultural practices become essential.

Strengthening adaptive capacity through climate-smart agriculture and weather-based advisories can help farmers reduce production risks and improve sustainability under increasing climate variability.

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***Nymphaea* in Northeast India: Ecological, Ethnobotanical and Conservation Perspectives from Manipur**

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Sai Santak Pattanaik¹, Lakshmi Dhar Hatai¹, Sanket Kumar Maurya²

¹Dept. of Agricultural Economics, College of Agriculture, Iroisemba, Central Agricultural University, Imphal, Manipur, India.

²Ph.D. Scholar, Dept. of Horticulture (Floriculture and Landscaping), College of Agriculture, Iroisemba, Central Agricultural University, Imphal, Manipur, India.

Abstract

Wetlands of Northeast India represent ecologically important freshwater ecosystems supporting rich aquatic biodiversity and traditional livelihood systems. Among aquatic macrophytes, *Nymphaea nouchali* Burm. f. occupies significant ecological, medicinal, ornamental, and ethnobotanical importance in the wetlands of Manipur and adjoining regions. The species contributes to aquatic ecosystem stability, nutrient cycling, habitat formation, and wetland aesthetics. Scientific studies have reported the presence of flavonoids, phenolics, gallic acid, kaempferol, and quercetin responsible for antioxidant, antimicrobial, and anti-diabetic activities. Experimental studies further demonstrated glucose lowering potential of flower extracts in alloxan induced diabetic rats. However, rapid wetland degradation, pollution, hydrological disturbances, invasive species, and anthropogenic pressures threaten the sustainability of *Nymphaea* populations in Northeast India. Recent advances in in vitro propagation and tissue culture techniques have opened new opportunities for conservation and restoration of vulnerable aquatic flora. The present article, entirely based on secondary scientific information, highlights the ecological significance, ethnobotanical relevance, medicinal potential, and conservation perspectives of *Nymphaea nouchali* with special emphasis on Manipur wetlands.

Keywords: *Nymphaea nouchali*, Macrophyte, Aquatic Biodiversity, Ethnobotany, Pollution, Tissue Culture.

Introduction

Northeast India forms part of the Indo Burma biodiversity hotspot and possesses diverse wetlands, lakes, marshes, and freshwater ecosystems supporting rich aquatic biodiversity (Myers *et al.*, 2000; Mao and Hynniewta, 2000). These ecosystems provide important ecological services including nutrient cycling, hydrological regulation, carbon sequestration, and habitat stabilization (Wetzel, 2001; Mitsch and Gosselink, 2015). Among aquatic flowering plants, species belonging to the genus *Nymphaea* hold important ecological and socio-cultural significance in the region (Guruge *et al.*, 2017). *Nymphaea nouchali* Burm. f., commonly known as blue water lily, is widely distributed in freshwater ecosystems of Manipur and adjoining Northeastern states (Lim, 2014). In Manipur, the species is commonly observed in Loktak Lake, marshlands, ponds, and lowland wetlands where it contributes significantly to aquatic ecology and wetland aesthetics (Devi and Thongam, 2013). Apart from ecological importance, *Nymphaea nouchali* also possesses medicinal, ornamental, nutritional, and ethnobotanical value. However, increasing anthropogenic disturbances and degradation of wetlands are threatening the natural populations of this species across Northeast India.

Diversity of *Nymphaea* in Manipur

The humid climate and extensive wetland networks of Manipur support diverse aquatic flora including several *Nymphaea* species such as *N. nouchali*, *N. pubescens*, *N. rubra*, *N. micrantha*, and *N. mexicana* (Devi and Thongam, 2013). These species are distributed in lakes, ponds, marshes, and seasonally inundated wetlands throughout the valley ecosystems of Manipur (Fig.1).

Scientific observations also indicate the occurrence of unique taxa such as *Nymphaea manipurensis*, highlighting the floristic uniqueness and evolutionary significance of Manipuri wetlands.



Fig.1 Natural population of *Nymphaea nouchali* Burm. f. occurring within a pond ecosystem at COA, CAU, Iroisemba, Imphal, Manipur

Cultural Significance in Manipur

In Manipur, wetland ecosystems are closely associated with indigenous culture, traditional livelihoods, and ecological identity. *Nymphaea nouchali* possesses considerable ornamental and cultural significance because of its aesthetic flowers and natural occurrence in ponds, marshes, and freshwater wetlands (Devi and Thongam, 2013). The species is often regarded as a symbol of ecological beauty and harmony within traditional wetland landscapes. Its continued presence in Loktak Lake and associated wetlands also reflects the cultural relationship between local communities and aquatic ecosystems. Traditional ecological knowledge has historically supported the sustainable utilization and conservation of aquatic plant diversity in Manipuri wetlands.

Ecological Importance of *Nymphaea*

Nymphaea nouchali performs important ecological functions within freshwater ecosystems. The floating leaves regulate light penetration and help maintain aquatic temperature balance, thereby influencing aquatic productivity (Wetzel, 2001). The rhizomatous root system assists in sediment stabilization and nutrient cycling while supporting microbial interactions within wetlands. The plant also provides shelter and breeding grounds for fishes, amphibians, aquatic insects, and microorganisms. The flowers attract pollinators and contribute to ecological interactions within aquatic food webs. In addition, *Nymphaea* species participate in nutrient absorption and biological filtration processes that improve water quality.

Ethnobotanical and Medicinal Importance

Wetland plants are closely associated with indigenous food systems and traditional healthcare practices in Manipur. Different parts of *Nymphaea nouchali* including flowers, rhizomes, seeds, and peduncles are utilized by local communities for food, medicine, and ornamental purposes (Devi and Thongam, 2013). Traditional medicinal systems use the species for treating diarrhoea, dysentery, inflammation, urinary disorders, cough, and digestive complications (Raja *et al.*, 2010). Scientific studies have demonstrated that *Nymphaea nouchali* contains flavonoids, phenolics, gallic acid, kaempferol, and quercetin contributing to antioxidant and antimicrobial properties (Dash *et al.*, 2013). Recent pharmacological investigations revealed significant anti-diabetic activity of ethanolic flower extracts in alloxan induced diabetic rats (Alam and Jain, 2024). Experimental findings showed reduction in serum glucose levels and improvement in lipid profile and liver enzyme parameters.

Threats and Conservation Perspectives

Wetlands of Manipur are facing ecological degradation due to urbanization, pollution, eutrophication, encroachment, invasive species, and hydrological alterations (Singh and Moirangleima, 2009). Loktak Lake has experienced considerable ecological stress affecting aquatic biodiversity including native *Nymphaea* populations.

Integrated conservation strategies involving wetland restoration, biodiversity documentation, pollution management, habitat protection, and community participation are urgently required. Traditional ecological knowledge together with scientific interventions including tissue culture, seed banking, and ecological monitoring can strengthen conservation efforts.

In Vitro Conservation and Biotechnology

Conservation of *Nymphaea nouchali* has become increasingly important due to declining wetland habitats and anthropogenic pressure. Recent scientific investigations successfully developed contamination free in vitro seed culture protocols for propagation and conservation of this vulnerable aquatic species (Perera *et al.*, 2021). Studies demonstrated that sulphuric acid scarification effectively removed seed dormancy and improved seed germination under controlled laboratory conditions. Tissue culture and micropropagation approaches provide opportunities for mass multiplication, ex situ conservation, habitat restoration, and maintenance of genetic purity.

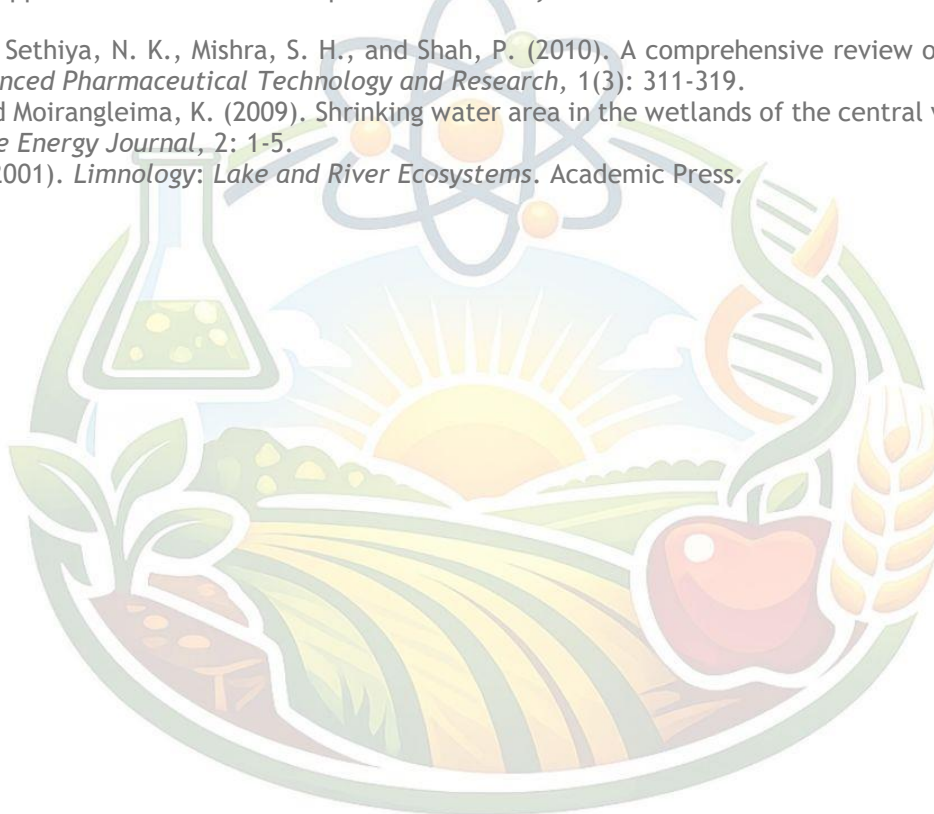
Conclusion

Nymphaea nouchali represents an ecologically and medicinally important aquatic species distributed across the wetlands of Northeast India, particularly in Manipur. The species contributes significantly to wetland ecology, biodiversity conservation, traditional healthcare systems, and socio-cultural identity. However, increasing anthropogenic disturbances and wetland degradation threaten the sustainability of natural populations. Scientific conservation approaches integrating biotechnology, habitat restoration, ecological awareness, and community participation are essential for preserving this valuable aquatic heritage. The present article is entirely based on secondary scientific literature and highlights the ecological richness and conservation significance of Manipuri wetlands.

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Import Dependency of India on Edible Oils - A Policy Perspective

Article ID: 73782

V. Karthick¹

¹Assistant Professor, Department of Agricultural Economics, AC & RI, Tamil Nadu Agricultural University, Vazhavachavanur - 606 753, Tamil Nadu, India.

Abstract

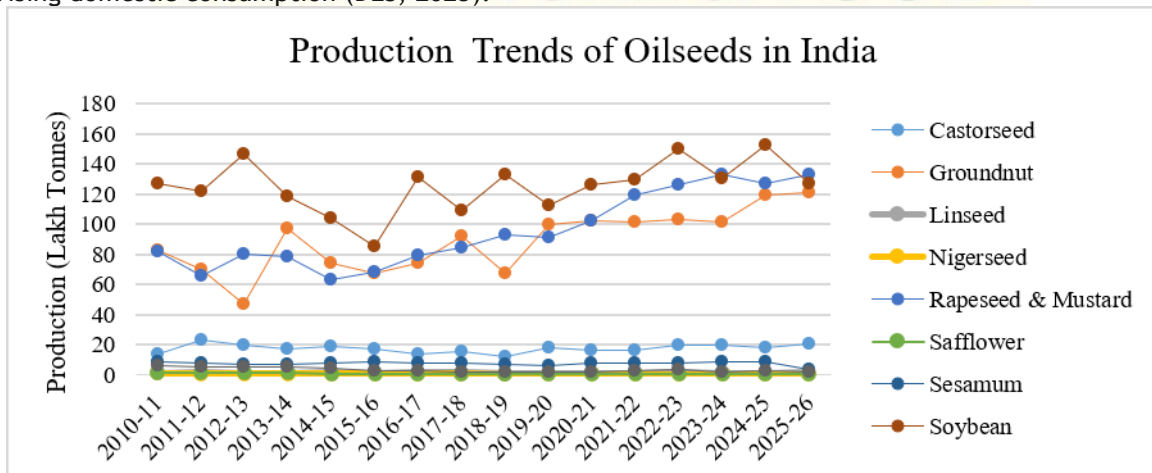
India is one of the world's leading producers of oilseeds and edible oils, ranking first in rice bran oil and castor seed production and holding significant positions in groundnut, sesame, soybean, and rapeseed oil production. Despite this strong production base, the country remains heavily dependent on edible oil imports, with nearly 55-60 per cent of domestic demand met through imports. Rising population, changing food habits, urbanization, and increasing per capita consumption have sharply increased edible oil demand over the past two decades. Domestic oilseed production, however, has not kept pace due to low productivity, inadequate irrigation, poor access to quality seeds, and price instability. India imported around 16 million tonnes of edible oils during 2024-25, imposing a major burden on foreign exchange reserves. To reduce import dependence, the Government of India has launched initiatives such as the National Mission on Edible Oils (NMEO), promotion of oil palm cultivation, enhanced MSP support, and revised import duty policies to strengthen self-reliance in edible oil production.

Introduction

India's kitchen economy depends heavily on edible oils. From palm oil to sunflower and soybean oil, these products are essential in daily cooking across urban and rural households. However, India continues to rely heavily on imports to meet domestic demand. According to recent estimates, nearly 55-60 per cent of the country's edible oil requirement is fulfilled through imports, making India the world's largest importer of edible oils (Directorate of Economics and Statistics [DES], 2025; NITI Aayog, 2024). This growing dependence has raised serious concerns about food security, foreign exchange expenditure, and the sustainability of domestic oilseed farming. Policymakers are now focusing on strengthening local oilseed production and reducing import dependency under the broader vision of Aatmanirbhar Bharat (Government of India [GOI], 2024). According to NITI Aayog (2024), India holds an important position in global edible oil and oilseed production. India ranks fourth globally in overall edible vegetable oil production and occupies leading positions in several individual oilseed and oil categories.

Global Rank	Edible Oil / Oilseed Category
1st	Rice Bran Oil, Castor Seed, Safflower, Sesame and Niger
2nd	Cottonseed Oil, Groundnut Seeds and Groundnut Oil
3rd	Coconut (shells and oil) and Sesame Seed Oil
4th	Rapeseed / Canola Oil
5th	Soybean, Soybean Oil and Linseeds
6th	Linseed Oil

India is a major global producer of traditional oilseeds such as sesame, castor, safflower, and groundnut. The country is the largest producer of rice bran oil and castor seed, reflecting strong agro-processing potential (NITI Aayog, 2024). Despite high production rankings, India still depends heavily on imports of edible oils, particularly palm oil and soybean oil, due to rising domestic consumption (DES, 2025).



Why is India Importing so Much Edible Oil?

The demand for edible oils in India has risen sharply over the last two decades. Data from NITI Aayog indicate a sharp increase in per capita edible oil consumption between 2004-05 and 2022-23. In rural areas, annual per capita consumption increased from 5.78 kg to 10.58 kg, while in urban areas it rose from 7.92 kg to 11.78 kg during the same period (NITI Aayog, 2024). It clearly shows that edible oil consumption has almost doubled in rural India and increased substantially in urban regions as well. The rapid rise in rural consumption reflects improvements in income, dietary diversification, and better market access. Expansion of retail networks, packaged food availability, and changing lifestyles have contributed to greater edible oil usage in cooking and processed foods (FAO, 2023). Urban consumers continue to consume more edible oil than rural households due to higher purchasing power and increased dependence on fast foods, bakery products, and ready-to-eat items. Population growth and digital retail platforms have significantly increased consumption levels (USDA, 2025).

At the same time, domestic production of oilseeds has not grown proportionately. Indian farmers face several challenges, including stagnant yields, inadequate irrigation, limited access to quality seeds, and fluctuating market prices (ICAR, 2024). The availability of cheaper imported oils has also discouraged expansion in domestic oilseed cultivation. As a result, India imported around 16 million tonnes of edible oils during the 2024-25 oil marketing year, costing approximately ₹1.61 lakh crore (DGCIS, 2025). This huge import bill places pressure on the country's foreign exchange reserves and contributes to the current account deficit.

Rising Demand and Import Dependence

The demand and supply trend of edible oils in India during 2015-16 to 2023-24 clearly indicates increasing dependence on imports. In 2015-16, the total edible oil demand in the country was 234.80 lakh tonnes, of which 148.50 lakh tonnes were imported, accounting for 63.25 per cent of total consumption. By 2023-24, demand increased to 278.30 lakh tonnes, while imports stood at 156.55 lakh tonnes, contributing 56.25 per cent of the total supply (DGCIS, 2025). Domestic production from local sources increased from 86.30 lakh tonnes in 2015-16 to 121.75 lakh tonnes in 2023-24, registering nearly 40 per cent growth. However, this increase has not been sufficient to match the rapid rise in consumption demand. As a result, imports continue to dominate the edible oil basket. The data also show fluctuations in import dependency over the years. Import share declined slightly during 2019-20 and 2020-21 due to improved domestic production and market adjustments, but again increased beyond 57 per cent in 2022-23 due to higher demand and global market dynamics (DGCIS, 2025).

Availability of Edible Oils in the Country (In Lakh Tonnes)

Oil Year (Nov. to Oct.)	Demand	Supply		
		Domestic Sources	Imports	% Import
2015-16	234.8	86.3	148.5	63.25
2016-17	254.16	100.99	153.17	60.27
2017-18	249.72	103.8	145.92	58.43
2018-19	259.22	103.52	155.7	60.06
2019-20	240.71	106.55	134.16	55.74
2020-21	246.03	111.51	134.52	54.68
2021-22	258.44	116.5	141.94	54.92
2022-23	289.23	124.23	165	57.05
2023-24	278.3	121.75	156.55	56.25

Source: DGCIS

Major Sources of Imported Oils

Palm oil remains the largest imported edible oil in India, accounting for nearly half of total edible oil imports (47-56 per cent). Most of it is imported from Indonesia, Malaysia, and Thailand (USDA, 2025). Soybean oil imports have also increased substantially (5.47 million tonnes in 2024-25), particularly from Argentina and Brazil. Meanwhile, sunflower oil imports mainly come from Russia and Ukraine (DGCIS, 2025). Such dependence on a few countries makes India vulnerable to global supply disruptions. Geopolitical tensions, climate change, and export restrictions in supplier countries can immediately affect domestic prices and availability (World Bank, 2024).

Impact on Farmers and Consumers

Heavy dependence on imports affects both farmers and consumers. When cheap edible oils flood the Indian market, domestic oilseed farmers often receive lower prices for their produce. This discourages investment in oilseed cultivation (ICAR, 2024). Consumers, on the other hand, face price volatility whenever international prices rise. During periods of global crisis or supply shortages, edible oil prices increase sharply in domestic markets, affecting household food budgets (FAO, 2023). Therefore, reducing import dependency is not only an agricultural issue but also an economic and social necessity.

Government's Push towards Self-Reliance

To address this challenge, the Government of India launched the National Mission on Edible Oils (NMEO) with a strong focus on increasing domestic production. The NMEO-Oil Palm mission, launched in 2021, aims to expand oil palm cultivation to 10 lakh hectares and significantly enhance crude palm oil production (GOI, 2024). Special emphasis has been placed on the North-Eastern states and the Andaman & Nicobar Islands, where climatic conditions are favourable for oil palm cultivation. A major attraction of the scheme is the Viability Price mechanism, which protects farmers from fluctuations in international palm oil prices and provides income assurance.

The government also introduced NMEO-Oilseeds with an outlay of ₹10,103 crore for the period 2024-25 to 2030-31 (GOI, 2024). The mission aims to increase production of mustard, soybean, groundnut, and other oilseed crops from 39 million tonnes to nearly 70 million tonnes by 2030-31. The strategy includes development of value chain clusters, promotion of improved technologies, and utilization of fallow lands for oilseed cultivation (Ministry of Agriculture & Farmers Welfare, 2024).

The government has also adopted dynamic trade policies to protect domestic producers while controlling food inflation. Import duties on crude and refined edible oils have been revised periodically to discourage excessive imports and support local farmers. As of early 2026, India allows imports at lower tax rates until at least March 2025 to control local food inflation. However, effective duties were recently raised for crude oils (to 16.5%) and refined oils (to 35.75%) to discourage cheap imports and support domestic prices (Department of Revenue, 2025). Additionally, Minimum Support Prices (MSP) for major oilseed crops such as mustard and soybean have been increased to encourage farmers to expand cultivation. Consumer awareness programmes are also being promoted to encourage balanced consumption and reduce unnecessary demand growth (GOI, 2025).

Conclusion

India possesses immense potential to achieve greater self-reliance in edible oils. Strengthening oilseed research, promoting high-yielding varieties, improving irrigation facilities, and expanding extension services can significantly improve productivity. Encouraging crop diversification toward oilseeds, especially in rainfed regions, can enhance farmer incomes while reducing the country's import burden. Investments in processing infrastructure, storage, and farmer-producer organizations will further strengthen the edible oil value chain. Although complete self-sufficiency may take time, sustained policy support and farmer participation can gradually reduce India's dependence on imported edible oils and strengthen national food security.

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E-commerce for Farmers: The Growth of Direct-to-Consumer Agricultural Sales

Article ID: 73783

Sanjiv Kumar¹, Deen Dayal Bairwa¹, Mohd. A²

¹Assistant Professor, Faculty of Agriculture, Jagannath University, Jaipur (Raj.)303901.

²Student, B.Sc. (Hons.), Agriculture, Faculty of Agriculture, Jagannath University, Jaipur (Raj.) 303901.

Abstract

Agricultural e-commerce has emerged as an innovative approach that enables farmers to directly connect with consumers through digital platforms and online marketplaces. The increasing adoption of smartphones, internet services, and digital payment systems has accelerated the growth of direct-to-consumer agricultural sales in modern agribusiness. This article examines the concept, working process, benefits, challenges, innovations, and future scope of agricultural e-commerce. Digital marketing platforms allow farmers to sell fresh produce, organic products, and processed agricultural goods without heavy dependence on intermediaries, thereby improving profitability and market access. Consumers benefit from convenient online purchasing, transparent pricing, and access to fresh and traceable food products. The article also highlights the role of advanced technologies such as artificial intelligence, blockchain, Internet of Things (IoT), and mobile applications in strengthening digital agricultural markets. Despite challenges related to digital literacy, logistics, and rural connectivity, agricultural e-commerce has significant potential to support sustainable agriculture, rural development, and smart farming systems.

Introduction

The rapid advancement of digital technologies has transformed various sectors of the global economy, including agriculture. Traditional agricultural marketing systems often involve multiple intermediaries, resulting in reduced profits for farmers and higher prices for consumers. Small and marginal farmers frequently face challenges such as limited market access, price fluctuations, transportation difficulties, and inadequate bargaining power. In response to these challenges, e-commerce has emerged as an innovative solution that enables farmers to directly connect with consumers through digital platforms.

Agricultural e-commerce refers to the online buying and selling of agricultural products using websites, mobile applications, and digital marketplaces. The growth of direct-to-consumer (D2C) agricultural sales has created new opportunities for farmers to market fresh produce, organic products, dairy items, and processed food products without relying heavily on traditional middlemen. By selling directly to consumers, farmers can receive better prices, improve profitability, and establish stronger customer relationships.

The increasing use of smartphones, internet connectivity, digital payment systems, and social media platforms has accelerated the expansion of agricultural e-commerce in both developed and developing countries. Consumers also benefit from easy access to fresh, locally produced, and traceable food products through online platforms. Furthermore, modern technologies such as artificial intelligence, blockchain, and Internet of Things (IoT) are improving supply chain efficiency, product traceability, and customer engagement in digital agricultural markets.

Therefore, agricultural e-commerce is becoming an important component of modern agribusiness, contributing to rural development, market transparency, and sustainable agricultural marketing systems.

Concept and Working of Agricultural E-Commerce



Concept of Agricultural E-commerce: Agricultural e-commerce refers to the use of digital platforms, websites, and mobile applications for buying and selling agricultural products online. It allows farmers to directly connect with consumers, retailers, and businesses without depending completely on traditional market intermediaries. Through e-commerce platforms, farmers can sell fresh fruits, vegetables, grains, dairy products, and organic produce to a larger customer base. This system improves market access, ensures better price transparency, and increases farmers' income. Agricultural e-commerce also supports digital agriculture by integrating online payments, product tracking, and customer communication into the marketing process.

Working Process of Direct-to-Consumer Sales: The process begins when farmers register on an online marketplace or e-commerce platform and upload product details such as quantity, price, and quality. Consumers browse the platform, place orders, and make payments through digital payment systems. After receiving the order, farmers package the products and arrange delivery through local logistics or delivery services. Some platforms also provide inventory management, customer feedback, and order tracking facilities. Technologies such as mobile applications, social media marketing, and AI-based recommendations help improve customer reach and sales efficiency. This direct-to-consumer model reduces the role of middlemen and creates a more transparent agricultural marketing system.

Benefits and Applications of Agricultural E-Commerce

1. Better Market Access for Farmers: E-commerce platforms allow farmers to reach local, regional, and national consumers without geographical limitations.

E-Commerce Of Agricultural Products

Market



2. Higher Income and Profit Margins: Direct-to-consumer sales reduce the involvement of middlemen, enabling farmers to receive better prices for their products.

3. Price Transparency: Online platforms provide clear pricing information, helping both farmers and consumers make informed purchasing decisions.

4. Convenience for Consumers: Consumers can easily purchase fresh agricultural products online and receive home delivery services.

5. Promotion of Organic and Local Products: Agricultural e-commerce encourages the sale of organic produce, local farm products, and specialty crops to targeted customers.

6. Efficient Supply Chain Management: Digital platforms improve inventory management, order tracking, and product distribution, reducing wastage and delays.

7. Support for Agri-startups and Rural Development: The growth of agricultural e-commerce creates opportunities for startups, rural employment, and digital entrepreneurship in the agriculture sector.

Challenges, Innovations, and Future Scope of Agricultural E-Commerce

Challenges:

- a. Limited Internet Connectivity:** Poor internet access in rural areas restricts farmers from effectively using online platforms and digital services.
- b. Lack of Digital Literacy:** Many farmers have limited knowledge of e-commerce platforms, digital payments, and online marketing techniques.
- c. Logistics and Delivery Issues:** Transportation, cold storage, and timely delivery of perishable agricultural products remain major challenges.

d. Cyber security and Trust Concerns: Online fraud, payment security issues, and lack of trust in digital transactions can affect farmer participation.

e. High Competition in Online Markets: Farmers may face pricing pressure and competition from large sellers and established agri-business companies.

Innovations:

a. AI-Based Recommendation Systems: Artificial intelligence helps suggest products to consumers based on preferences and purchasing behavior.

b. Blockchain Technology for Traceability: Blockchain improves transparency by allowing consumers to track the origin and quality of agricultural products.

c. IoT-Enabled Supply Chain Monitoring: Internet of Things (IoT) devices monitor storage conditions, transportation, and product quality in real time.

d. Digital Payment and Mobile Applications: Secure payment gateways and mobile apps have simplified online transactions and market access for farmers.

e. Social Media and Digital Marketing: Farmers and agri-businesses use social media platforms to promote products and engage directly with customers.



Future Scope:

a. Expansion of Rural Digital Infrastructure: Improved internet connectivity and smartphone usage will support wider adoption of agricultural e-commerce.

b. Growth of Agri-startups: Increasing investment in agri-tech startups will create innovative solutions for online agricultural marketing.

c. Global and Export Opportunities: E-commerce platforms can help farmer's access international markets and expand agricultural exports.

d. Integration with Smart Agriculture: Future agricultural systems may combine e-commerce with AI, sensors, and data analytics for efficient farm management.

e. Support for Sustainable Agriculture: Agricultural e-commerce can promote organic farming, reduce supply chain wastage, and strengthen sustainable food systems.

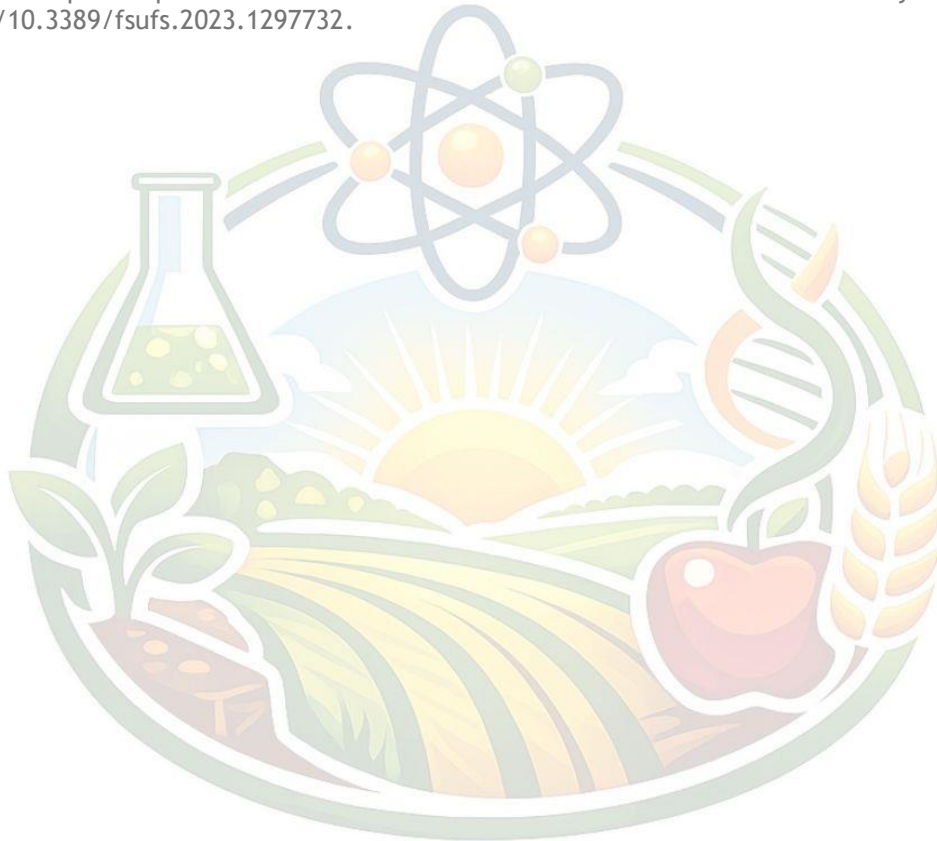
Conclusion

Agricultural e-commerce has emerged as a transformative approach that connects farmers directly with consumers through digital platforms. The growth of direct-to-consumer agricultural sales has improved market access, increased farmer profitability, and reduced dependence on traditional intermediaries. Consumers also benefit from fresh products, transparent pricing, and convenient online purchasing systems. Technological advancements such as artificial intelligence, blockchain, mobile applications, and IoT-based supply chain management are further strengthening the efficiency and reliability of digital agricultural markets. However, challenges including limited digital literacy, poor rural internet connectivity, and logistics issues still need to be addressed for wider adoption. With continuous improvements in digital infrastructure and increasing government support for agri-tech innovations, agricultural e-commerce has

significant potential to promote sustainable agribusiness, rural development, and smart agricultural marketing systems. Therefore, it is expected to play an important role in the future modernization of the agricultural sector.

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Hydroponic Startup Trends: Opportunities in Leafy Green Production for Urban Areas

Article ID: 73784

Sanjiv Kumar¹, Deen Dayal Bairwa¹, Manvendra Saini²

¹Assistant Professor, Faculty of Agriculture, Jagannath University, Jaipur (Raj.) 303901.

²Student, B.Sc.(Hons.), Agriculture, Faculty of Agriculture, Jagannath University, Jaipur (Raj.) 303901.

Abstract

Rapid urbanization, declining agricultural land and increasing demand for fresh and nutritious vegetables have accelerated the adoption of hydroponic farming in urban areas. Hydroponics, a soilless cultivation technique, has emerged as an efficient and sustainable method for producing leafy greens such as lettuce, spinach, kale, basil, and microgreens under controlled environmental conditions. This article examines recent startup trends and opportunities associated with hydroponic leafy green production in urban regions. The study highlights the growing role of vertical farming, smart technologies, automation, and IoT-based monitoring systems in improving productivity and resource efficiency. It also discusses emerging market trends, including consumer preference for pesticide-free and locally produced vegetables, hyperlocal supply chains, and investment growth in agritech startups. In addition, the article analyzes major opportunities and challenges related to hydroponic enterprises, including resource conservation, premium market potential, high investment costs, and technical requirements. The findings suggest that hydroponic startups can significantly contribute to sustainable urban agriculture, food security, and environmentally responsible farming systems.

Introduction

Urbanization and the increasing demand for fresh and nutritious food have created major challenges for conventional agricultural systems. Limited land availability, climate change, water scarcity, and long supply chains have encouraged the development of alternative farming methods that can support sustainable food production in cities. Among these alternatives, hydroponic farming has gained significant attention due to its ability to cultivate crops without soil while using controlled nutrient and water systems. The method is particularly suitable for urban areas where agricultural land is limited and consumer demand for high-quality vegetables is continuously increasing.

Hydroponic farming has become an important component of modern urban agriculture because it allows year-round cultivation with efficient use of water, nutrients, and space. Leafy greens such as lettuce, spinach, kale, basil, and microgreens are widely produced through hydroponic systems because of their short growth cycles, high market demand, and adaptability to indoor and vertical farming environments. As a result, many agri-tech startups are investing in hydroponic technologies to establish sustainable and profitable business models in urban markets.

Recent advancements in automation, LED lighting, climate control, and smart monitoring technologies have further accelerated the growth of hydroponic startups. Consumers are also becoming more health-conscious and increasingly prefer pesticide-free and locally produced vegetables. This changing market behavior has created new opportunities for entrepreneurs in urban agriculture. Therefore, hydroponic leafy green production represents a promising approach for improving urban food security, promoting environmental sustainability, and supporting innovative startup ecosystems in modern cities.

Startup Trends in Hydroponic Agriculture

The hydroponic startup ecosystem has expanded rapidly in recent years due to increasing urbanization, changing consumer preferences, and advancements in agricultural technology. Urban consumers are increasingly demanding fresh, pesticide-free, and locally produced vegetables, which has encouraged entrepreneurs to adopt hydroponic farming as a sustainable business opportunity. Startups focusing on leafy greens such as lettuce, spinach, basil, kale, and microgreens are growing particularly fast because these crops have short production cycles and strong market demand.

1. Growth of Urban Hydroponic Startups: Rapid urbanization and limited agricultural land have encouraged entrepreneurs to establish hydroponic farms in cities. Startups are increasingly focusing on leafy greens because of their high market demand, quick harvest cycles, and suitability for indoor cultivation.

2. Adoption of Vertical Farming Systems: Many hydroponic startups are using vertical farming models to maximize production in limited urban spaces. Rooftops, warehouses, and shipping containers are being converted into controlled farming units that enable year-round cultivation.



3. Integration of Smart Technologies: Modern hydroponic enterprises are adopting advanced technologies such as Internet of Things (IoT) sensors, artificial intelligence, automated irrigation systems, and climate-control technologies. These innovations help improve productivity, monitor crop health, and reduce resource wastage.

4. Increasing Demand for Pesticide-Free Produce: Urban consumers are becoming more health-conscious and prefer fresh, chemical-free vegetables. This growing demand has created profitable opportunities for startups producing hydroponically grown leafy greens such as lettuce, spinach, kale, and basil.

5. Development of Hyperlocal Supply Chains: Hydroponic startups are increasingly supplying produce directly to restaurants, supermarkets, cafés, and households. The farm-to-consumer model reduces transportation costs, ensures freshness, and strengthens local food systems.



6. Rise in Investment and Government Support: Agritech investors and government agencies are supporting hydroponic startups through funding programs, incubation centers, and sustainability initiatives. Urban farming is being recognized as an important solution for food security and resource conservation.

7. Focus on Sustainable and Resource-Efficient Farming: Hydroponic startups are promoting water-efficient and environmentally sustainable agricultural practices. Compared to conventional farming, hydroponics uses less water, requires minimal land, and reduces dependence on chemical pesticides and fertilizers.

Opportunities in Leafy Green Production

High Market Demand for Fresh Leafy Greens: Urban consumers are increasingly demanding fresh, nutritious, and pesticide-free vegetables due to rising health awareness. Leafy greens such as lettuce, spinach, kale, basil, and microgreens are widely preferred in salads, fast food outlets, hotels, and restaurants. This consistent demand creates strong business opportunities for hydroponic startups in urban markets.

Faster Crop Cycles and Year-Round Production: Leafy greens are highly suitable for hydroponic systems because they grow quickly and can be harvested multiple times in a year. Controlled-environment farming enables continuous production regardless of seasonal changes, ensuring a stable supply and regular income for startups.

Efficient Use of Urban Space and Resources: Hydroponic cultivation requires less land and water compared to conventional agriculture. Vertical farming techniques allow startups to produce large quantities of leafy vegetables in small urban spaces such as rooftops, warehouses, and indoor facilities. This improves productivity while reducing pressure on natural resources.



Premium Pricing and Diverse Marketing Channels: Hydroponically grown leafy greens are often sold at premium prices because of their quality, freshness, and chemical-free nature. Startups can market their produce through supermarkets, restaurants, online delivery platforms, farmers' markets, and subscription-based models, increasing profitability and customer reach.

Contribution to Sustainable Urban Food Systems: Leafy green production through hydroponics supports sustainable urban agriculture by reducing transportation costs, minimizing post-harvest losses, and lowering carbon emissions. Local production also strengthens urban food security and promotes environmentally responsible farming practices.

Challenges and Constraints in Hydroponic Startups

- 1. High Initial Investment Costs:** Establishing a hydroponic farm requires significant capital for infrastructure, LED lighting, climate-control systems, pumps, sensors, and nutrient management equipment. For many startups, the high setup cost becomes a major barrier to entry and expansion.
- 2. Technical Knowledge and Skilled Management:** Hydroponic farming requires continuous monitoring of pH levels, nutrient concentration, temperature, humidity, and water quality. Lack of technical expertise can negatively affect crop productivity and quality, making skilled management essential for successful operations.
- 3. High Energy Consumption:** Indoor hydroponic systems depend heavily on artificial lighting, cooling, ventilation, and automation technologies. These systems consume large amounts of electricity, increasing operational expenses and reducing profitability, especially in regions with high energy costs.
- 4. Market Competition and Consumer Awareness:** Hydroponic startups often face competition from conventional vegetable producers who offer products at lower prices. In some regions, limited consumer awareness regarding the benefits of hydroponically grown vegetables also affects market acceptance and sales growth.
- 5. Scalability and Financial Sustainability Issues:** Although hydroponic farming offers high productivity, scaling operations while maintaining profitability can be challenging. Fluctuating market demand, supply-chain management, maintenance costs, and limited access to long-term funding may affect the sustainability of startup businesses.

Conclusion

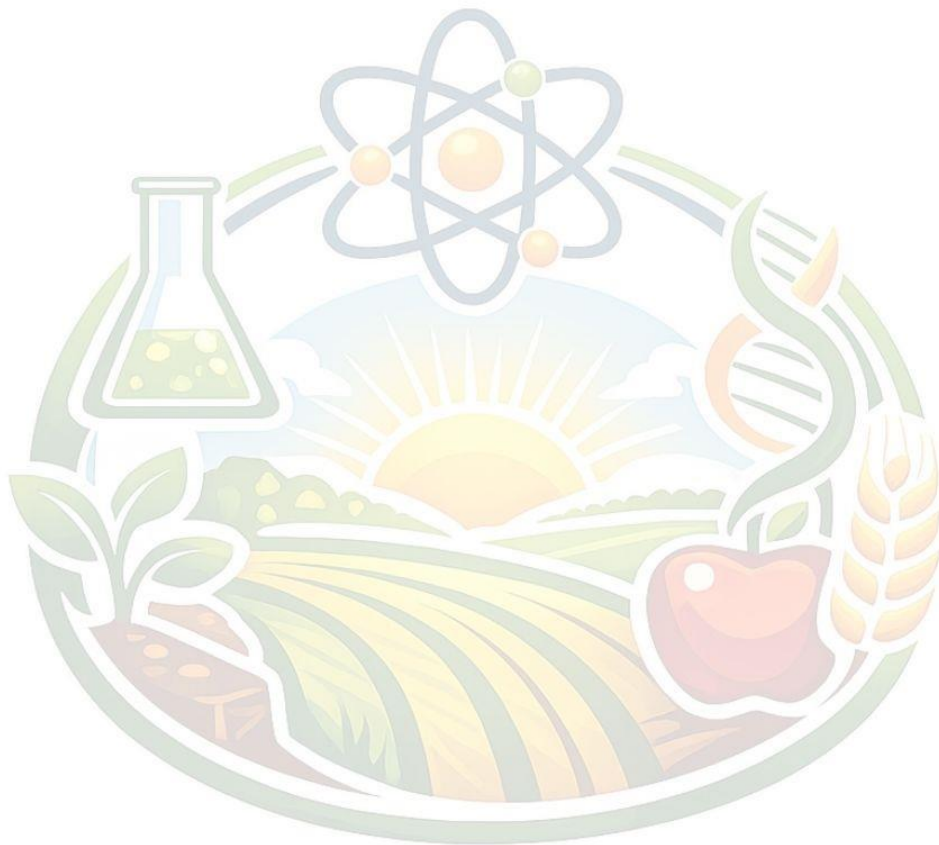
Hydroponic farming is emerging as a promising solution for sustainable food production in rapidly growing urban areas. The increasing demand for fresh, pesticide-free, and locally produced vegetables has created significant opportunities for startups specializing in leafy green cultivation. Technological advancements such as vertical farming, automation, and smart monitoring systems have further strengthened the growth potential of hydroponic enterprises. In addition to economic benefits, hydroponic systems contribute to water conservation, efficient land utilization, and reduced environmental impact, making them suitable for modern urban agriculture.

Despite its advantages, the sector still faces challenges related to high investment costs, energy consumption, technical expertise, and market competition. However, with continuous innovation, supportive government policies, and increasing consumer awareness, hydroponic startups are likely to play an important role in strengthening urban food security and promoting sustainable agricultural development. Therefore, leafy green production through hydroponics represents a valuable opportunity for future agritech entrepreneurship and resilient urban food systems.

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Vermicomposting: Turning Organic Agricultural Waste into High-Value Fertilizer

Article ID: 73785

Sanjiv Kumar¹, Mayank Singh Tanwar²

¹Assistant professor, Faculty of Agriculture, Jagannath University, Jaipur (Raj.) 303901.

²Student, B.Sc. (Hons.), Agriculture, Faculty of Agriculture, Jagannath University, Jaipur (Raj.) 303901.

Abstract

Vermicomposting is an environmentally sustainable technique for converting organic agricultural waste into nutrient-rich organic fertilizer through the activity of earthworms and microorganisms. The increasing generation of agricultural residues, vegetable waste, and animal manure has created significant environmental challenges, including pollution and nutrient loss. Vermicomposting offers an efficient solution by transforming biodegradable waste into high-quality vermin-compost that improves soil fertility, enhances microbial activity, and supports crop growth. This article discusses the concept, process, materials, benefits, challenges, innovations, and future scope of vermicomposting in sustainable agriculture. The process involves the decomposition of organic waste using earthworm species such as *Eisenia fetida* and *Eudrilus eugeniae* under controlled environmental conditions. Vermi-compost enhances soil structure, moisture retention, and nutrient availability while reducing dependence on chemical fertilizers. Furthermore, recent technological advancements such as automated systems, sensors, and smart agriculture integration have increased the efficiency and commercial potential of vermicomposting in modern farming systems.

Introduction

The rapid growth of agricultural activities has resulted in the generation of large quantities of organic waste, including crop residues, fruit and vegetable waste, animal manure, and agro-industrial by-products. Improper disposal of these materials often leads to environmental pollution, greenhouse gas emissions, and loss of valuable nutrients. In recent years, sustainable waste management practices have gained considerable attention as agriculture seeks environmentally responsible alternatives to chemical-based farming systems. Among these approaches, vermicomposting has emerged as an efficient and eco-friendly method for converting organic agricultural waste into nutrient-rich organic fertilizer.

Vermicomposting is a biological process in which earthworms and microorganisms work together to decompose biodegradable waste into a stable, humus-like material known as vermi-compost. Earthworm species such as *Eisenia fetida* and *Eudrilus eugeniae* play an important role in accelerating decomposition by consuming organic matter and enhancing microbial activity. The final product contains essential nutrients, beneficial microbes, enzymes, and plant growth-promoting substances that improve soil fertility and crop productivity.

Compared with conventional composting, vermicomposting is faster, cost-effective, and capable of producing high-quality organic manure with improved nutrient availability. Its application contributes to better soil structure, increased water retention capacity, and reduced dependence on synthetic fertilizers. Furthermore, vermicomposting supports sustainable agriculture by promoting nutrient recycling and minimizing environmental degradation. Therefore, it is increasingly recognized as an important strategy for transforming agricultural waste into high-value fertilizer and strengthening environmentally sustainable farming practices.

Concept, Process and Materials of Vermicomposting

Vermicomposting is a biological method of converting organic agricultural waste into nutrient-rich fertilizer with the help of earthworms and microorganisms. The process transforms biodegradable waste into stable organic manure called vermin-compost, which improves soil fertility and plant growth.

Concept of Vermicomposting: Vermicomposting is an eco-friendly process that converts organic agricultural waste into nutrient-rich fertilizer through the activity of earthworms and microorganisms. Agricultural residues such as crop waste, vegetable peels, leaves, and animal manure are biologically decomposed to produce vermin-compost, a stable organic manure rich in essential nutrients and beneficial microbes. Earthworms consume organic matter and break it into smaller particles, which enhance microbial activity and accelerate decomposition. The resulting compost improves soil fertility, structure, water-holding capacity, and plant growth. Vermicomposting is widely considered a sustainable waste management technique that supports organic farming and reduces dependence on chemical fertilizers.

Process of Vermicomposting: The vermicomposting process begins with the collection of biodegradable agricultural waste such as crop residues, vegetable waste, and animal manure. The waste is partially decomposed and placed in a vermibed or compost container containing bedding materials like dry leaves or straw. Earthworms, commonly *Eisenia fetida* or *Eudrilus eugeniae*, are introduced into the bed to feed on the organic matter. Proper moisture, aeration, and temperature are maintained throughout the process to support earthworm activity. Over several weeks, the waste is

transformed into dark, fine-textured compost called vermin-compost. The finished product is harvested, dried, and used as an organic fertilizer for crops.



Materials Required:

- a. Organic agricultural waste
- b. Earthworms *Eisenia fetida*, *Eudrilus eugeniae*
- c. Vermi-bed or compost container
- d. Water for moisture maintenance
- e. Dry leaves or straw for bedding
- f. Shade or covered area for protection

These materials and processes make vermicomposting an efficient and sustainable technique for organic waste management and soil improvement.

Benefits and Applications of Vermicomposting

1. **Improves Soil Fertility:** Vermi-compost enriches the soil with essential nutrients such as nitrogen, phosphorus, and potassium, improving overall soil productivity.
2. **Enhances Plant Growth:** The presence of beneficial microorganisms and plant growth hormones in vermin-compost supports healthier and faster crop development.



3. **Improves Soil Structure and Moisture Retention:** Vermi-compost increases soil aeration, porosity, and water-holding capacity, which helps plants grow efficiently even under limited water conditions.
4. **Reduces Agricultural Waste:** It provides an effective method for recycling crop residues, vegetable waste, and animal manure into useful organic fertilizer.
5. **Decreases Dependence on Chemical Fertilizers:** Regular use of vermin-compost reduces the requirement for synthetic fertilizers, promoting sustainable and eco-friendly farming practices.
6. **Supports Environmental Sustainability:** Vermicomposting minimizes pollution, reduces greenhouse gas emissions from waste burning, and contributes to sustainable waste management.

7. Creates Economic Opportunities: Vermi-compost production can generate additional income for farmers, rural entrepreneurs, and organic farming businesses due to increasing demand for organic fertilizers.

Challenges, Innovations, and Future Scope of Vermicomposting

Challenges:

- a. Moisture and Temperature Management:** Earthworms require suitable moisture and temperature conditions for proper growth and compost production. Extreme conditions can reduce their activity and survival.
- b. Lack of Awareness:** Many farmers and rural communities still have limited knowledge about vermicomposting techniques and benefits.
- c. Pest and Odor Problems:** Improper waste handling and poor maintenance may lead to foul smell, flies, and pest infestation in compost units.
- d. Initial Setup Requirements:** Construction of vermibeds, procurement of earthworms, and regular monitoring may require initial investment and labor.



Innovations:

- a. Automated Vermicomposting Systems:** Modern systems use automated moisture control, aeration, and feeding mechanisms to improve efficiency and reduce labor requirements.
- b. IoT and Sensor-Based Monitoring:** Sensors are used to monitor temperature, moisture, and pH levels in real time, ensuring better compost quality and earthworm health.
- c. AI and Smart Agriculture Integration:** Artificial intelligence and data analysis help optimize composting conditions, improve waste management, and support precision agriculture practices.

Future Scope:

- a. Role in Sustainable Agriculture:** Vermicomposting has strong potential to support organic farming and reduce dependence on chemical fertilizers.
- b. Waste Management Solution:** It can play an important role in managing agricultural and household organic waste in both urban and rural areas.
- c. Commercial and Startup Opportunities:** Increasing demand for organic products creates opportunities for small businesses and agri-startups involved in vermin-compost production.
- d. Contribution to Climate-Smart Farming:** By recycling waste and improving soil health, vermicomposting contributes to environmentally sustainable and climate-resilient agriculture.

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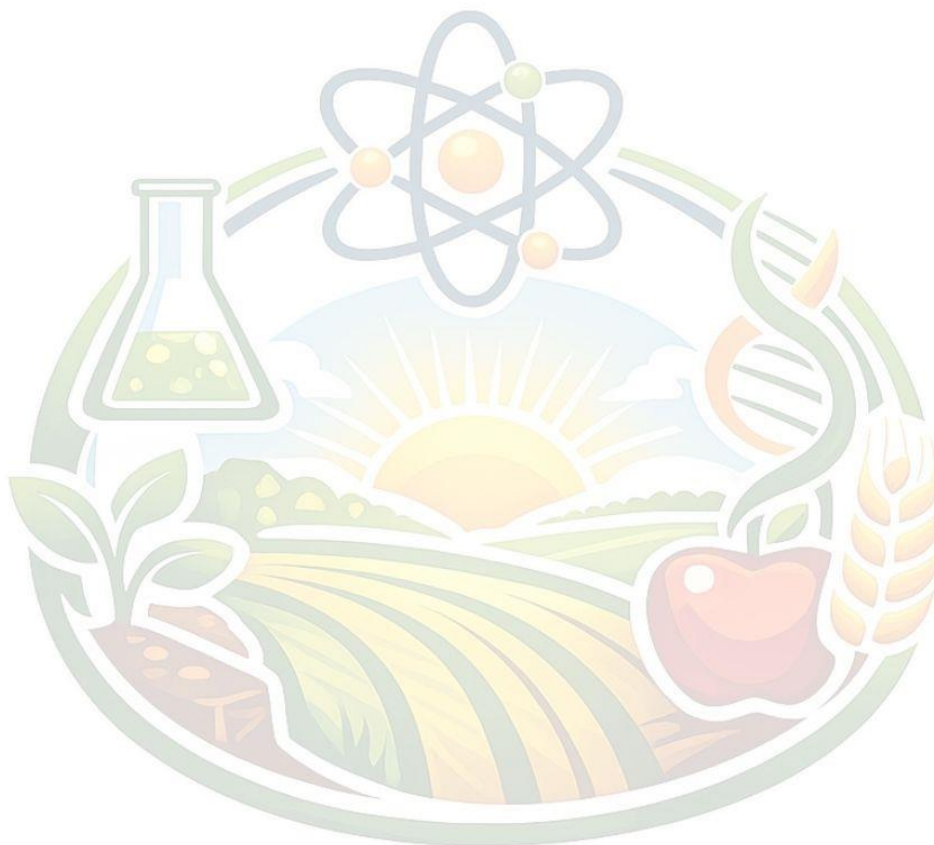
Conclusion

Vermicomposting is an effective and sustainable method for converting organic agricultural waste into high-value organic fertilizer. The process not only helps in efficient waste management but also improves soil fertility, enhances crop productivity, and reduces dependence on chemical fertilizers. By utilizing earthworms and natural biological processes, vermicomposting supports environmentally friendly and climate-smart agricultural practices. Recent technological advancements such as automated systems and sensor-based monitoring have further increased its efficiency and commercial potential. Therefore, vermicomposting plays a significant role in promoting sustainable agriculture, resource recycling, and environmental conservation while creating economic opportunities for farmers and organic farming enterprises.

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Plant-Based Bio-Pesticides: An Alternative to Chemical Pesticides for Organic Farming

Article ID: 73786

Ketan F. Satashiya¹, Patel Krutika Subodh¹, Anjali Kachhadia², Alvira A. Rajwadi³, Sonali B. Chaudhari⁴

²Assistant Research Scientist, A.R.S., J.A.U., Amreli.

^{1,3,4}Assistant Professor, College of Agriculture, J.A.U., Mota Bhandariya.

Introduction

Crop production is greatly affected by different insect pests and diseases, which drastically reduce both yield as well as quality of the produce. Farmers have traditionally relied on chemical pesticides for pest management because they provide quick and effective control. However, excessive and continuous use of chemical pesticides has led to several problems such as environmental pollution, pesticide resistance in various pest, harmful effects on beneficial organisms along with that it has also caused various health hazards to humans also. In organic farming systems, the use of synthetic chemicals is restricted and therefore, eco-friendly, sustainable alternatives are essential for crop protection.

Plant-based bio-pesticides and other natural formulations prepared from locally available materials such as neem, cow urine, buttermilk, chilli, garlic and medicinal plant extracts have emerged as an effective alternatives to chemical pesticides. These bio-pesticides are biodegradable, less toxic and safer for the environment. They help in controlling various insect pests and diseases while also support soil health and sustainable agriculture. Farmers can easily prepare many of these formulations on their farms at low cost, making them suitable for organic and natural farming practices. Some of the formulations which can be prepared on farm are described below.

1. Cow Urine: A mixture of cow urine and water in the ratio of 1:30 can be sprayed on crops. It helps in protecting crops from pests and also acts as a plant growth promoter.

2. Buttermilk: In some regions of central India, Buttermilk is used for controlling sucking pests such as whitefly, aphids and jassids.

3. Botanical Insecticides: Many plants possess insecticidal properties. Extracts prepared from such plants are effective against various insect pests. Some of the plant based insecticides are :

a. Neem: Neem is highly effective against nearly 200 insect pests. Neem leaf or neem seed kernel extract at 5% concentration or neem oil at 0.5% concentration, is sprayed for pest management.

b. Neemastra (Neem + Cow Urine Extract): Mix 10 liters cow urine, 2 kg cow dung and 10 kg neem leaves in 200 liters water. Keep the mixture in shade for 25-30 days. Filter and spray a 3-5% solution against sucking pests and mealy bugs.



c. Brahmastra (Mixed Leaf Extract): Prepare extract using neem leaves, custard apple leaves, papaya leaves, pomegranate leaves and guava leaves mixed with cow urine and water. Boil properly, filter and spray a 2-3% solution for control of sucking pests and caterpillars.



d. Agniastra (Garlic-Chilli Extract): Mix 1 kg tobacco leaves, 500 g green chilli, 500 g garlic and 5 kg neem leaves in 10 liters cow urine. Boil several times and filter. Spray a 2-3% solution for control of borers and leaf-eating caterpillars.

e. Dashparni Ark: Prepare using leaves of ten plants such as neem, dhatura, papaya, custard apple, tulsi, karanj, guava etc. Mixed with cow urine and cow dung slurry and fermented for 25-30 days. Filter and spray a 3-5% solution. Additional ingredients like turmeric, ginger, garlic, chilli and tobacco may improve effectiveness.



f. Broad Spectrum Formulation - 1: Prepare a mixture of neem leaves, neem seed powder and cow urine in a copper vessel. Ferment for 10 days and boil until the volume is reduced. Add green chilli and garlic extracts. This broad-spectrum formulation can be used against many pests in different crops.

g. Broad Spectrum Formulation - 2: Mix neem seed powder, karanj seed powder, tobacco leaf powder and neem leaf powder in water and ferment for 8-10 days. Filter the solution. It acts as an effective insecticide and plant growth promoter.

h. Preparation of NPV (Nuclear Poly-hydrosis Virus) Solution: Collect diseased larvae from the field and prepare a suspension in clean water. Spray the solution on fresh leaves and feed them to healthy larvae. Keep infected larvae separately in clean containers. After a few days, larvae become soft and die due to viral infection. Crush dead larvae in water and filter through a fine cloth. Allow the suspension to settle and collect the virus-rich liquid. Use distilled water where possible for better effectiveness. Spray the prepared NPV solution during evening hours for better control. The prepared solution may remain effective for 2-3 years when stored in a cool and dark place. NPV is safe for beneficial insects, humans and animals.



Conclusion

Plant-based bio-pesticides offer an environmentally safe, economical and sustainable alternative to synthetic chemical pesticides in organic farming. Formulations such as neem extract, Neemastra, Brahmastra, Agniastra, Dashparni Ark and NPV are effective in managing a wide range of insect pests and diseases without causing harmful effects on humans, animals or beneficial insects. These natural products can be prepared easily using locally available resources, which can help the farmers' to reduce the dependence on costly chemical inputs. In addition to pest control, they contribute to improved soil health, ecological balance and production of safe agricultural products. Hence, the adoption of plant-based bio-pesticides can play a significant role in promoting sustainable agriculture and ensuring long-term environmental and agricultural health.

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Speed Breeding: How Accelerated Generation Redefines Crop Improvement

Article ID: 73787

Jitendra Kumar Meena, Shiva Shankar, Deep Shikha, Pravalika, Kiran Kadam, Pratima Usendi

Speed breeding is a technology that aims to shorten the agricultural breeding cycle and accelerate crop improvement through rapid generation advancement. Techniques that involves the manipulation of environmental conditions under which crop genotypes are grown, aiming to accelerate flowering and seed set, to advance to the next breeding generation as quickly as possible.

Recently, researchers are utilizing speed breeding to accelerate the development of innovative crop varieties for addressing the challenges of climate change, rising global populations, and shifting market demands. By compressing breeding cycles from years into seasons, it allows breeders to move from idea to improved cultivar far more quickly than with conventional methods.

Under traditional breeding, many major crops produce only one or two generations per year, which limits how fast desirable traits can be combined and fixed. Speed breeding systems routinely raise this to three to nine generations per year, so it is increasing the number of selection cycles available to breeders.

Core Principles of Speed Breeding

Speed breeding manipulates photoperiod, light intensity, temperature, and CO₂ to hasten vegetative growth, flowering, and seed set. Growth chambers, glasshouses, or specialized speed breeding facilities provide stable conditions for rapid cycling while protecting plants from field stresses that would slow development. Plants grow in sealed chambers or glasshouses with multilayer racks to maximize space.

Protocols use extended lighting (up to 22 hours/day) with LEDs optimized for photosynthetically active radiation (400–700 nm). Crop-specific adjustments ensure fertility: long-day crops like wheat thrive under continuous light, while short-day crops like rice need modified cycles.

Key environmental parameters include:

- a. Light: 500–1000 $\mu\text{mol}/\text{m}^2/\text{s}$ for 16–24 hours daily.
- b. Temperature: 20–28°C day, 15–22°C night.
- c. Humidity: 60–80% to prevent stress.
- c. Nutrient delivery: Hydroponics or soilless media for precise fertigation.

Redefining Crop Improvement Timelines

Conventional breeding often needs 8–10 years or more to develop and release a new variety because many generations are required to fix traits and test performance. Speed breeding can shorten generation length by 2–5 times, which can reduce several years from the varietal development pipeline.

In practice, this allows faster development of homozygous lines, quicker backcrossing, and more rapid trait pyramiding, especially for complex traits like disease resistance or stress tolerance. By increasing the number of generations and selections per unit time, can achieve higher annual genetic gain, meaning more improvement per year for yield, resilience, and quality.

Integrating Genomics and Editing

Speed breeding become more powerful when combined with modern genomic and molecular tools. Marker-assisted selection and genomic prediction allow breeders to identify promising genotypes early, then use accelerated generation to advance and fix those genotypes in few seasons.

Genome editing systems such as CRISPR/Cas create precise genetic changes, but multiple generations are still needed to recover edited lines and stack edits; speed breeding compresses this timeline. Speed breeding combined with rapid cycling, dense genotyping, high-throughput phenotyping, and editing form an integrated pipeline for fast, targeted crop improvement.

Applications Across Crops and Traits

Speed breeding has been applied in cereals, legumes, oilseeds, and vegetables to accelerate improvement for yield, quality, and resilience. For example, wheat and other cereals have been cycled through several generations in under two years to develop lines better adapted to water-limited and heat-stressed environments.

Oilseed crops such as rapeseed have achieved four to five generations per year in optimized systems, allowing faster enhancement of traits like oil quality and stress tolerance. Across crops, breeders use accelerated generation to quickly assemble combinations of resistance genes, improve nutritional profiles, and adapt varieties to new regions and climates.

Advantages Over Conventional Breeding

Speed breeding transforms the timing and design of breeding programs rather than replacing classical methods. Key advantages include:

1. Higher numbers of generations per year, enabling faster fixation of favorable alleles and more rapid genetic gain.
2. Year-round breeding removes seasonal dependencies, allowing for the maximum efficiency of facilities and specialized human resources
3. Integration with controlled-environment phenotyping, allowing precise assessment of traits such as disease response or abiotic stress tolerance.
4. These advantages make speed breeding especially attractive for responding to emerging pests and diseases, where rapid deployment of resistant varieties can reduce losses.

Benefits

Multiple breeding cycles annually: Allows 3-9 generations per year by optimizing photoperiod, temperature, and LED lighting.

Trait combining capability: Incorporates multiple desirable traits such as disease resistance and stress tolerance into one variety, enhancing crop resilience against environmental challenges.

Broader applications: Supports genetic mapping, modification, and resilient crop development, integrating with gene editing and genomics for sustainable agriculture.

Rapid experimentation: Speeds up data collection, hypothesis testing, and understanding of plant physiology, informing better cultivation practices and decision-making.

Challenges

Light intensity management: Maintaining optimal levels throughout accelerated cycles prevents plant stress but demands real-time monitoring and adjustable systems.

High operating costs: Intensive lighting leads to elevated energy use, electricity bills and also need technical expertise that make more costly.

Genetic stability risks: Rapid techniques may cause instability in crop genomes, requiring collaboration with geneticists for stable lighting regimes.

Maintaining genetic diversity: Limited parent lines can narrow variability, so diverse germplasm must be incorporated to preserve population health.

Environmental relevance: Controlled conditions do not fully replicate field realities, demanding extensive trials for real-world validation.

Protocols must be optimized for each crop and sometimes each genotype; some lines may respond poorly to extended photoperiods or high densities, affecting fertility or seed quality. Another concern is that selection in highly controlled environments may not perfectly reflect performance under diverse field conditions, requiring careful multi-environment testing before release.

Future Directions in Speed Breeding

The next phase of accelerated generation is moving toward more automated and data-rich systems. Integration with high-throughput imaging, environmental sensors, and machine learning can improve trait measurement under speed breeding conditions.

New initiatives are also exploring “Speed Breeding 3.0” concepts that coordinate rapid cycling with climate-resilient breeding targets across international networks. As costs of LED lighting and controlled-environment technologies decline and open protocols spread, speed breeding is expected to become a core component of mainstream crop improvement, particularly in the face of climate change and growing food demand.

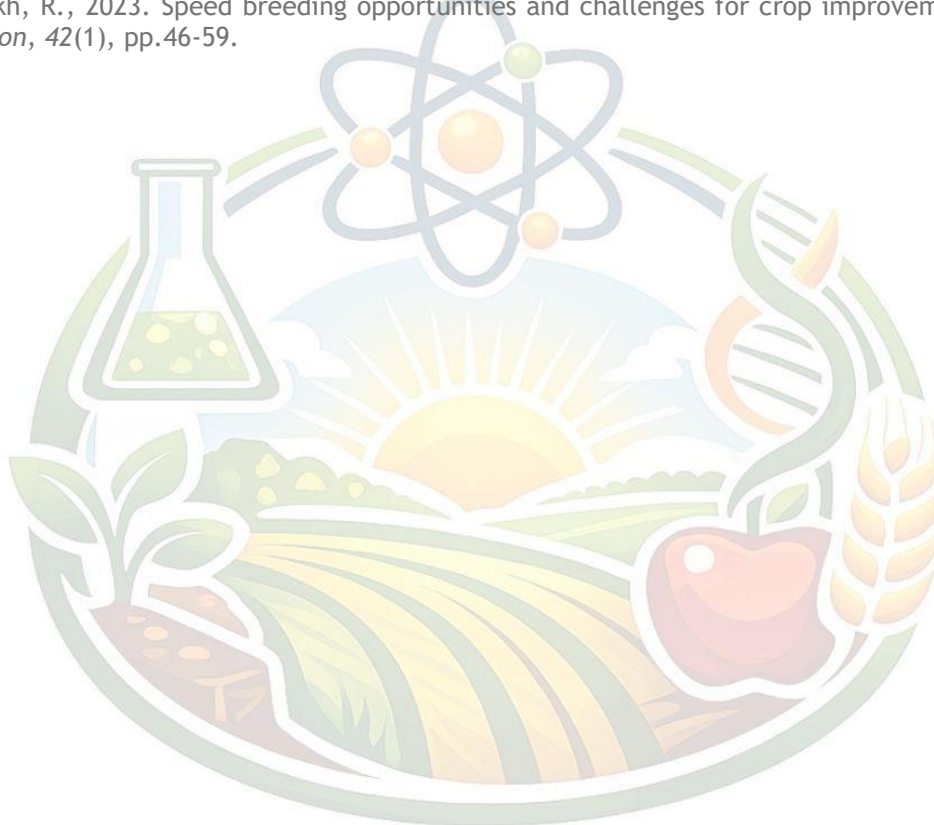
Conclusion

Many advancements have been made in the field of genomics and the breeding of food and industrial crop plants with the advent of next-generation sequencing and genome manipulation techniques. In order to stay up with the advancements in plant science research, speed breeding is only the next appropriate step to support the extensive screening of the many plant genotypes. Modern breeding and genetic engineering methods combined with speed breeding

will help create custom crops with high yield, high nutritional value, and resistance to biotic and abiotic challenges. By shortening the breeding cycles for building nutritional security and sustainable agriculture, speed breeding technology has more potential to accelerate the aims of food and industrial crop improvement.

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Life Along the Slope: Beach Profiles and Intertidal Biodiversity

Article ID: 73788

Alla Bhumika Reddy¹, Annappaswamy T. S.¹, Abhishek M.S.²

¹Department of Aquatic Environment Management, ²Department of Aquaculture College of Fisheries, KVAFSU, Mangaluru - 575002.

Abstract

Are beach locations an interesting combination of coastal and marine environments? The interaction between wind, water and soil is responsible for the constant changes in their state. Despite their appearance as being without any waves or sand, beaches are actually quite intricate. Species living in the area are highly dependent on factors such as beach elevation and shape. The form influences the wave energy, sand/dig or dirt placement, water retention in soil and wild animal dwelling types between high and low tide. The combination of these factors affects the variety of life on the beach, its location, and how it will persist. It is the shape of the beach that has an impact on biodiversity in a region between tides. The presentation will address the impact of environmental and human factors on delicate ecosystems, emphasising the need for action to conserve our coastal waters.

Keywords: Coastal ecology, beach structure, waves, tide patterns.

Introduction

At first glance, the beach appears as sand, with the fine sandy waves gently covering it. The seemingly unimportant system is concealed by a complex and dynamic system that is controlled by an ongoing transfer of energy (and matter) between land and sea. The characteristics of beaches are subject to constant change due to a variety of coastal conditions, including tides and waves, along with winds and sediment transport. The ecological patterns of a beach are heavily influenced by the profile or slope, which is one of the physical characteristics that define it.

The beach profile goes beyond the obvious topographical aspects. The equilibrium of beneficial and detrimental forces on the beach, as well as the distribution of energy across it, is emphasised. This has significant implications for living beings situated in the intertidal area between the high and low tide levels. The intertidal zone poses a significant challenge for the inhabitants of this habitat, necessitating exceptional adaptability.

Intertidal biodiversity and the effects of beach profiles require knowledge derived from three perspectives: geomorphology, ecology and environmental science. Understanding these relationships will allow us to understand the fundamental mechanisms that control coastal ecosystems and how they are impacted by both natural and human factors.

Beach Profile Formation and Dynamics

Sediment features are constantly influenced by hydrodynamic forces, leading to the formation of beach profiles. The movement of sediments along the coastline is largely controlled by waves, which have a significant impact on this process. The slope of the beach is influenced by the wave's energy, which determines whether sediments are gently deposited or gradually eroded.

The formation of gently sloping beaches in low-energy wave environments is often due to the presence of fine-grained sediments like mud. In these conditions, sediments settle over a larger area as waves gradually dissipate. Unlike in low-energy environments, where pebbles and gravel have the upper hand, high-energy environments are linked by steep beach surfaces. These areas experience stronger waves, resulting in fast sediment movement and sudden land-to-sea transition.

The impact of tides on beach profiles is profound. The wider coverage of the intertidal zone and lower slope is attributed to areas with a significant amount of tidal variability. In contrast, areas with a lesser tidal range tend to have more closely spaced zones and profiles. The alterations in beach morphology are caused by seasonal changes, storms and long-term climatic conditions.

The interplay between sediment size, wave energy, and tidal processes, such as reflection and dispersion on steep slopes, can lead to different beach characteristics. Intertidal life distribution is determined by the environmental conditions encountered along each tide.

A Challenging Climactic Fold, the Intertidal Zone

The intertidal area represents a unique ecological transition from land to sea. The zone's inhabitants encounter alternating waves of submergence and exposure, creating a highly dynamic and frequently stressful environment for organisms. Due to the extreme alterations in temperature, salinity, moisture availability, and wave action over short time scales, these conditions are both physically demanding and ecologically complex.

Direct sunlight exposure during low tide can cause organisms to become desiccated, resulting in increased temperature. The occurrence of high tide is affected by the movement of waves and changes in salinity. Strong selective pressures are triggered by the conditions that promote specific adaptations for species survival.

In spite of the challenges, the intertidal zone remains a remarkable source of life for many species. Not only small algae and bacteria, but also larger invertebrates like molluscs/ crustaceans and polychaete worms have evolved to survive in harsh environments. Other adaptations involve a tendency to burrow into sediment deposits, the formation of protective shells, close bonding with substrates and control of the internal water balance.

This distribution is not random, but rather follows a pattern called zonation. Significantly, this pattern is linked to its physical characteristics: a beach's profile defines the extent and nature of the environmental gradient.

The Importance of Specific Beach Locations in Determining Biodiversity

Coastal conditions and the physical factors that determine habitat availability and bioavailability are significant contributors to the intertidal biodiversity relationship. Both the width of the intertidal area on sand and the intensity of waves that organisms experience are affected by the slope. This leads to wider slopes in the intertidal zones, widening habitat diversity. The presence of niches and relatively stable conditions in these environments contributes to a higher level of biodiversity.

Compared to other waves, steep beaches exhibit greater wave energy and narrower intertidal zones. The limited surface area and high physical pressure in these environments result in a restricted range of living organisms. These conditions are only suitable for species that have developed adaptable characteristics, such as quick burrowing or strong attachment mechanisms.

Moisture retention, nutrient availability and substrate stability are all factors that contribute to the formation of these patterns. Water and organic matter in the sediments form intricate burrowing communities of organisms that converge to create food webs. While other sediment types can drain rapidly and are often disturbed, coarse ones may not be suitable for many species.

By utilising wave energy to filter through and identify potential organisms for physical disturbance, this is accomplished. This mechanism works wonders. The characteristics of high-energy environments favour rapid and durable species, whereas low-energy environments are marked by greater diversity and intricate ecological interactions.

Ecological Zonation and Community Structure

The beach profile, sediment characteristics and wave energy are all factors that cause significant variations in coastal ecological zonation patterns. Coastal zone formations vary greatly. The topmost intertidal space is open and contains organisms that can survive extreme conditions, such as drought or temperature fluctuations. Many of these species have behavioural adaptations that help them avoid stress and maintain moisture.

The mid-intertidal zone is frequently submerged and exposed, which results in a more uniform environment for all species. It is the bedrock of tides, and it's where competition for resources and time takes place, resulting in complex interactions among living beings.

The marine life is mainly submerged in the lower intertidal zone, despite the pressures. Thus, species diversity is raised, and biodiversity is increased. The availability of nutrients can be increased due to the absence of environmental stress, which can also lead to intricate food webs and complex ecological relationships.

The limits of these regions are not rigidly set but rather fluctuate with the surrounding environment, particularly in relation to the beach's configuration. The slope of these zones can vary, leading to the formation of distortions and changes in their boundaries.

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Human Activity and its Impact on the Beach Profile

Human activities in coastal environments have caused significant changes in intertidal biodiversity and beach profile. The coastal development coastline is characterised by seawalls, groynes, and other structures that can alter the shape of beaches and disrupt natural processes of sediment transport. And that is especially problematic in this area. Tidal marine life habitat accessibility can be impacted by the tilt or deflation of beach profiles caused by these changes.

The destruction of essential sediments through sand mining and dredging amplifies these effects, which are crucial for maintaining the natural structure of beaches. These operations, habitat degradation caused by tourism and recreational activities, can also lead to disturbance of wildlife and trampling.

The environmental impact of beach nourishment programs, even though they are designed to protect beaches, can be unexpected. Introducing sediments of various grains or compositions near the coast can impact organisms that require particular conditions for their sustenance.

Climate Change and Coastal Transformation

Coastal ecosystems are greatly affected by climate change, which has the potential to modify intertidal biodiversity and shape beach profile patterns. With rising sea levels, it is likely that shoreline migration will move towards the coast, potentially reducing the size of these areas and decimating habitat along with habitat loss. Storms that occur frequently and frequently may result in accelerated erosion, as they will also alter the shape of existing beach areas and disrupt pre-existing ecological communities.

Coastal waves and ocean currents can alter the physical characteristics of beach morphology, which can also impact sediment transport. Intertidal ecosystems can exhibit cascading effects that impact species distribution, community organisation and biodiversity.

The capacity of organisms with limited tolerance ranges or mobility to adapt and relocate is significantly impacted by these changes, as they may be unable to cope with shifting environmental conditions.

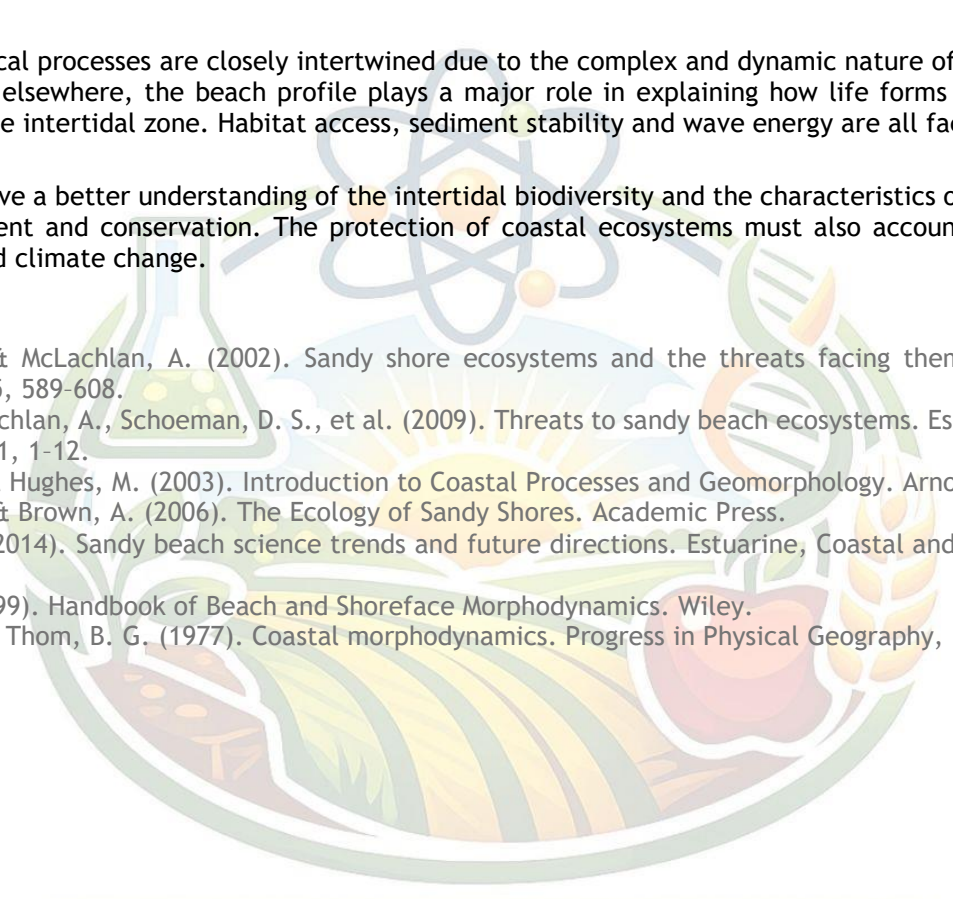
Conclusion

Physical and biological processes are closely intertwined due to the complex and dynamic nature of beaches. While not extensively studied elsewhere, the beach profile plays a major role in explaining how life forms are distributed and diversified during the intertidal zone. Habitat access, sediment stability and wave energy are all factors that affect the environment.

It is important to have a better understanding of the intertidal biodiversity and the characteristics of beaches in coastal areas for management and conservation. The protection of coastal ecosystems must also account for the impact of human activities and climate change.

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Biodegradable Packaging of Film from Fish Gelatine and Chitosan

Article ID: 73789

Gayatri S. Avchar¹, Pallavi V. Jogdand², Shweta P. Vaidya²

¹Department of Fisheries Resource Management, College of fisheries science, Nagpur- 440006.

Abstract

Fish and fishery products are healthy foods, but they spoil quickly because of bacteria, oxidation, and natural enzymes. To keep them fresh for a longer time, proper packaging is very important. Since synthetic plastic packaging can harm the environment and may be toxic, natural substitutes like chitosan (from shrimp or crab shells) and gelatine have become popular. These materials have natural antibacterial and antioxidant properties and can be made into thin films for food packaging. Scientists also add other active substances to enhance their ability to stop microorganisms and slow spoilage. Chitosan- and gelatine-based active packaging helps sustain the quality and safety of fish products and increases their shelf life in an eco-friendly way.

Introduction

Fish and fishery products are considered highly nutritious because they provide excellent-quality protein, essential vitamins, minerals, and healthy polyunsaturated fatty acids (PUFA). Fish contains a balanced nutritional composition, including 70-84% water, 15-24% protein, and 0.1-22% fat. Fish is highly perishable because it contains a lot of moisture, protein, and easily oxidized fats (PUFAs). During processing and storage, fish can spoil due to biochemical, physical, and microbial changes. Microbial contamination and oxidation of fats and proteins are major reasons for spoilage in meat and fish products. Packaging plays an important role in keeping food safe and maintaining quality. Bio-based active packaging made from natural antimicrobial substances like essential oils, plant extracts, organic acids, and antimicrobial peptides. Natural biopolymers such as chitosan and gelatine are widely used because they are safer and more eco-friendly than synthetic plastics. Chitosan and gelatine work well together to form strong films due to chemical interactions between them. These films already show some antimicrobial and antioxidant properties, but adding natural functional ingredients can improve their effectiveness even more. Chitosan/gelatine-based active packaging is considered a clean, green, and environmentally friendly technology that can help preserve fish and fishery products while meeting consumer demand for high-quality and safe food.

Chitosan

Chitosan is the second most common natural polymer after cellulose. It is a natural material that can break down easily in the environment. Chitosan is obtained from the hard outer shells of shrimp, crabs, lobsters, and other shellfish.

Chitosan is prepared from raw material by first removing minerals and proteins using hydrochloric acid and sodium hydroxide. This process forms chitin. The chitin is then treated with sodium or potassium hydroxide to remove acetyl groups, converting it into chitosan.

Properties of Chitosan

- 1. Biodegradable Nature:** Chitosan decomposes naturally and is eco-friendly compared to synthetic plastics.
- 2. Film-Forming Ability:** It forms thin, flexible films useful for food coating and packaging.
- 3. Antimicrobial Property:** Chitosan inhibits the growth of bacteria (Gram-positive and Gram-negative), yeasts, and moulds by damaging microbial cell membranes.
- 4. Antioxidant Activity:** It reduces oxidation and helps maintain food quality and shelf life.
- 5. Barrier Property:** Chitosan acts as a barrier against oxygen and carbon dioxide, helping preserve freshness of foods.

Gelatine

Gelatine is a natural biopolymer obtained through thermal denaturation or partial acid/alkaline hydrolysis of collagen, a fibrous protein found in the terrestrial and aquatic animal connective tissue, cartilage, skin, scales, tendons and bones.

Gelatine is prepared by collecting collagen-rich raw materials such as skin, bones, scales, and connective tissues. These materials are treated with acid or alkali to break down the collagen structure, followed by heating in water to extract gelatine.

The extracted gelatine is then purified to remove impurities and finally dried into powder, granules, or sheets for industrial use. It is mainly composed of amino acids such as glycine, proline, and hydroxyproline. Its typical composition includes about 85-92% protein, 2-4% mineral salts, and 8-12% water.

Properties of Gelatine

- 1. Water Solubility:** Gelatine readily dissolves in water and has the ability to absorb 5-10 times its weight in water.
- 2. Gel-Forming Ability:** It forms soft, transparent, and thermally reversible gels, making it suitable for various food and biomedical applications.
- 3. Biodegradability and Biocompatibility:** Gelatine is biodegradable, non-toxic, and compatible with the human body, making it safe for consumption and medical use.
- 4. Functional Properties:** Gelatine exhibits excellent functional properties and acts as a thickening agent, gelling agent, emulsifier, and foaming agent in different industrial application

Fish Gelatine-Chitosan Composite Films

Chitosan and gelatine are widely used biopolymers in food packaging method because of their excellent film-forming properties. Chitosan, a carbohydrate-based biopolymer, is biodegradable, edible, non-toxic, and environmentally friendly. It can be processed into packaging films with good protective and visual characteristics. Additionally, chitosan shows strong antimicrobial activity along with desirable structural and biodegradable properties, making it highly suitable for active food packaging applications. Gelatine, a protein-based biopolymer, also holds good film-forming ability and contributes flexibility and transparency to packaging films.

Preparation of Composite Film

Biodegradable films are generally prepared by the casting method. Gelatine and chitosan are dissolved separately in suitable solvents such as distilled water and acetic acid. Plasticizers like glycerol are added to enhance film flexibility. The solutions are mixed thoroughly to obtain a homogeneous film-forming solution. Active compounds such as essential oils or antioxidants may also be integrated. The solution is then poured onto casting plates and dried under controlled conditions to form thin biodegradable films.



Application in Seafood Preservation

Fish gelatine and chitosan-based films are widely used for preserving fish fillets, shrimp, and other seafood products. These films reduce microbial growth, lipid oxidation, and moisture loss during refrigerated storage. Active compounds such as oregano oil, clove oil, curcumin and grape seed extract, and tea polyphenols are often incorporated into the films to enhance antimicrobial and antioxidant properties. These films help maintain texture, flavour, and sensory quality while extending shelf life.



Advantages

Biodegradable films from fish gelatine and chitosan provide several advantages over synthetic plastics. They are biodegradable, edible, renewable, and eco-friendly. These films reduce plastic pollution and support sustainable food packaging systems. They also improve food quality, extend shelf life, and increase consumer acceptance of eco-friendly products.

Limitations

Despite their benefits, fish gelatine and chitosan films have some disadvantages such as poor water resistance, low mechanical strength, and sensitivity to humidity. Researchers are working on enhancing these properties through the use of nanoparticles, cross-linking agents, essential oils, and hydrophobic compounds.

Conclusion

Fish gelatine and chitosan-based biodegradable films are effective possibilities to conventional plastic packaging materials. Their biodegradability, antimicrobial activity, and film-forming ability make them highly suitable for seafood preservation. These films help reduce environmental pollution while improving the safety and quality of fish and fishery products. With continued research and technological advancements, biodegradable packaging films are expected to play an important role in eco-friendly food packaging.

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Role of Probiotics in Aquaculture

Article ID: 73790

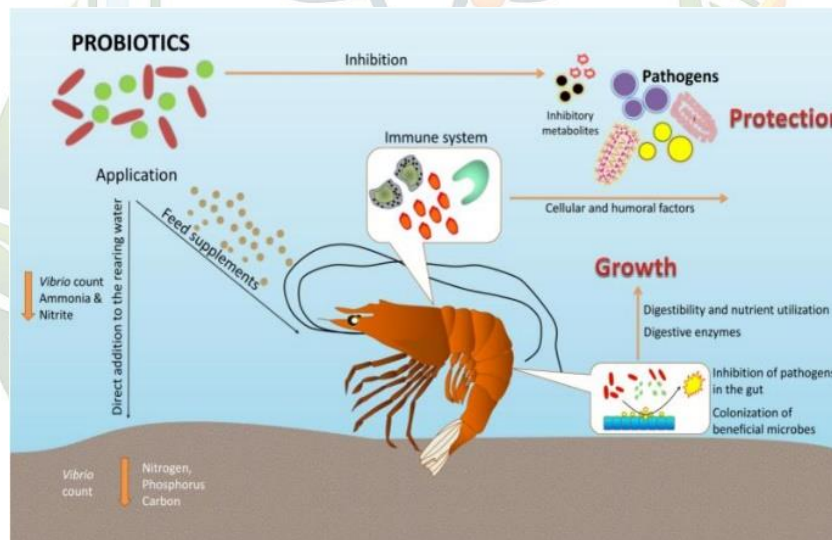
 Pallavi V. Jogdand¹, Gayatri S. Avchar², Shweta P. Vaidya²
¹Department of Fisheries Resource Management, College of Fisheries Science Nagpur-440006.

Abstract

Aquaculture has emerged as one of the fastest-growing sector for food production worldwide. However, the amplification of aquaculture practices has led to increased disease outbreaks, environmental degradation and reliance on antibiotics. In aquaculture probiotics are beneficial microorganisms that improve the health, growth, and survival of aquatic organisms such as fishes and shrimps. Common probiotic bacteria include *Bacillus*, *Lactobacillus*, and *Pseudomonas* species, these microorganisms help in reducing the accumulation of toxic substances like ammonia and nitrite while improving feed utilization and disease resistance. Overall, probiotics play an important role to enhance sustainability and maintaining environmental balance in modern aquaculture practices.

Introduction

Aquaculture is the farming of aquatic organisms by intervention in the rearing process to enhance production and private ownership of the stock being cultivated. However, diseases, poor water quality, and excessive use of antibiotics are major challenges in aquaculture. To defeat these problems, probiotics are increasingly being used as a safe and eco-friendly solution.



Probiotics are effective microorganisms that improve the health and growth of aquatic animals. In aquaculture, they help maintain water quality, improve digestion, boost immunity, and protect fish and shrimp from harmful pathogens. The use of probiotics reduces the dependence on antibiotics and supports sustainable aquaculture practices. The aim of this article is to present an updated concept of probiotics, and its role in modern aquaculture system.

Use of Probiotics in Aquaculture

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The term “probiotic” comes from Greek words pro means for and bios means life, together its meaning “prolife”. Probiotics are defined as live microorganisms that, when administered in appropriate amounts, provide health benefits to the host. In fish and shrimp farming, probiotics are commonly used to enhance gut microbiota balance, improve digestion and nutrient absorption, boost immune responses, and intensify resistance to pathogenic infections. Commonly used probiotics species that contribute to better water quality by reducing organic waste and harmful ammonia are *Bacillus*, *Lactobacillus*, *Pseudomonas*, and *Saccharomyces*. The application of probiotics has occurred as an environmentally sustainable alternative to antibiotics and chemical treatment, supporting healthier production systems and reducing the risk of antimicrobial resistance in aquaculture practices.

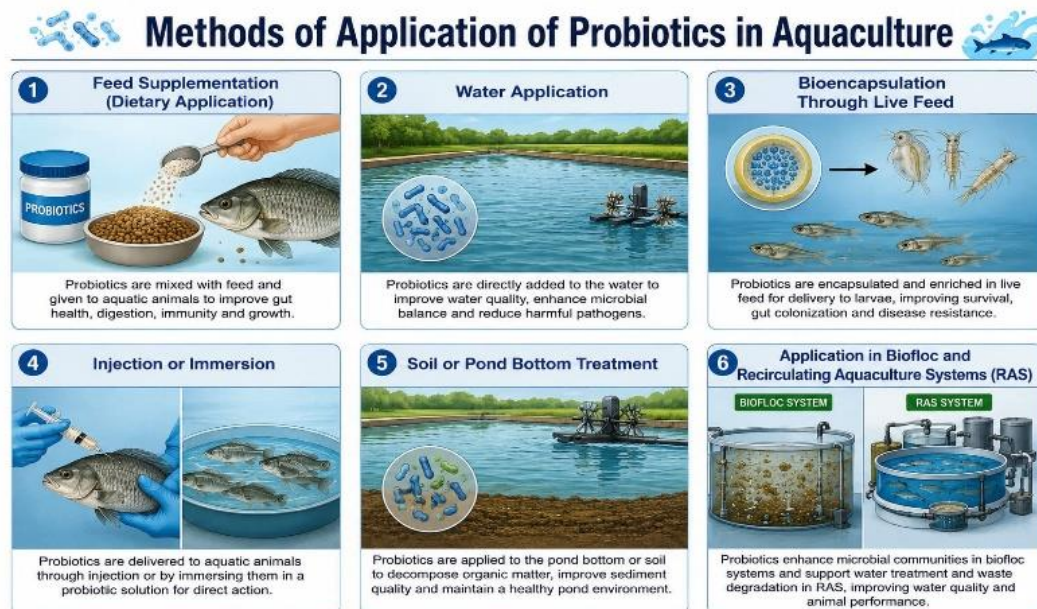
Types of Probiotics Used

Types of Probiotic	Common examples	Main function in Aquaculture	Benefits
Bacillus spp. (Bacterial)	<i>Bacillus subtilis</i> , <i>Lactobacillus acidophilus</i> ,	Produces digestive enzymes, breaks down organic waste, improves nutrient availability	Better growth, improved feed

			efficiency, improved water quality
Lactobacillus spp. (Bacteria)	Balances gut microbiota, inhibits harmful bacteria, produces lactic acid	Balances gut microbiota, inhibits harmful bacteria, produces lactic acid	Stronger immunity, better digestion, disease prevention
Nitrosomonas & Nitrobacter (Nitrifying bacteria)	<i>Nitrosomonas europaea</i> , <i>Nitrobacter winogradskyi</i>	Converts toxic ammonia → nitrite → nitrate (nitrification process)	water quality, reduced toxicity
Pseudomonas spp. (Bacterial)	<i>Pseudomonas fluorescens</i>	Competes with pathogens, degrades organic matter	Reduced disease risk, improved tank environment
Saccharomyces cerevisiae (Yeast)	<i>Saccharomyces cerevisiae</i>	Enhances nutrition, stimulates	Faster growth, better stress

Methods of Application of Probiotics in Aquaculture

1. Feed Supplementation (Dietary Application)
2. Water Application
3. Bioencapsulation Through Live Feed
4. Injection or Immersion
5. Soil or Pond Bottom Treatment
6. Application in Biofloc and Recirculating Aquaculture Systems (RAS).



In the selection of the adequate probiotics, the choice of the species regarding the acid or alkaline desirable environment is one of the basic starting points. Some probiotic strains are more resistant to low or high pH than others, and this is a normal physiological property affiliated with the biological nature of all living organisms.

They are applied through several methods depending on the culture system and purpose.

1. The most common method is feed supplementation, where probiotics are mixed with or coated onto feed to improve digestion, nutrient absorption, immunity, and disease resistance.
2. Alternative important method is direct water application, in which probiotics are added to ponds or tanks to enhance water quality by reducing harmful substances like ammonia and controlling pathogenic microorganisms.
3. In larval rearing, probiotics are supervised through bioencapsulation, where live feed organisms such as Artemia and rotifers are enriched with probiotics before being fed to larvae.
4. Probiotics may also be applied through immersion techniques, where fish or shrimp are susceptible to probiotic-containing water for a specific duration to enhance immunity and stress tolerance.
5. Additionally, probiotics are used in pond bottom or soil treatment to decompose organic waste and maintain a healthy pond environment.

6. In intensive systems such as biofloc and recirculating aquaculture systems (RAS), probiotics help maintain microbial balance and improve overall system efficiency.

These application methods make probiotics an eco-friendly alternative to antibiotics and contribute to sustainable aquaculture practices.

Result after Use of Probiotics

Aquatic Specie	Bacteriocin	Pathogen or Challenge	Clinical Impact
Epinephelus areolatus	CAMT2	Listeria monocytogenes, Staphylococcus aureus	Antimicrobial activity against tested pathogens
Labeo rohita	Bacteriocin produced by Bacillus subtilis LR1	Aeromonas hydrophila, Aeromonas salmonicida, Bacillus mycoides, Pseudomonas fluorescens	In vitro antimicrobial activity against Aeromonas hydrophila, Aeromonas salmonicida, Bacillus mycoides, Pseudomonas fluorescens
Oncorhynchus tshawytscha	Enterocina AS-48	Lactococcus garvieae	Antimicrobial activity against tested pathogen (in vitro and in vivo)
Penaeus monodon	Bacteriocin homologous to that produced by Bacillus sp.	Vibrio alginolyticus, Aeromonas hydrophila, Pseudomonas stutzeri	In vitro inhibitory activity against tested pathogens

Advantages of Probiotics in Aquaculture

1. Improves Growth Rate
2. Enhances Disease Resistance
3. Reduces Use of Antibiotics
4. Improves Water Quality
5. Increases Survival Rate
6. Enhances Feed Efficiency
7. Eco-Friendly and Sustainable
8. Controls Harmful Microorganisms
9. Improves Reproductive Performance
10. Reduces Stress.

Limitations of Probiotics in Aquaculture

1. Variable Effectiveness
2. Short Survival in Water
3. Need for Proper Management
4. Slow Results

Conclusion

Probiotics play an important role in modern aquaculture by enhancing growth, improving immunity, maintaining water quality, and reducing the use of antibiotics. They assist sustainable and eco-friendly fish farming practices. While some limitations exist, proper selection and management of probiotics can significantly improve aquaculture productivity and animal health.

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Microplastic Pollution and Its Impact on Fishes and Human

Article ID: 73791

Shweta P. Vaidya¹, Pallavi V. Jogdand², Gayatri S. Avchar²
¹Department Of Fisheries Resources Management, College Of Fisheries Science Nagpur-440006.

Abstract

Pollution poses a significant issue, primarily due to human activities that adversely affect the environment & natural resources. Microplastics, defined as plastic particles smaller than 5 mm, originate from the degradation of larger plastic materials and from industrial and domestic sources. These particles are widely distributed in marine, freshwater, and estuarine environments, where they are readily ingested by fish and other aquatic organisms. Fish are particularly vulnerable to microplastic exposure through feeding, respiration, and trophic transfer. The accumulation of microplastics in fish tissues can lead to physiological, biochemical, and behavioral alterations, including reduced growth, oxidative stress, intestinal damage, and impaired reproduction. Furthermore, microplastics can adsorb toxic pollutants such as heavy metals, pesticides, and persistent organic pollutants, increasing the risk of contaminant transfer through the food chain to humans. This review thoroughly examines microplastic pollution in aquatic settings and its consequences for fisheries and aquaculture. It discusses 'microplastics' environmental dispersion, and their impact on fish population and human health.



Introduction

The term microplastic pollution was first used by Thompson et al. (2004) to raise awareness about the dangers of plastic particles, known as microplastics or microbeads. Microplastics are the tiny plastic particles and fragments that range from 5mm to 1nm in size. Microplastics are classified into two categories based on their origins, namely, primary & secondary microplastics. Primary microplastics are defined as plastics particles that enter the environment directly, such as cosmetics of microfibers shed from clothing and textile, while the secondary microplastics originate from the degradation and breakdown of larger particle items. Sources of microplastics include the degradation of synthetic textiles, cosmetics, detergents, paints, pharmaceuticals, & insecticides. They are transported to rivers, streams, and lakes through precipitation and wind. More than 690 marine species have been found to ingest MPs, which may induce physical and chemical toxicity, such as intestinal inflammation, oxidative stress, altering the behaviour and nutritional composition in fish. MPs ingested by fish increases human health risk through fish consumption.

Sources of Microplastics in Aquatic Environments

Sources of microplastics pollution includes textile fibres, microbeads, and the breakdown of large plastic debris into microplastics over time. Other sources are wastewater treatment plants, runoff from urban, agricultural, tourist and industrial areas, sewage sludge, and maritime activities such as beach litter, fishing, and harbours.

Sampling and Analysis of Microplastics in Water

The determination of MPs in water samples involves 5 steps: sampling, separation, clean up, identification, and confirmation.

1. Sampling: for large surface water bodies Neuston nets are dragged to filter large volumes. For sample collection other methods like submersible pumps, nets and sieves are used.

2. Separation and clean up: samples often contain natural organic matter that masks microplastics. Hydrogen peroxide or potassium hydroxide is used to digest this biological material without degrading synthetic polymers. Digested sample is mixed with density solution so the particles separate according to their density, causing the plastics float on the surface are extract. The supernatant is passed through micro filters.

3. Identification and confirmation: using visual inspection filters are examined using microscope to document color, shape and size. Visual identification may prone to error and must be confirmed using chemical techniques like μ -FTIR (Micro-Fourier Transform Infrared Spectroscopy)/ μ -Raman Spectroscopy.

Effects of Microplastic Pollution on Fishes

Microplastics are a significant pollutant across aquatic and marine environments, impacting essential habitats like estuaries critical for many fish species. The contamination affects all levels of the food chain, from zooplankton to seabirds and marine mammals. The presence of microplastics in fish can cause physical damage to digestive organs, reduced growth, altered feeding behavior, stress, and reproductive problems. Ingestion of pollutants like heavy metals and pesticides leach into the fish's system causing DNA damage, reproductive disorders, and liver toxicity.

Effects on Human Health

Contaminated food, especially seafood, is a significant route of humans can encounter microplastics. When ingested or inhaled, microplastics may induce local particle toxicity, promoting immune reactions. The consumption microplastic laden food might pose several health risks, including cancer, immunotoxicity, gastrointestinal and pulmonary diseases, cardiovascular issues, inflammatory conditions, and complications during pregnancy. Microplastic particles can enter the gastrointestinal system through food contaminated with plastics. Intake leads to various negative health effects, including increased gut permeability, alterations in gut microbe composition, and changes in metabolism causing inflammation and gut barrier dysfunction.

Remediation Strategies

Strategies to solve the problem of MPs pollution should focus on

1. Source control commonly achieved by legislation and awareness programs
2. Remediation and clean up (to eliminate the MPs already present in water)

Remediation technologies can be divided in

- a. Engineering tools:** waste water treatment plant (WWTPs) eliminate a high percentage of the MPs present in the influents (between 90 & 98%). The advanced wastewater technologies more frequently used are membranes, electrodeposition, and coagulation.
- b. Biobased/ biodegradable polymers:** biodegradable plastics are capable of undergoing biological anaerobic or aerobic degradation.
- c. Bioengineering based solutions:** new biodegradation routes for classical plastics, like different types of bacteria and fungi or isolate the involved enzymes to ensure the enzymatic hydrolysis of plastic.

Conclusion

Microplastic pollution is a life-threatening environmental problem with far reaching impacts on aquatic life and human health. Microplastics, originating from cosmetic, textiles, and breakdown of larger debris, are widely distributed in marine, freshwater, and estuarine systems where fish ingest them through feeding, respiration, and trophic transfer. For humans, contaminated seafood is a major exposure route. Ingested MPs may cause local particle toxicity, immune reactions, increased gut permeability, altered gut microbiota, inflammation. It can be concluded that different types of microplastics have been detected in aquatic environments by using different methods such as Raman spectroscopy & FTIR spectroscopy. While WWTPs eliminate 90-98% of MPs using membranes, electrodeposition, and coagulation, and bioengineering solutions like bacteria/fungi show promise for plastic degradation, the problem persists.

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Trash to Treasure: The Rise of Upcycled Superfoods

Article ID: 73792

Pavithra G¹, Dr. V. Hema², Nivetha E³, Dr. Shanmugasundaram⁴
^{1,3}Ph.D. Research Scholar, Department of Food Process Technology, NIFTEM-T, Thanjavur-613005.

²Professor, Department of Food Plant Operation, Incubation and Entrepreneurship Management, NIFTEM-T, Thanjavur-613005.

⁴Professor & Head, Department of Food Plant Operation, Incubation and Entrepreneurship Management, NIFTEM-T, Thanjavur-613005.

Abstract

Food waste is one of the most pressing global challenges, with nutritious by-products like skins, kernels, stalks, pomace, and pulp being wasted during food production and preparation. These by-products contain important nutrients like dietary fiber, antioxidants, vitamins, minerals, and phytochemicals. Upcycled superfoods can be seen as a breakthrough solution to transform food waste into useful nutritional ingredients that help prevent food waste, pollution, and global warming. Products like aquafaba, spent barley grain, okara, grape pomace, coffee cherry flour, and fruit seed oils are getting commercial significance because of their health benefits and sustainability.

Keywords: Upcycled foods, food waste upcycling, sustainability, functional foods, circular economy, superfoods.

Introduction

The problem of food waste has emerged as one of the major issues on a global scale. In this context, about one-third of the world's total food production is either lost or wasted. These residues have been found to be a source of various nutrients, such as dietary fibers, antioxidants, polyphenols, and others. As a result of recent studies, these products have gained recognition for their nutritional value, paving the way for the creation of “upcycled superfoods.” Food upcycling has thus proved instrumental in addressing the issue of waste and promoting the production of healthy foods.

Nutritional Value of Food Byproducts

Peels, seeds, stems, and residues are examples of food by-products that have substantial health advantages because they are high in dietary fiber, antioxidants, vitamins, and fatty acids (Table 1). For instance, citrus peels contain potent antioxidant flavonoids, watermelon peels offer heart-healthy citrulline, and materials like spent barley grain, okara, and coffee cherries are increasingly being used to make functional foods (Lau et al., 2021).

Table 1: Food By-Products and its health benefits:

By-product	Key Nutrients	Health Benefits	Industrial Applications	References
Watermelon Rind	Citrulline, Lycopene	Cardiovascular health, Muscle recovery	Functional foods	(Burton-Freeman et al., 2021)
Orange/Citrus Peel	Flavonoids, Vitamin C	Antioxidant, Immune support	Flavoring, Nutraceuticals	(Li et al., 2023)
Banana Peel	Fiber, Potassium	Digestive and Heart health	Flour, Supplements	(Liu et al., 2023)
Broccoli Stem	Fiber, Sulforaphane	Gut health, Anti-cancer	Functional ingredients	(Yan et al., 2023)
Grape Pomace	Polyphenols, Resveratrol	Antioxidant, Cardioprotective	Supplements, Colorants	(Kokkinomagoulos et al., 2023)
Tomato Seed	Healthy fats, Polyphenols	Antioxidant, Cardiovascular protection	Oils, Cosmetics	(Kaseke et al., 2020)
Coffee Cherry	Chlorogenic acid, Fiber	Antioxidant, Energy support	Functional beverages	(Nemzer et al., 2021)
Okara	Fiber, Protein, Isoflavones	Bone and Gut health	Gluten-free products	(Asghar et al., 2023)
Spent Barley Grain	Beta-glucan, Fiber	Cholesterol and Blood sugar control	High-fiber foods	(Umego et al., 2023)

Aquafaba	Proteins, Saponins	Plant-based binding	Vegan products	(de Barros Miranda et al., 2024)
Watermelon	Protein, Polyphenols	Immunity, Anti-inflammatory	Functional foods	(Nissar et al., 2025)

Scientific Basis of Upcycled Superfoods

To fully realize the potential of repurposed food ingredients, sophisticated processing methods are essential. While dehydration and milling increase shelf life and streamline product integration, fermentation reduces anti-nutrients to boost mineral bioavailability. Enzymatic treatments can optimize recovery of important bioactive substances, antioxidants, fiber, and oils (Marcelli et al., 2025).

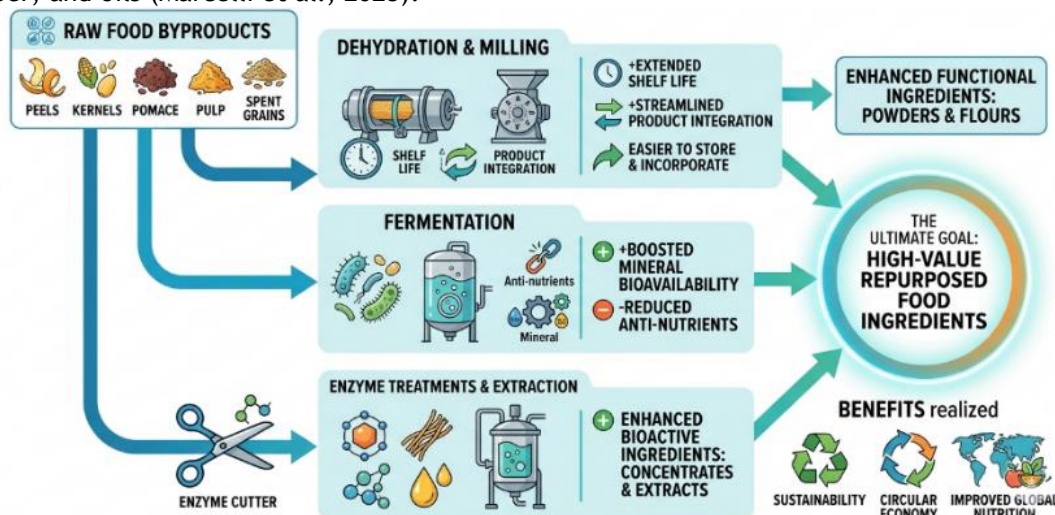


Fig 1: Enhancing Repurposed Ingredients: Sophisticated Processing Methods

Emerging Upcycled Superfood Ingredients

Cacao fruit pulp, coffee cherry flour, and brewers' grains are examples of emerging upcycled superfoods that turn nutrient-dense by-products into valuable functional components. These materials, which have been saved by sophisticated bioprocessing and stabilization, are rich in concentrated proteins, fibers, and antioxidants. By successfully incorporating them into contemporary food formulations, a sustainable, circular economy is established while promoting global nutrition (Santos et al., 2022).

Environmental and Economic Significance

The disposal of food waste significantly contributes to global warming and pollution, and depletion of natural resources since the decomposition of the organic matter in the landfill produces methane gas, which is a powerful greenhouse gas. Food upcycling serves the purpose of minimizing food waste by making food waste valuable in the process of manufacturing new products. Economically, it provides a new income stream by turning food-processing waste into functional ingredients for foods (Bekavac et al., 2025).

Challenges in the Upcycled Food Industry & Future Perspectives

The upcycled food sector has a very bright future despite obstacles like poor consumer acceptability due to safety concerns, erratic seasonal supplies, and a lack of uniform rules (Moshtaghian et al., 2021). By identifying novel nutritional sources-such as pineapple core flour, avocado seed extracts, and watermelon seed protein-and improving byproduct identification, advanced food technology, biotechnology, and artificial intelligence are propelling the industry forward. The industry is expected to increase significantly due to the increasing consumer desire for sustainability.

Conclusion

By converting nutrient-rich manufacturing by-products-rich in fiber, protein, and antioxidants-into functional foods, upcycled superfoods present a fresh approach to nutrition, sustainability, and food waste reduction. This method promotes a circular food economy and resource efficiency. Ongoing scientific study is anticipated to support this field's future expansion and success despite current market obstacles.

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Export of Food and Agri Products Registered as GI from Maharashtra

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Sangita J. Kadlag¹

¹Assistant Professor of Agricultural Economics, MVP's K.D.S.P College of Agriculture, Chachadgaon, Nashik-Peth Highway Nashik.

Introduction

GI stands for **Geographical Indication**. It is a certification mark used on agricultural and food products to indicate that they possess specific qualities, reputations, or characteristics largely attributable to their region of origin.

A Geographical Indication acts essentially as an intellectual property right. It serves several key purposes:

- 1. Proof of Origin:** It guarantees consumers that the product was indeed grown, harvested, or processed in a specific, defined geographic area.
- 2. Quality Assurance:** It signifies that the item has unique, authentic qualities derived from local natural factors (like soil and climate) or traditional production methods.
- 3. Legal Protection:** It prevents unauthorized producers outside the designated region from falsely marketing their goods under that famous name.

Why GI Matters Agri-Food Products?

- 1. Local Identity:** It preserves centuries-old farming techniques, regional recipes, and local knowledge.
- 2. Economic Value:** Products with recognized GI tags often fetch premium prices in the market because of their authenticity and high quality.

Role of GI products in export for India: Geographical Indication (GI) products drive India's export growth by guaranteeing authenticity, securing premium prices, and protecting traditional knowledge from counterfeits. They act as a powerful branding tool, allowing regional producers to bypass middlemen and tap into lucrative international markets.

Key Roles of GI Products in India's Exports

- 1. Premium Pricing & Market Premium:** International consumers associate GI tags with assured origin and quality. Exporters of GI products often command a 20-30% price premium over non-tagged equivalents.
- 2. Legal Protection & Trust:** The GI tag prevents the unauthorized use of regional names (e.g., stopping international companies from selling fake Darjeeling tea or Basmati rice). It eliminates information asymmetry, assuring foreign buyers of the product's true origin.
- 3. Empowering Rural Economies:** By boosting export value, GI tags directly improve the livelihood of rural artisans, weavers, and farmers. It helps preserve regional heritage while transforming local manufacturing into a global business.
- 4. Boosting Niche & Agricultural Exports:** Beyond major commodities, the government actively promotes niche GI-tagged agri-products (like Alphonso mangoes, Nagpur oranges, and Indi Lime) to diverse international destinations such as the UAE, USA, Japan, and the EU.

Government & Institutional Support

To enhance the global reach of these regional treasures, India has rolled out several export facilitation programs:

APEDA Initiatives: The Agricultural and Processed Food Products Export Development Authority (APEDA) regularly organizes Virtual Buyer-Seller Meets and international promotional events to connect GI producers with global importers.

Trade Promotion: Trade bodies and Export Promotion Councils (EPCs) highlight GI-tagged handicrafts and agricultural goods at international trade fairs to gain visibility.

Registration & Guidance: The Geographical Indications Registry and associated bodies guide local communities on securing international IP protection. From India there are 123 food and agri products registered as GI products. Out of India's GI products 24 food and Agri products (nearly 20 % products) are from Maharashtra. These includes Foodgrains (Rice & Jowar), Fruits (12 fruits) Vegetables (3 vegetables) Spices (2 types) and one food products.

List of GI Tag for Agri and Food Products from Maharashtra

Sr no	Type	Geographical Indication	Geographical Area	Class	Journal no
1	Food	Ajara Ghansal Rice	Taluka Ajara, District-Kolhapur	30	76
2	grains	Ambemohar Rice	Mulshi TalukaDist- Pune	30	88

3		Mangalwedha Jowar	Taluka Mangalwedha, District: Solapur	30	78
4	Fruits	Nashik Grapes	Maharashtra	31	35
5		Nagpur Orange	Akola , Maharashtra	31	55
6		Sindhudurg and Ratnagiri Kokam	Taluka - Malvan Dist-Sindhudurg	29	76
7		Beed Custard Apple	Tal - Dhanur Dist-Beed	31	79
8		Jalna Sweet Orange	Dist- Jalna	31	79
9		Purandar Fig	Pune	31	80
10		Solapur Pomegranate	Pune	31	80
11		Dahanu Gholvad Chikoo	Tal -Dahanu Dist- Thane	31	88
12		Jalgaon Banana	Tal -Raver Dist- Jalgaon	31	88
13		Marathwada Kesar Mango	Dist- Aurangabad	31	88
14		Alphonso	Tal -Dapoli Dist- Ratnagiri	31	106
15		Mahabaleshwar Strawberry	Tal - Mahabaleshwar Dist- Satara	31	33
16	Vegetable	Waghya Ghevada	Taluka - Koregaon Dist-Satara	31	77
17		Lasalgaon Onion	Taluka - Niphad , Dist- Nashik	31	77
18		Jalgaon Brinjal	Dist-Jalgaon	31	80
19	Spices	Waigaon Turmeric	Tal -Samudrapur Dist - Wardha	30	80
20		Bhivapur Chilli	Tal - Bhivapur Dist - Nagpur	30	88
21		Sangli Turmeric	Dist- Sangli	30	108
22	Food Product	Kolhapur Jaggery	Dist- Kolhapur	31	54
23		Navapur Tur Dal	Tal - Navapur Dist- Nandurbar	31	77
24		Sangli Raisins	Tal - Miraj Dist - Sangli	31	78

What is Meant by Class in GI Products in India?

In India, a "class" refers to the specific product category under which a Geographical Indication (GI) is registered. India uses a standardized classification system (similar to the international Nice Classification) with **34 distinct classes**, which determines exactly what type of goods a GI tag protects.

Why Classes Matter?

- 1. Scope of Protection:** A GI tag only protects a product within its assigned class. For example, a registered GI for "Alphonso" under Class 31 (Fruits) stops anyone from falsely labeling unverified mangoes as Alphonso, but it doesn't cover "Alphonso" flavored chocolates or cotton fabric.
- 2. The 34 Categories:** The registry divides all registerable goods into 34 classes ranging from agricultural products, foodstuff, and alcoholic beverages to handicrafts, textiles, and chemicals.
- 3. Common GI Classes in India:** The majority of India's hundreds of recognized GIs fall into these primary classes:
 - a. Class 23 & 24:** Textiles and Textile Goods (e.g., Banarasi Silk, Kashmir Pashmina, Chanderi Fabric).
 - b. Class 30:** Agricultural and Food Products (e.g., Hyderabad Haleem, Dharwad Pedha).
 - c. Class 31:** Raw Agricultural Products (e.g., Darjeeling Tea, Basmati Rice, Alphonso Mango).
 - d. Class 1 to 22:** Handicrafts and Manufactured Goods (e.g., Jaipur Blue Pottery, Bidriware, Mysore Sandal Soap).

How to Check Product Class?

When artisans, farmers, or cooperatives apply for a GI tag, they must specify the exact class of their product. You can view the entire registry and the class assigned to every verified product by checking the official Intellectual Property India (GI Registry) portal.

What is Mean by Journal Number in GI Products in India?

In the context of Geographical Indication (GI) products in India, a Journal Number refers to the specific edition of the official *Geographical Indications Journal* where a product's GI application was published.

- 1. The Public Notice:** Before a GI tag is officially granted, the GI Registry in India publishes the details of the product (its name, origin, unique qualities, and producers) in its official journal. This journal number tells you exactly *where* to look to find this public notice.
- 2. Opportunity for Opposition:** The publication of an application in a specific journal starts a clock (usually 3 months) during which the public or other interested parties can file an opposition or objection to the GI registration.

3. **Journal Reference:** Once the tag is registered, the journal number remains on the product's official registration records as a permanent reference point.

Foodgrains

		
Ajara Ghansal Rice	Mangalwedha Jowar	Ambemohar Rice

Fruits

			
Nashik Grapes	Nagpur Oranges	Sindhudurg	Alphonso

Ratnagiri Kokam

Vegetables		Spices	
			
Waghya Ghevada	Lasalgaon Onion	Waigaon Turmeric	Bhivapur Chilli

Food Products

		
Kolhapur Jaggery	Navapur Tur Dal	Sangli Raisins

Different Methods of Storage of Onion in Tropical Region

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Dr. S. D. Wankhade¹

¹Assistant Professor, Department of Horticulture.

Abstract

Onion is one of the most important commercial vegetable crops cultivated widely in tropical and subtropical regions. Due to its seasonal production and year-round demand, proper storage is essential to reduce post-harvest losses and maintain market availability. In tropical regions, high temperature and humidity cause severe losses through sprouting, rotting, and physiological weight reduction. Traditional storage methods often result in 30-40% losses, whereas improved scientific storage structures can considerably reduce these losses. Various storage techniques such as traditional storage, ventilated storage structures, cold storage, modified atmospheric storage, and improved NHRDF structures have been developed to enhance onion shelf life and preserve bulb quality. Adoption of suitable storage technology along with proper curing and grading practices can significantly improve onion quality, farmer income, and market stability in tropical regions. ([ACS Publisher])

Introduction

Onion (*Allium cepa* L.) is an indispensable vegetable and spice crop used daily in households and food industries across the world. India is among the leading onion-producing countries, and a large quantity of onions is cultivated under tropical climatic conditions. However, onions are highly perishable after harvest and are prone to moisture loss, sprouting, and fungal decay during storage. The problem becomes more severe in tropical regions due to high ambient temperature and humidity. Storage of onions is therefore necessary to ensure continuous supply during off-seasons and stabilize market prices.

Proper storage management begins with selection of suitable cultivars, harvesting at proper maturity, curing, grading, and maintaining appropriate storage conditions. Scientific storage structures with good ventilation and controlled environmental conditions have shown promising results in reducing post-harvest losses. Different traditional and modern storage methods are being adopted depending on climatic conditions, economic feasibility, and scale of operation. ([Indian Journals][2])

Storage Losses of Onion

Traditional storage systems in tropical regions often experience **30-40% losses** because of poor ventilation and unsuitable environmental conditions.

Scientific ventilated storage structures can reduce storage losses to approximately **20-25%**. Storage losses vary greatly among onion varieties, ranging from **5% to 85%** depending on genotype and storage environment.

Under experimental storage conditions, physiological weight loss in selected onion genotypes remained as low as **5.80-6.83%** over 90 days.

Excess rainfall and poor ventilation may cause up to **50% spoilage** in stored onions.

Traditional Onion Storage Methods

Traditional storage methods are commonly practiced by farmers in tropical regions because of their low cost and easy construction. These methods include open heaps, bamboo structures, mud-plastered houses, and storage under thatched roofs. Although economical, these methods provide poor ventilation and inadequate protection from moisture and pests. Consequently, storage losses are generally high.

Improved Ventilated Onion Storage Structures

Improved ventilated structures were developed to minimize losses by enhancing airflow around onion bulbs. These structures are generally elevated above ground level and constructed using wooden slats, bamboo, or metal mesh to permit free movement of air.



Features of Improved Structures

1. Raised platform to avoid moisture accumulation
2. Slatted side walls for proper ventilation
3. Protection from rain and direct sunlight
4. Better aeration reduces sprouting and rotting.



Cold Storage Method

Cold storage is an advanced storage method where onions are maintained at low temperature (0-2°C) and relative humidity of 65-70%. This method effectively suppresses sprouting and microbial growth, thereby increasing storage duration.

Modified Atmospheric and Controlled Storage

Modified atmosphere storage (MA) and controlled atmosphere storage (CA) involve regulating oxygen, carbon dioxide, temperature, and humidity levels to reduce respiration and delay sprouting. Scientific reports suggest that MA and CA storage systems can effectively reduce storage losses in onions under tropical conditions.



Modern NHRDF Onion Storage Structure

The National Horticultural Research and Development Foundation (NHRDF) developed improved onion storage structures suitable for tropical and subtropical regions. These structures maintain relatively stable temperature and humidity while providing proper ventilation.

Comparative Performance of Different Storage Method

Storage Method	Storage Duration	Major Advantages	Major Limitations
Traditional Storage	1-2 months	Low cost	Hiss losses
Ventilated Storage	3-5 months	Better areation	Moderate investment
Cold Storage	6-8 months	Excellent preservation	High operational cost
MA/CA Storage	6-8 months	Reduced spoilage	Expensive technology
NHRDF Structure	5-6 months	Reduced total loss	Require scientific construction

Summary and Conclusion

Onion storage is a major challenge in tropical regions due to high temperature and humidity, which promote sprouting, rotting, and physiological weight loss. Traditional storage methods are economical but suffer from heavy post-harvest losses. Improved ventilated storage structures and modern NHRDF storage systems have demonstrated considerable success in reducing losses and maintaining bulb quality. Cold storage and controlled atmosphere storage provide excellent preservation but involve higher costs and technical expertise. Adoption of scientific storage practices including proper curing, grading, ventilation, and environmental management can greatly improve onion shelf life and profitability for farmers. Therefore, improved onion storage technologies should be promoted widely in tropical onion-growing areas to ensure year-round availability and reduce economic losses.

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Cotton Residue Degradation: A Microbial Approach to Sustainable Farming

Article ID: 73795

V H Vinuthana¹, Pole Akhila², Venkatanna³

¹Ph.D Scholar, Tamil Nadu Agricultural University, Coimbatore.

²Young Professional-II, ICAR-Indian Institute of Rice Research, Hyderabad.

³Young Professional-II, ICAR-Indian Institute of Rice Research, Hyderabad.

Introduction

Agriculture generates enormous quantities of crop residues every year in the form of stalks, straw, husks, leaves, and stubbles. Among these, cotton residues are one of the major agricultural wastes produced after cotton harvesting. India is among the world's largest cotton-growing countries, and millions of tonnes of cotton residues are generated annually. After picking cotton bolls, large amounts of stalks and stems remain in the field, creating serious residue management challenges for farmers.

Traditionally, many farmers remove or burn cotton residues to prepare fields quickly for the next crop. Burning is often considered quick and conventional method of residue disposal, especially during labour shortages and limited time between cropping seasons. However, residue burning has become a major environmental concern in recent years. Burning releases harmful gases such as carbon dioxide, methane, nitrous oxide, and particulate matter into the atmosphere, contributing to air pollution and climate change. It also destroys valuable soil organic matter and beneficial microorganisms that are essential for maintaining soil fertility.

Cotton residues contain large amounts of nutrients and organic carbon. Instead of treating them as waste, they can be recycled back into the soil to improve soil productivity and sustainability. However, cotton residues are highly fibrous and rich in lignocellulosic compounds, making them resistant to natural decomposition. Under normal field conditions, they degrade very slowly and may interfere with tillage operations and sowing of subsequent crops. In this situation, microorganisms offer an effective biological solution for residue management. Soil microbes such as bacteria, fungi, and actinomycetes possess the natural ability to decompose complex plant materials through the production of specialized enzymes. These microorganisms convert tough cotton residues into simpler organic compounds, releasing nutrients back into the soil and improving soil health.

Microbial degradation of cotton residues is therefore emerging as an important strategy in climate-smart agriculture and sustainable residue management. By utilizing the natural potential of microorganisms, agricultural waste can be transformed into a valuable resource for maintaining soil fertility, conserving the environment, and improving long-term crop productivity.

Why Cotton Residues Need Proper Management

Cotton cultivation leaves behind huge quantities of residues in the form of stalks, roots, leaves, and unopened bolls after harvest. These residues occupy the field and often create difficulties during land preparation for the next crop. Since cotton residues are woody and fibrous in nature, farmers usually find them difficult to remove manually. As a result, many farmers prefer burning the residues directly in the field for quick clearance.

Although residue burning saves time and labour, it causes severe damage to both the environment and soil ecosystem. Burning destroys beneficial soil microorganisms that are responsible for nutrient cycling and soil fertility. It also leads to the loss of valuable nutrients such as nitrogen, phosphorus, sulfur, and organic carbon that are present in the crop residues. Studies have shown that continuous residue burning reduces soil organic matter and adversely affects soil structure over time.

Majorly, the smoke released from burning cotton residues contains harmful gases and fine particulate matter that contribute to air pollution and respiratory problems in humans and animals. In addition, greenhouse gas emissions from burning accelerate global warming and climate change. Therefore, alternative eco-friendly methods of residue management are becoming increasingly important in modern agriculture.

Proper decomposition of these residues enriches soil organic carbon, improves microbial activity, enhances moisture retention, and supports better crop growth. However, cotton residues contain high amounts of lignin and cellulose contributing to slow natural decomposition. This is where microorganisms play a crucial role. Beneficial microbes possess the ability to degrade complex plant materials through enzymatic activity.

By accelerating decomposition, these microbes convert cotton residues into nutrient-rich organic matter within a shorter period. Microbial degradation therefore offers an economical, sustainable, and environmentally safe solution for managing cotton residues in agricultural fields.

Composition of Cotton Residues

Cotton residues consisting 32 - 46% of cellulose followed by 20 - 28% of hemicellulose serves as an important carbon source for microorganisms. However presence of 15 - 30% of lignin provides high resistant to decomposition because of its complex aromatic structure. This high lignin makes cotton residues harder to degrade compared to softer crop residues such as paddy straw or vegetable waste. The high C: N ratio in cotton residues also slows microbial activity because microorganisms require nitrogen for their growth and enzyme production. The tough nature of cotton residues makes decomposition a slow biological process under natural conditions. Therefore, external application of efficient microbial decomposers is often necessary to accelerate breakdown and nutrient release.

Role of Microorganisms in Biomass Degradation

Microorganisms are known as nature's decomposers because they recycle dead organic matter back into the ecosystem. Different groups of microorganisms participate in the degradation of cotton residues through enzymatic action.

Bacteria: Bacteria play an important role during the early stages of residue decomposition. lignocellulolytic bacteria produce enzymes such as laccases, cellulase and xylanase that degrade lignocellulosic biomass into simple sugars. Genera such as *Bacillus*, *Pseudomonas*, *Azotobacter*, and *Cellulomonas* are commonly associated with crop residue degradation. Some bacteria also improve decomposition indirectly by fixing atmospheric nitrogen and enhancing nutrient availability for microbial growth. Their rapid multiplication helps initiate the decomposition process soon after residue incorporation into soil.

Fungi: Fungi are among the most efficient degraders of lignocellulosic biomass. They possess strong enzyme systems capable of degrading lignin, cellulose, and other complex polymers. Fungi penetrate deeply into plant tissues through their hyphal network and break down hard fibrous materials. Species of *Trichoderma*, *Aspergillus*, *Penicillium*, and white-rot fungi are widely studied for their residue-degrading abilities. White-rot fungi are particularly important because they produce lignin-degrading enzymes such as laccase and peroxidase.

Actinomycetes: Actinomycetes are filamentous bacteria that function actively during the later stages of decomposition. They degrade resistant organic compounds and contribute to humus formation. These microorganisms also produce several extracellular enzymes and antimicrobial compounds that improve soil biological activity. Together, bacteria, fungi, and actinomycetes form a dynamic microbial community responsible for efficient biomass recycling in agricultural soils.

Enzymes Involved in Cotton Residue Degradation

Microbial degradation mainly occurs through the action of extracellular enzymes. These enzymes break complex organic molecules into smaller compounds that microorganisms can utilize as energy sources.

Important enzymes involved in biomass degradation include:

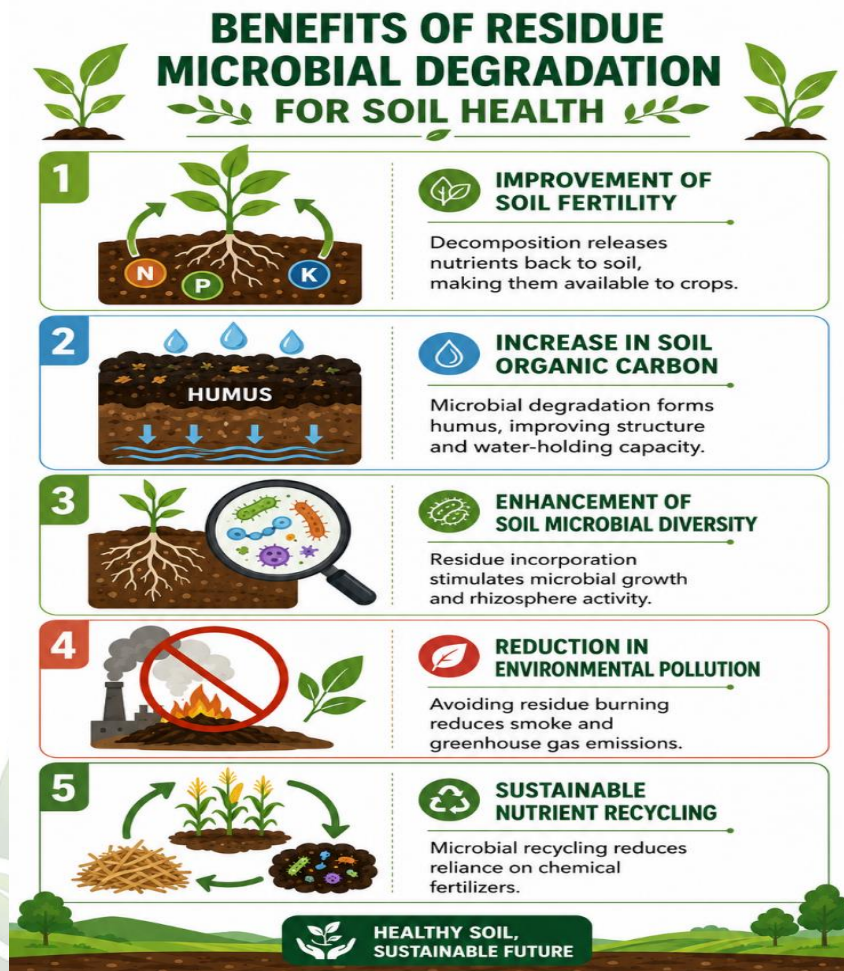
1. Cellulase - degrades cellulose
2. Hemicellulase - breaks down hemicellulose
3. Lignin peroxidase - degrades lignin
4. Laccase - oxidizes lignin compounds
5. Pectinase - degrades pectin substances
6. Xylanase - hydrolyzes xylan components

The production of these enzymes depends on microbial species, environmental conditions, and substrate composition

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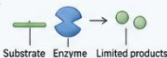
Benefits of Microbial Degradation of Cotton Residues



Microbial Consortia for Faster Decomposition

Single microorganisms may not efficiently degrade all components of cotton residues. Therefore, scientists are developing microbial consortia containing multiple compatible microorganisms.

DIFFERENCE BETWEEN SINGLE CULTURE AND MICROBIAL CONSORTIA

ASPECT	SINGLE CULTURE	MICROBIAL CONSORTIA
 DEFINITION	Involves one microbial species working alone. 	Involves multiple microbial species working together. 
 MECHANISM	Performs limited range of enzymatic reactions; degrades specific components. 	Performs complementary enzymatic reactions; degrades complex components synergistically. 
 DEGRADATION EFFICIENCY	Lower efficiency; slower degradation of complex substrates. 	Higher efficiency; faster and more complete degradation. 
 STABILITY & RESILIENCE	Less stable; performance affected by environmental changes. 	More stable and resilient; species compensate for each other under changing conditions. 
 SUBSTRATE UTILIZATION	Utilizes a narrow range of substrates. 	Utilizes a wide range of substrates. 
 METABOLIC INTERACTIONS	No interactions; no exchange of metabolites. 	Strong interactions; exchange of metabolites, signaling, and synergistic activities. 
 APPLICATIONS	Suitable for simple waste; limited use in complex or recalcitrant waste treatment. 	Suitable for complex lignocellulosic waste; widely used in bioremediation, composting, and industrial applications. 
 COST	Lower initial cost but may require longer time and more inputs. 	Higher initial cost but cost-effective due to higher efficiency and shorter time. 
 TIME REQUIRED	Longer time for complete degradation. 	Shorter time for complete degradation. 

Future Prospects of Microbial Biomass Degradation

Modern agricultural research is focusing on advanced microbial technologies for efficient residue recycling. Metagenomics, enzyme engineering, and microbial biotechnology are helping scientists identify superior decomposer microorganisms with enhanced lignocellulose degradation ability.

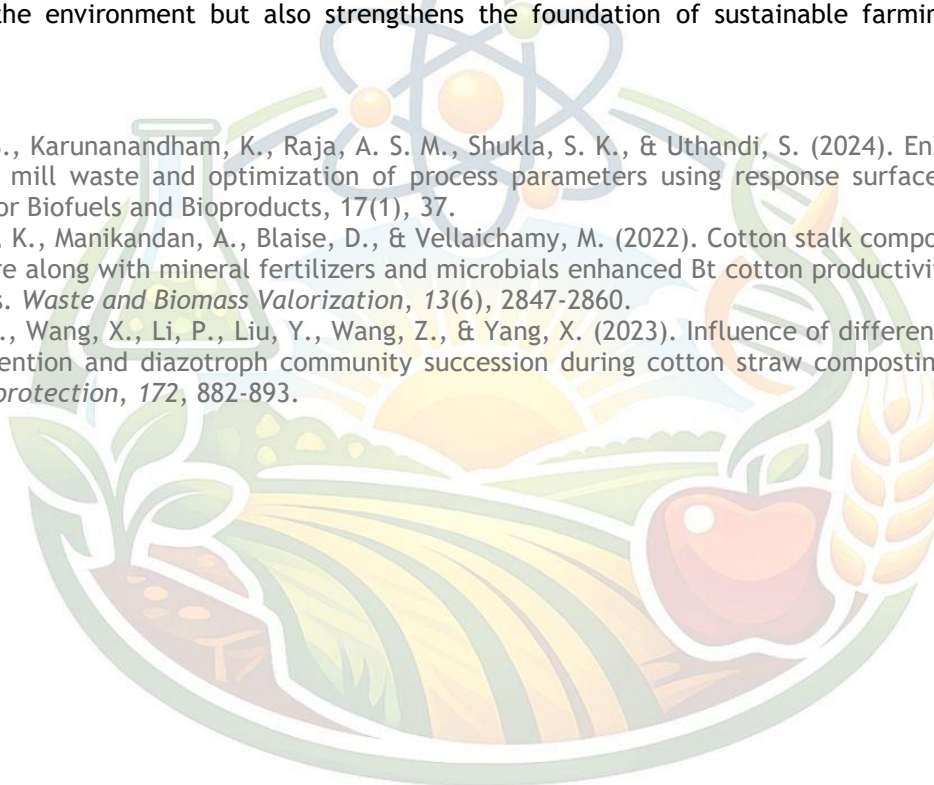
Development of low-cost microbial inoculants and farmer-friendly decomposition technologies can greatly reduce residue burning practices in the future. Integration of microbial residue management with natural farming and regenerative agriculture may help improve soil health and environmental sustainability.

Conclusion

Cotton residue degradation through microorganisms offers an eco-friendly, economical, and sustainable solution for agricultural waste management. Instead of burning cotton residues and causing environmental pollution, farmers can utilize beneficial microbes to recycle residues into valuable organic matter. Microbial decomposition improves soil fertility, enhances nutrient availability, supports soil biodiversity, and contributes to sustainable crop production. As awareness about environmental protection and soil health increases, microbial approaches to biomass degradation are expected to play a major role in future agriculture. Harnessing the power of microorganisms for residue management not only protects the environment but also strengthens the foundation of sustainable farming systems for future generations.

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Sustainable Utilization of Millet By-Products in Food and Non-Food Sectors

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Parashuram Patroti¹, Mahesh Mohan Shinde¹, Payal Kardikar¹, Priya Ayyar¹
¹ICAR-Indian Institute of Millets Research, Regional station, Centre on Rabi Sorghum, Shelgi, Solapur, Maharashtra-413006, India.

Introduction

Global millet production is estimated at 30.1-30.9 million tonnes annually, with India accounting for 38.4% of total production (PIB, 2025). Millet processing generates 15-30% by-products, mainly bran and husk (Galanakis *et al.*, 2022), while cultivation produces 1.5-2.5 tonnes of crop residues per tonne of grain harvested (Kaur *et al.*, 2023). As a result, India produces between 27 and 45 million tons of millet biomass leftovers each year, which presents a substantial opportunity for value addition and circular economy applications (Reddy *et al.*, 2025). India produced 18.01 million tonnes of millets from the area of cultivation 12.86 million hectares during FY 2024-25 (APEDA,2025). The structure of millets includes the outer layer pericarp, starchy endosperm, and oil-rich germ. Millets such as Proso, foxtail, and finger millets are classified as utricles in which the pericarp easily detaches from the seed coat. In caryopses in which the pericarp is attached tightly to the seed, as observed in the millets, like sorghum and pearl millet. The grain composition of millets varies among species, with the endosperm constituting the major fraction (45-82%), followed by the germ (3-15%) and bran/pericarp (8-15%) (Satyavathi *et al.*, 2021). Millet such as pearl millet, finger millet, and sorghum possess negligible husk content, whereas 13.5% in foxtail millet to 37% in Kodo millet, little millet contains 20-25% husk, barnyard millet around 23%, and proso millet 12-17% Millet by-products mainly include husk, bran, and other residues like stalks and cobs residue (Source of lignocellulosic biomass for energy production) formed during processing (Gurumeenakshi *et al.*, 2025).

Nutritional Value of Millet By-Products

Polyphenol content in the millet by-products varies in the range from 3.87 to 779.0 mg GAE/g and 4.35-14.87 mg RE/g of flavonoids. The highest content of phenolic acid is present in the finger millet in the range 2.98 mg FAE/g dry weight (Kaur *et al.*, 2025). Nutritional parameters for the Husk and bran of the millet in % are mentioned in Table 1.

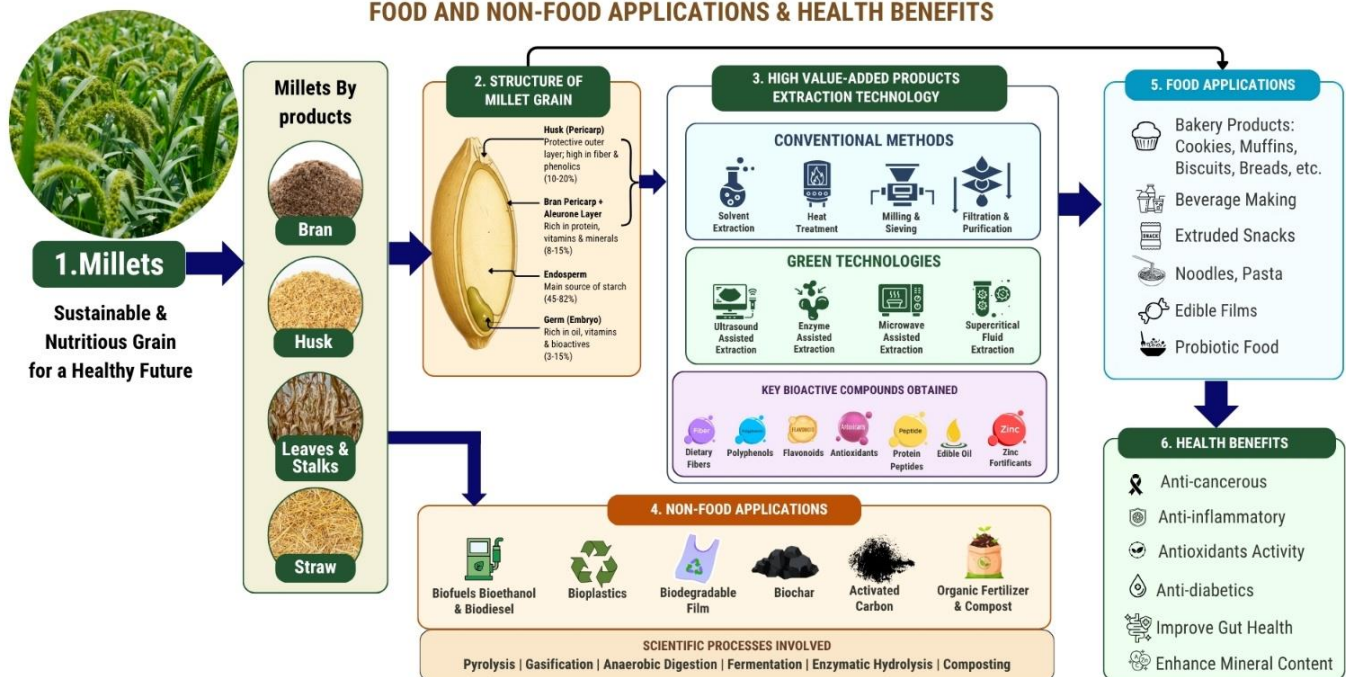
Table 1. Husk and Bran By-Products Nutritional Value:

By-product	Millet	Proximate analysis (weight %)						Reference
		Moisture (%)	Fat (%)	Protein (%)	Fiber (%)	Carbohydrates (%)	Ash (%)	
Husk	Pearl	11.27	6.42	9.48	-	69.57	2.05	Kaur <i>et al.</i> , 2025
Husk	Finger	8.45	1.7	8.94	25.26	43.28	12.37	Joby <i>et al.</i> , 2025
Husk	Barnyard	11.7	2.4	7.27	18.08	48.98	11.57	Joby <i>et al.</i> , 2025
Husk	Kodo	9.67	3.5	6.6	15.62	57.48	7.13	Joby <i>et al.</i> , 2025
Husk	Little	6.8	4.76	8.87	7.6	69.9	2.07	Indirani <i>et al.</i> , 2021
Husk	Proso	9.4	5.1	12.9	8.5	61.8	2.3	Li <i>et al.</i> , 2022
Husk	Foxtail	-	0.62	4.64	-	-	-	Kaur <i>et al.</i> , 2025
Bran	Pearl	10.5	9.38	11.02	78.8	64.3	3.6	Kaur <i>et al.</i> , 2025
Bran	Sorghum	8.29	5.34	11.58	-	64.18	2.36	Kaur <i>et al.</i> , 2025
Bran	Finger	8.29	9.39	12.48	51.69	10.65	7.5	Kittur <i>et al.</i> , 2024
Bran	Barnyard	8.5	4.2	11.2	45.8	25.3	5	Kittur <i>et al.</i> , 2024
Bran	Kodo	7.07	2.83	4.92	48.42	31.43	5.33	Kittur <i>et al.</i> , 2024
Bran	Little	9.75	2.1	8.42	46.2	28.53	5	Indirani <i>et al.</i> , 2021
Bran	Proso	8.5	9	14	36	26	6.5	Kittur <i>et al.</i> , 2024; Li <i>et al.</i> , 2022
Bran	Foxtail	5.13	5.4	5.57	72.61	3.63	-	Kaur <i>et al.</i> , 2025

The considerable amounts of bran and husk generated during millet processing an important source of nutrient-rich by-products with potential applications in food, feed, bioenergy, and other value-added sectors. Valorisation is the process that involves waste (Husk, bran, and straw) used for the preparation of functional food, bio-energy, and antioxidant applications (Tagade & Sawarkar, 2023).

Figure 1: Millet By-Products Applications in Food and Non-Food Sector:

MILLETS BY-PRODUCT UTILIZATION: FOOD AND NON-FOOD APPLICATIONS & HEALTH BENEFITS



Millet by-Product Application in Food and Non-Food Sectors

Valorization techniques used for the extraction of high-value components from the millet by-products using conventional methods such as drying, Milling, fermentation, hydrolysis, solvolysis, pyrolysis and gasification, composting, anaerobic digestion, biorefining, hot water method, solvent extraction, and chemical treatment (Ravichandran & Dixit, 2025). Green technologies recommended for millet waste utilization include microwave-assisted extraction, ultrasound, supercritical fluid extraction, sequential extraction, supercritical water extraction, and enzyme-assisted extraction (Kaur *et al.*, 2025). By utilizing these techniques, various products and extraction from the millet by-products are used for making functional food products. Proso millet bran 10% incorporation used in breads, muffins, and biscuits, which improves dietary fibre and polyphenol content. Xylose oligosaccharide made from the finger millet bran is used in cookies, exhibiting more antioxidant characteristics i.e 12% of antioxidant activity. Bran from finger millet, rich in polyphenols and amino acids is used for making wine products. Biodegradable film made by mixing millet husk, poly lactic acid, along with water, improves the tensile strength and enhances its biodegradable properties. 1 % of finger millet extract could be utilized in film, which provides good mechanical strength, 65% higher thickness, and increased film opacity. Millet by-product utilization in terms of the non-food sector helps to maintain sustainability in the environment and is also a part of the circular economy principle, such as animal feeds, biofuels (bioethanol, biodiesel, etc.), biomaterials (Bioplastics, bio-composites, Fertilizers, activated carbon, etc.). Pyrolysis is the thermochemical treatment used for energy recovery by converting biomass into biofuel and syngas under controlled oxygen conditions at temp. 300-700 °C (Kaur *et al.*, 2025). Gasification, in which carbon-rich residue is used for the production of combustible gas for renewable energy generation (Kaur *et al.*, 2025). Anaerobic digestion occurs in the absence of oxygen conditions, and microorganism culture for degradation produces methane-rich biogas. Process of fermentation and hydrolysis, which convert cellulose and hemicellulose parts into sugar and bioethanol (Ravichandran & Dixit, 2025). By using all these technical ways, cutting down waste and turning leftovers into useful meals, biofuels, and biomaterials, millet by-products promote sustainable development. Through recycling, reuse, and effective resource use, these procedures advance the ideas of the circular economy. Making bioenergy from millet by-products also lessens reliance on fossil fuels and reduces pollution in the environment.

Table 2. Examples for Utilization of the by-product of millet:

Sr. No.	Millet	By-product	Application/Process	Key Benefits	Reference
1	Foxtail Millet	Bran Fiber	Functional Food Ingredients added to food products	Cholesterol-lowering effect	(Zhu <i>et al.</i> , 2018)
2	Proso Millet	Bran Rich Fraction	Gluten-Free Bread with the addition 10% bran fraction	Increases dietary fibre and phenolic content	(Mustač <i>et al.</i> , 2020)

3	Finger Millet	Bran of Proso Millet	Addition of Bran of proso millet (10 %), cryo-ground buckwheat husk (2 %) in Biscuits	High antioxidant, polyphenols, minerals	(Palaniappan <i>et al.</i> , 2017)
4	Foxtail Millet	Bran	Bran Fermentation Antioxidant Wine	Rich in antioxidant phenolics	(Guo <i>et al.</i> , 2018)
5	Barnyard Millet	Bran Rich Fraction	Branyard millet bran fraction addition to the Buns & Muffins	Decreases Antinutritional content	(Nazni & Karuna, 2016)
6	Foxtail Millet and Kodo	Bran Rich Fraction	Bun - 20% foxtail Bran rich fraction Muffins - 30% Kodo Bran rich fraction	Enhanced Nutritional components, Reduced glycemic index	(Barbhai <i>et al.</i> , 2021)
7	Millet	Bran Proteins	Food Additive: Protein extraction	Good nutritional functionality	(Hadidi <i>et al.</i> , 2023)
8	Foxtail Millet	Bran Oil	Food Additives: Edible Oil Extraction	Rich in linoleic acid & tocopherols	(Hadidi <i>et al.</i> , 2023)
9	Millet	Protein Hydrolysate	Zinc Fortificant (SDDVL Peptide)	Strong zinc-chelating ability; potential bioavailable zinc fortificant for functional foods	(Liang <i>et al.</i> , 2010)

Conclusion

Millet significance in food production, consumption, and processing has drawn more attention in recent years. They have a comprehensive nutritional profile that includes several bioactive substances, dietary fiber, and polyphenols. Large amounts of bran and husk are produced as by-products during the processing of millet. The circular economy's core principle encourages reducing waste and increasing resource efficiency, generating extra revenue via residue processing. Through processes such as pyrolysis, millet bran and husk can be valorized to create bioenergy and other value-added products, supporting the sustainable use of biomass. Additionally, these by-products are abundant in minerals (calcium, iron, zinc, chromium), vitamins (B, C, and E), bioactive components (phenols, flavonoids, dietary fibre, and bioactive peptides), which lead to several health-promoting qualities, such as anti-inflammatory, antidiabetic, antioxidant, and anticancer effects. Hence, Millet could be treated as the next-generation climate-resilient smart crop for our sustainable future.

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Beyond Yield: Climate Change Impacts on Crop Nutritional Composition

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Gopakumar Pillai¹, Sanika Ranadive¹

¹Department of Biotechnology, Pillai College of Arts, Commerce and Science (Empowered Autonomous),
New Panvel, Navi Mumbai, Maharashtra, India.

Abstract

Climate change is increasingly affecting not only crop productivity but also the nutritional quality of major food crops. Elevated CO₂ levels, heat stress, drought, salinity, and soil degradation alter the nutritional composition of staple crops such as wheat and rice by reducing protein, iron, zinc, and vitamin content while increasing carbohydrate accumulation. These changes may contribute to “hidden hunger,” a condition in which caloric intake is sufficient but essential nutrient intake remains inadequate. Among climate-related factors, elevated atmospheric CO₂ has emerged as a major driver of nutrient dilution in crops. This review summarizes the major mechanisms underlying climate-induced nutritional decline, including carbon-nutrient imbalance and reduced nitrogen assimilation, and discusses potential mitigation strategies such as climate-resilient breeding, biofortification, improved agronomic practices, and crop diversification to support future food and nutritional security.

Keywords: Climate Change, Carbon - Nutrient Dilution, Hidden Hunger, Biofortification.

Introduction

Atmospheric CO₂ concentrations have risen from about 280 ppm in the pre-industrial era to nearly 425 ppm today and are projected to approach 550 ppm by 2050-2065. Along with rising temperatures, drought, and soil salinity, elevated CO₂ is affecting both crop productivity and nutritional quality by reducing protein, iron, zinc, and vitamin content in major food crops. This is particularly concerning because wheat, rice, and maize provide nearly half of the world's caloric intake and are major sources of dietary protein and micronutrients. These changes may increase the prevalence of “hidden hunger,” where populations consume adequate calories but insufficient essential nutrients. [1].

Elements Associated with Climate Change that Affect the Nutritional Quality of Crops

Climate change continually threaten both the quality of nutrition from food as well as the adequacy of food production.

1. Elevated Atmospheric Carbon Dioxide: FACE (Free Air CO₂ Enrichment) studies have shown that elevated CO₂ increases photosynthesis by about 30% and crop yield by nearly 18% [2]. However, these gains are often accompanied by reductions of 5-10% in zinc, iron, and protein concentrations in major cereal crops such as wheat, rice, and soybean [3]. Although higher atmospheric CO₂ promotes plant growth by increasing carbon accumulation, nutrient quality may decline due to impaired nitrogen utilization. Elevated CO₂ can reduce effective nitrate assimilation, leading to lower organic nitrogen availability and decreased nutritional quality despite increased biomass production [4].

The CO₂ Fertilization Effect: Elevated atmospheric CO₂ enhances photosynthesis in C3 crops such as wheat, rice, and soybean by increasing carbon fixation through the enzyme Rubisco, leading to higher biomass production and grain yield. Increased CO₂ also improves water-use efficiency by partially closing stomata and reducing water loss [5,6]. However, faster crop growth under elevated CO₂ often causes nutrient dilution, where rapid starch accumulation reduces the concentration of proteins and essential minerals such as iron, zinc, calcium, magnesium, and nitrogen. Reduced stomatal opening further limits nutrient uptake through decreased transpiration. As a result, staple crops may become more energy-rich but nutritionally poorer, with potential negative effects on human nutrition as well as herbivore and insect growth and reproduction [3,7].

2. Heat Stress: High temperatures during crop growth adversely affect plant metabolism, reducing both yield and nutritional quality. Heat stress shortens the grain-filling period, disrupts enzyme activity, and limits nutrient accumulation, leading to lower starch, protein, and mineral content. Elevated temperatures also impair root development and nutrient uptake, particularly of iron, zinc, and phosphorus. In addition, heat stress alters nitrogen metabolism, reduces essential amino acids, and increases oxidative stress, resulting in the degradation of antioxidants and water-soluble vitamins such as vitamin C and B vitamins. These combined effects ultimately diminish the nutritional value of major food crops [8].

2. Drought Stress: Drought stress significantly reduces crop quality by impairing photosynthesis, nutrient uptake, and metabolic activity [9]. Dry soil conditions restrict root growth and limit the absorption and transport of essential nutrients such as nitrogen and phosphorus. Combined heat and drought stress can cause even greater damage than either stress alone. Drought also reduces nitrogen fixation in legumes, weakens carbohydrate transport, and lowers nutrient density through reduced Rubisco activity. In addition, increased oxidative stress under drought conditions generates reactive oxygen species that damage plant cells and accelerate nutrient degradation.

2. Salinity and Soil Degradation: Soil salinity and degradation significantly reduce crop nutrition and productivity by disrupting nutrient uptake and transport within plants. High salt concentrations interfere with the absorption of essential nutrients such as potassium, calcium, magnesium, iron, zinc, and boron, leading to reduced protein synthesis, enzyme activity, and overall crop quality [10,11]. Salinity can also promote the accumulation of harmful elements in plant tissues. Climate change further intensifies salinity through drought, increased evaporation, and saltwater intrusion, ultimately accelerating nutrient loss and contributing to hidden hunger [10,11,12].

Nutritional Decline in Major Food Crops

Nutrient depletion refers to the reduction of essential vitamins, minerals, and micronutrients in food crops due to soil degradation and intensive agricultural practices. Studies indicate that the levels of important nutrients such as iron, zinc, and magnesium in major crops including wheat, rice, and vegetables have declined considerably over the past several decades [1,13]. Major contributing factors include modern breeding practices focused on yield and pest resistance rather than nutrient density, soil nutrient exhaustion from intensive farming, and elevated atmospheric CO₂ levels, which increase carbohydrate accumulation while reducing protein and mineral concentrations in crops.

1. Cereals:

Wheat: Elevated CO₂ levels (550-600 ppm) are associated with reductions of approximately 5-15% in wheat protein content, along with declines in important micronutrients such as iron and zinc. Rapid carbohydrate accumulation under elevated CO₂ causes a dilution effect, producing grains with higher starch content but lower nutritional quality [14].

Rice: Rice, a major staple food for a large global population, is also vulnerable to climate-induced nutrient decline. Rising CO₂ levels are projected to reduce several B vitamins and essential minerals such as iron and zinc. Long-term studies have reported significant declines in zinc and iron concentrations in rice over recent decades. Nutrient losses are further intensified by milling and polishing processes, resulting in rice that is energy-rich but nutritionally poor [15].

Maize: Maize, a C₄ crop, is comparatively less affected by the carbon dilution effect under elevated CO₂ conditions because of its efficient CO₂-concentrating mechanism. However, high CO₂ levels can still reduce dietary protein and important minerals such as iron, zinc, phosphorus, and potassium. Elevated CO₂ may also alter lignin composition, affecting fodder quality. Due to better nitrogen and water-use efficiency, maize and other C₄ crops generally perform better under heat and drought stress, helping maintain more stable nutrient quality under changing climatic conditions [3].

2. Legumes: Legumes such as soybean, lentil, chickpea, and field pea are also vulnerable to climate-induced nutritional decline. Elevated CO₂ levels reduce nitrogen assimilation and grain protein concentration, with soybean protein reported to decline by nearly 5%. Important micronutrients such as iron and zinc are also negatively affected, while heat stress further reduces protein, starch, and reproductive performance, particularly in lentils and chickpeas [16]. Long-term studies have reported substantial declines in zinc and iron concentrations in legumes over recent decades. In addition, breeding strategies focused mainly on higher yield may unintentionally compromise protein quality and nutrient density in these crops [17].

3. Fruits & vegetables: Modern fruit and vegetable varieties have become noticeably less nutrient dense as breeding and production have prioritized yield, size, sweetness, and shelf life over mineral and vitamin content. Long-term studies report reductions in iron, calcium, magnesium, copper, phosphorus, and several B vitamins, along with variable but generally decreasing vitamin C levels. Increased yields, higher water content, and elevated CO₂ levels further contribute to nutrient dilution by increasing sugar accumulation while reducing protein and mineral concentrations. As a result, many modern crops now provide lower nutrient density despite improved productivity and appearance.

Mechanisms Behind Nutritional Decline

Food has lost quality and nutrition at an alarming rate because of various intertwined causes of this phenomenon called 'hidden hunger' in our diets today.

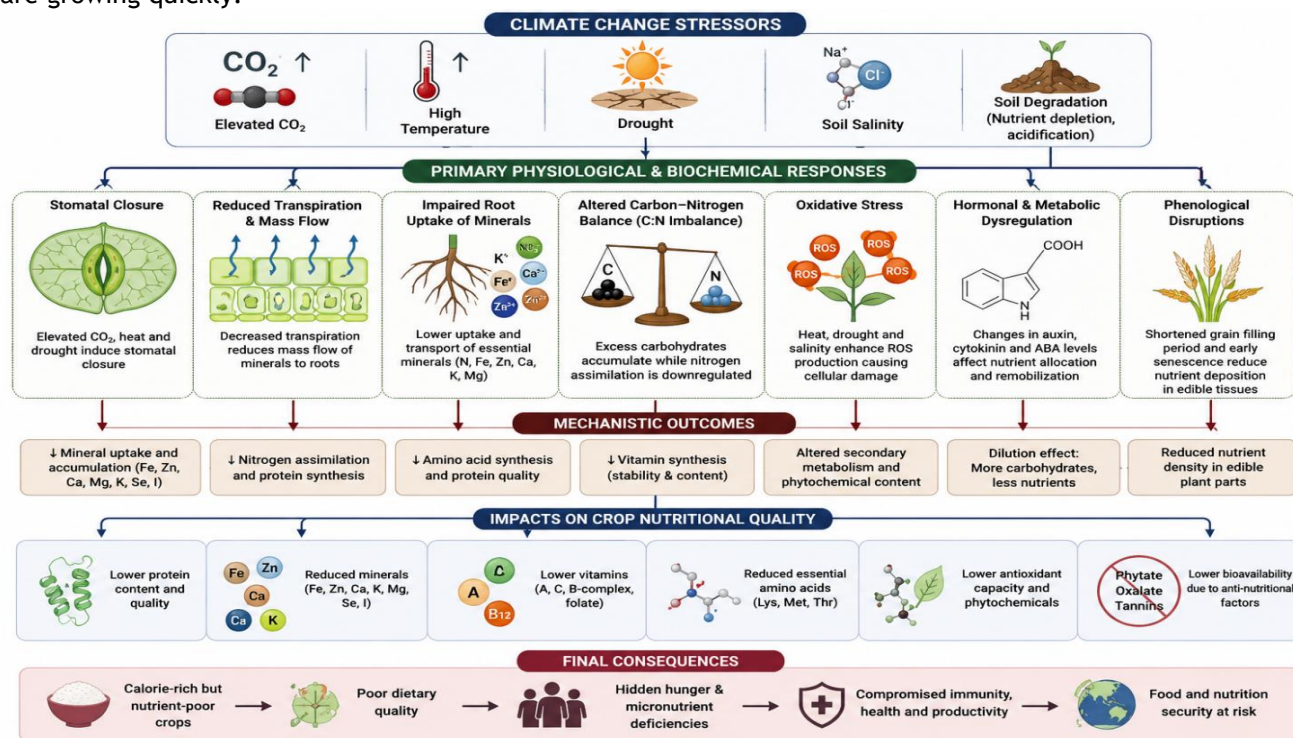
1. Carbon - Nutrient Dilution Effect: The carbon nutrient dilution phenomenon of ultimate emergence whereby as levels of CO₂ have increased and led to higher rates of plant growth, crops (generally C₃ crops such as wheat and rice) are now producing more starches (carbohydrates), leading to lower levels of fats (lipids), micronutrients (iron/zinc), etc., than before.

Figure 1. Proposed mechanisms underlying climate change-induced decline in crop nutritional quality.

2. Variation in Nitrogen Metabolism: Changes in nitrogen metabolism, essentially related to limitations in the action of nitrate reductase (NR), which is essential for the reduction of nitrates to ammonium (NH₄⁺) in plants. With the increase of CO₂, there are earlier inhibitions in the ability of plants to assimilate nitrate, resulting in the limited production of amino acids/proteins that are essential for plant growth [18].

3. Reduced Mineral Uptake and Water Loss: Elevated CO₂ causes plants to have less wide stomatal openings which will cause less transpiration (water movement carrying minerals from the soil to the leaves) and therefore to have less water

movement for the uptake of main nutrients such as iron and zinc, causing plants to be deficient in nutrients even though they are growing quickly.



4. Metabolic and Oxidative Stress: Environmental stresses such as heat, drought, and salinity disrupt normal cellular processes and increase the production of reactive oxygen species, leading to oxidative damage in plant cells. These stresses impair photosynthesis, nutrient uptake, enzyme activity, and antioxidant production, ultimately reducing plant growth and survival. Elevated CO_2 further alters nitrogen metabolism and promotes excessive carbohydrate accumulation, which dilutes protein and mineral concentrations. Under stress conditions, plants also divert energy toward protective compounds such as proline and phenolics rather than improving nutritional quality. [4].

Consequences for Human Health and Food Safety

Deficiencies of essential micronutrients such as iron, zinc, vitamin A, iodine, and folate can impair growth, cognitive development, immunity, and reproductive health, particularly in children and pregnant women. Iron deficiency anemia remains a major global health concern, causing fatigue and pregnancy-related complications. In addition, diets rich in calories but poor in nutrients are increasingly associated with chronic diseases such as diabetes and cardiovascular disorders [19]. Climate change and declining soil fertility also threaten food security by reducing crop quality, destabilizing yields through extreme weather and water scarcity, and increasing food prices, thereby limiting access to diverse and nutrient-rich foods [17].

Mitigation and Adaptation Strategies

To address the loss of crop nutrients from elevated levels of CO_2 as well as the impacts of emerging climate change scenarios, there are two main strategies to employ: mitigation through a reduction in the underlying factors contributing to loss and adaptation which includes modifying agricultural production systems to maintain both food quality as well as resilience against rapid environmental changes.

1. Cultivating Resilient Nutrition-Rich Varieties: Biofortification and climate-resilient breeding strategies are being used to develop crop varieties with improved tolerance to heat, drought, salinity, and waterlogging while maintaining higher nutritional quality [20]. Conventional breeding, marker-assisted selection, and related approaches have enabled the development of nutrient-rich crops such as iron-rich pearl millet, zinc-enriched rice, and provitamin A-rich sweet potato to help address micronutrient deficiencies and hidden hunger.

2. Reducing Root Cause by Agronomic Interventions: Efficient agronomic practices can help maintain crop nutritional quality under climate change. Drip irrigation improves water and nutrient uptake, while zero tillage and residue retention enhance soil organic matter and nutrient availability. Precision fertilization using AI systems optimizes nutrient application and reduces waste. Biofertilizers improve soil health and nutrient absorption, whereas agroforestry and cover crops support carbon sequestration and nutrient cycling. Improved fertilizer management and slow-release nanofertilizers can further reduce nutrient loss and environmental impacts. Integrated farming systems combining crops, livestock, and trees also promote sustainable nutrient recycling and reduce dependence on external inputs [20].

3. Genetic Approach: Genetic approaches such as genetic engineering, metabolic engineering, genome editing (CRISPR/TALENs), and marker-assisted selection (MAS) are being used to enhance the nutritional quality of crops by increasing the levels of essential vitamins, minerals, amino acids, and bioactive compounds, while also improving nutrient retention and accelerating the development of nutrient-rich crop varieties [20,21]. Examples include high zinc wheat and rice (Formulate zinc translocation to grains, to provide a solution for zinc deficiency), Plants Engineered to Create Beta Carotene, Golden Rice A solution for Vitamin A Deficiency.

4. Crop Diversification: Crop diversification with resilient C4 and orphan crops can help maintain nutritional security under climate change. C4 crops such as sorghum, maize, sugarcane, and millets use water and nitrogen more efficiently, tolerate heat and drought better, and are less affected by CO₂-induced nutrient dilution [22]. Millets are particularly valued for their high nutritional content and adaptability to poor soils and low water conditions. Similarly, orphan crops such as cowpea, pigeon pea, taro, cassava, and Bambara groundnut possess greater resilience to drought, salinity, and diseases while also providing important vitamins and minerals [23].

Research Gaps and Future Perspectives

Key research gaps remain in understanding climate-induced nutritional decline in crops. Long-term, multi-location studies are needed to better assess nutrient changes and soil interactions over time [24]. More FACE (Free Air CO₂ Enrichment) studies across diverse crops, soils, and climatic regions—especially in nutritionally vulnerable developing countries—are also required. Future research should focus on the combined effects of elevated CO₂, heat, and drought stress rather than studying these factors individually [25]. The absence of a standardized global database on crop nutritional composition further limits comparative analyses and meta-studies [25]. Addressing these challenges will require multidisciplinary approaches integrating plant physiology, nutrition, climate science, and advanced technologies such as genomics-assisted breeding and CRISPR to develop climate-resilient and nutrient-rich crops.

Conclusion

Climate change threatens the balance between crop yield and nutritional quality, making food security a growing global concern. Addressing this challenge will require coordinated efforts in climate-resilient agriculture, sustainable soil and water management, nutrient-focused crop improvement, and supportive policies. Future progress depends on long-term research, transparent nutritional databases, and the adoption of innovative and sustainable farming practices to ensure both food quantity and nutritional quality under changing climatic conditions.

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Text Meets Taste: Leveraging Natural Language Processing (NLP) for Next-Generation Food Science

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Hanuman Anshiram Jadhav¹, Chandrasekar Veerapandian¹, V. Eyarkai Nambi²

^aDepartment of Food Process Technology,

^bDepartment of Food Plant Operations, Incubation and Entrepreneurship,

National Institute of Food Technology, Entrepreneurship and Management, Thanjavur (NIFTEM-T), 613005, Tamil Nadu, India.

Introduction

Unhealthy eating habits involving high levels of consumption of saturated fats, sodium, and sugar are still among the most significant preventable risk factors for NCDs worldwide. With increasing modernization of food production, more than 120,000 branded foods are included in data collection tools such as the FLIP database in the University of Toronto. This development makes current systems of food classification and nutrient profiling inadequate and unsustainable. The current process, which involves human coding, is highly resource intensive and can result in policy implementation delays. Although traditional computational approaches employing bag-of-words methods and binary ingredient occurrence have been utilized to predict nutrient levels, these techniques face challenges with unstructured food label text and lack generalizability across various databases and time periods. Natural Language Processing (NLP), particularly pretrained language models like BERT (Bidirectional Encoder Representations from Transformers), offers a transformative solution by learning contextual relationships between words from extensive text corpora. This study represents the inaugural application of pretrained language models to food label text processing and the first utilization of NLP for nutrient profiling in large-scale food composition databases. By converting complex food label information, including product names, brands, and ingredients, into standardised 384-dimensional vectors and integrating these with supervised machine learning algorithms (XGBoost, KNN, elastic net), researchers achieved remarkable accuracy: 97-98% for food category classification across 172 subcategories and 87% prediction accuracy for nutrition quality scores. This automated approach not only surpasses traditional methods but also provides a rapid, cost-effective, and highly generalizable solution for monitoring dynamic food environments and evaluating nutrition policies globally (Hu et al., 2023).

How NLP is Transforming Food Science

In addition to being responsible for nearly 30% of global greenhouse gas emissions, the global food system is also associated with the state of public health where more than 60% of adults in industrialized countries are either obese or overweight. The increasing cost of health care because of illnesses caused by unhealthy diets calls for new methods to foster sustainable healthy diets. NLP and AI can provide transformative potential through their applications to analyze nutritional and environmental aspects of food and recipes at a previously unparalleled scale. The applications have already been found in nutritional science, computational gastronomy, allergen detection, and Semantic Web applications among others (Hausmann et al., 2019). Nevertheless, the use of computational techniques to analyze sustainability metrics of recipes needs more development. Numerous barriers block this path: the lack of unified recipe corpora, inconsistency between coding schemes of nutrition databases of key organizations such as the FAO, WHO, USDA, and EFSA, and sustainability data availability problems. Moreover, inconsistencies of linguistic, conceptual, and terminological types occur between information sources (Eftimov et al., 2017). The complexity of linking environmental impact databases to food terminology remains prohibitively time-consuming without advanced AI and NLP tools. Addressing these multifaceted challenges requires an interdisciplinary approach that combines cutting-edge NLP and AI techniques with expert domain knowledge to create comprehensive analytical frameworks for advancing sustainable and healthy food systems globally.

Recipe Generation & Flavour Innovation

Natural Language Processing can prove to be highly effective in the field of recipe generation and taste exploration owing to the ability to process huge volumes of information from recipes and foods. Tokenization, Lemmatization, Part-of-Speech tagging techniques are used to determine the relations between ingredients and the process involved. Pre-trained NLP models like BERT allow one to find novel flavours through transformation of the recipe data into a numerical form. Correspondence analysis, hierarchical clustering algorithms provide further opportunities for exploration of flavours. The problem of distinguishing sensory attributes from other categories is still crucial (Hamilton & Lahne, 2020).

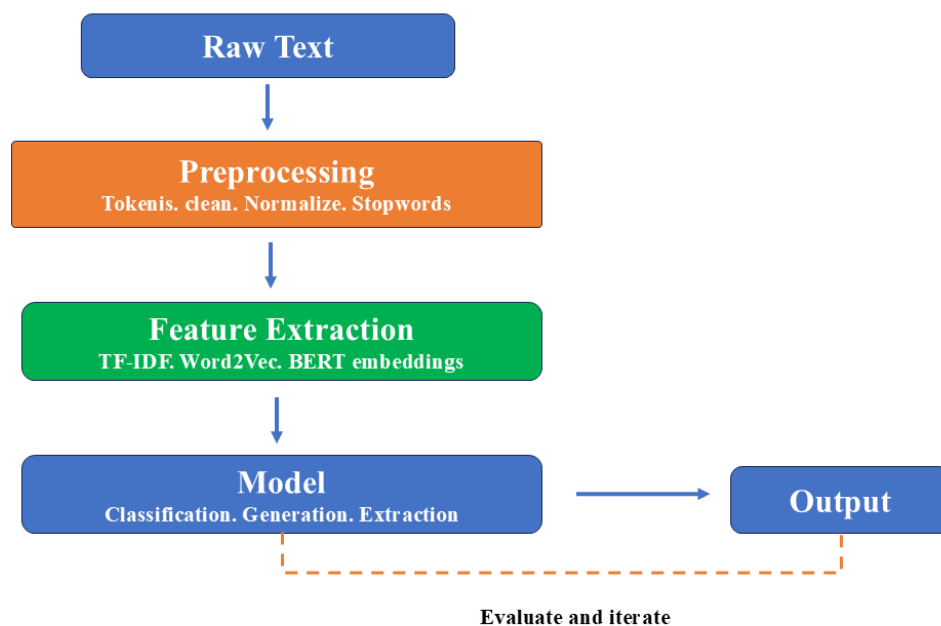


Figure 1 General pipeline for Natural Language Processing (NLP) projects, illustrating the sequential stages from raw text input through preprocessing, feature extraction, and model application to final output, with an evaluation feedback loop for iterative refinement.

Benefits of NLP in Food Science

One of the most valuable benefits that can be provided by Natural Language Processing (NLP) in the modern-day field of food science is that NLP will provide for the analysis of extensive volumes of unstructured textual data, such as recipes, sensory reviews, scientific articles on foods, and consumer opinions. Using the technologies of NLP, researchers will manage to discover the relations between ingredients, flavor combinations, culinary trends, and other characteristics based on multiple recipes, thus helping with recipe writing and innovative products. Such advanced technologies as BERT provide additional opportunities for the understanding of the language related to foods by providing numerical representations of textual data. Moreover, the use of NLP in sentiment analysis will allow food businesses to evaluate consumers' sentiments and market trends using online reviews and social media data. Also, in the sphere of sensory science, NLP will help in structuring flavor descriptions and creating flavor wheels with the help of clustering techniques.

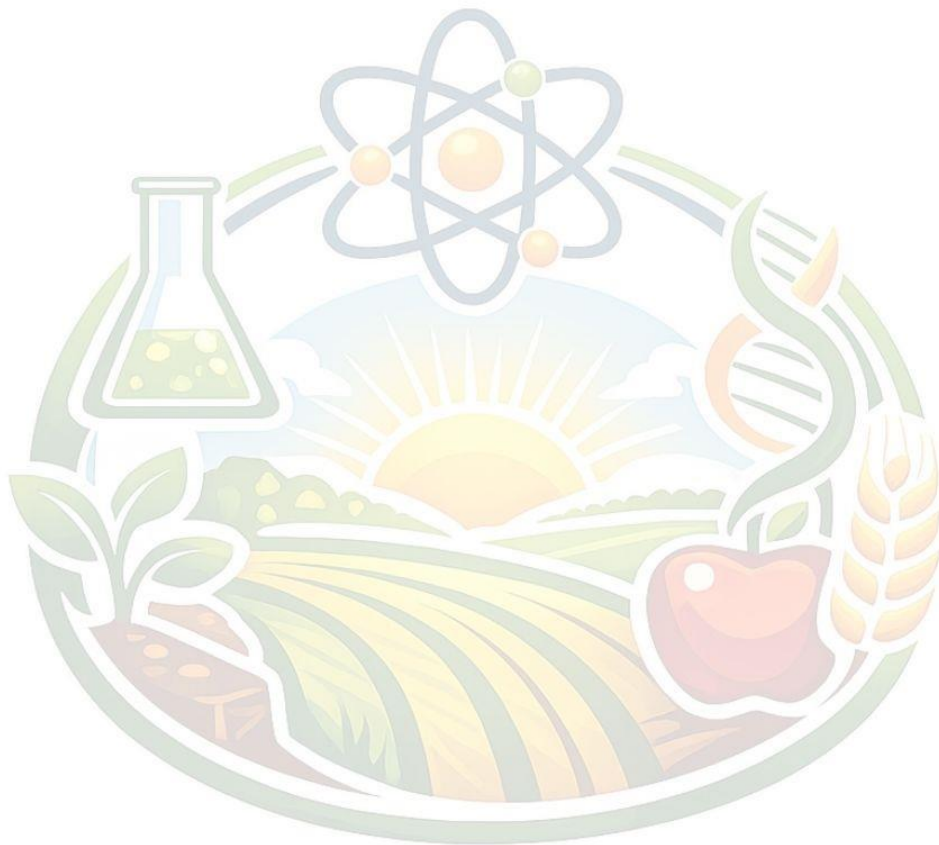
Conclusion

Integration of natural language processing in food science is definitely a groundbreaking approach that makes it easier to tackle food-related problems associated with the contemporary world. By implementing automated tools to examine unstructured information provided by food labels and recipes, NLP can help achieve highly accurate nutrient profiling, classification of foods, and new flavor combinations without spending too much time and resources. The benefits of using NLP are not limited to nutrition only, as the technology can facilitate assessments of sustainability, analyze customer opinions about different foods, and provide sensory evaluation. It might be challenging to overcome difficulties caused by standardizing data or accounting for domain-specific language, but NLP and AI models such as BERT coupled with extensive expertise in the field promise enormous improvements to food research, evaluation of policies and products, and much more.

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AgriCast: From ARIMA to Transformer New Roots in Agriculture

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Raj Shekar M^{1,2}, Sujith Arokia Swamy B^{1,2}, Bhavana Kabber³, Ramya Jagadish⁴

¹ICAR-Indian Agricultural Research Institute, New Delhi, India - 110012.

²ICAR-Indian Agricultural Statistics Research Institute, New Delhi, India - 110012.

³University of Agricultural Sciences, Raichur, Karnataka, India- 584104 ⁴Tamil Nadu Agricultural University, Coimbatore, India- 641003.

Summary

Time series analysis has evolved from classical ARIMA models to deep learning-based Transformer architectures, fundamentally reshaping how agricultural decisions are made. This article traces that journey, highlights applications in crop yield prediction, weather pattern recognition, and market price forecasting, and examines why modern AI frameworks are becoming indispensable tools for the twenty-first century farmer and policymaker.

Introduction

Agriculture has always been a discipline governed by time viz., the rhythm of seasons, the cyclic return of monsoons, the periodic fluctuation of commodity prices. For decades, statisticians and agronomists attempted to capture this rhythm through mathematical models. The Autoregressive Integrated Moving Average (ARIMA) framework, introduced in the 1970s, became the gold standard for agricultural forecasting. Yet as datasets grew larger and the relationships between variables more complex, ARIMA's limitations became apparent. The emergence of machine learning and most recently Transformer-based deep learning architectures, has created a paradigm shift that is quietly revolutionizing the way modern agriculture operates.

The transformation is not merely academic. Farmers in Punjab are now receiving mobile alerts generated by AI models predicting the optimal sowing window. Commodity exchanges in Mumbai process price forecasts derived from neural networks trained on decades of historical data. Irrigation authorities in Maharashtra schedule water releases based on ensemble models that integrate satellite imagery, soil moisture readings and atmospheric pressure - all assembled into a coherent time series. Understanding how these tools evolved and why they matter, is essential for any stakeholder in the agricultural ecosystem.

From Arima to Machine Learning

ARIMA models assume stationarity - the statistical properties of a time series must remain constant over time. For agricultural data, this assumption is frequently violated. Crop yields respond to irregular climate shocks, soil degradation, policy interventions and technological breakthroughs. To overcome, researchers introduced Seasonal ARIMA (SARIMA) and ARIMAX variants that incorporated exogenous variables. These extensions helped, but they still relied on linear relationships and required extensive manual tuning.

Machine learning methods such as Support Vector Regression (SVR), Random Forests and Long Short-Term Memory (LSTM) neural networks offered a fundamentally different approach. Rather than specifying a model structure in advance, these algorithms learned patterns directly from data. LSTM networks, in particular, demonstrated remarkable capability in capturing long-range temporal dependencies - critical when modelling multi-year drought cycles or delayed price responses to production shocks. Studies published in journals such as Computers and Electronics in Agriculture reported forecast accuracy improvements of twenty to thirty percent over classical methods when LSTM models were applied to rice yield prediction across the Indo-Gangetic Plain.

Transformer Revolution

Transformer models, originally designed for natural language processing, have now firmly entered the agricultural domain. Unlike LSTM networks that process sequences step by step, Transformers use a mechanism called multi-head self-attention that evaluates relationships between the time points simultaneously. This allows them to identify complex, non-linear interactions across very long sequences - precisely what is needed when analysing thirty years of rainfall data alongside corresponding crop production statistics.

Recent architectures such as Temporal Fusion Transformers (TFT) and Informer have demonstrated state of the art performance on agricultural datasets. A study conducted across twelve districts in Madhya Pradesh found that a TFT model, trained on historical wheat yield data combined with Normalized Difference Vegetation Index (NDVI) readings and district-level temperature anomalies, achieved a mean absolute percentage error of 4.3 percent -substantially lower than the 11.7 percent achieved by the best ARIMA variant tested. Such improvements, when scaled across national

planning bodies, translate into billions of rupees in more efficient procurement, reduced food wastage and timely market interventions.

Applications Across the Agricultural Value Chain

Time series forecasting now permeates every node of the agricultural value chain. At the production stage, AI models predict crop health deterioration by analysing sequences of satellite-derived vegetation indices. A sudden downward trend in NDVI values, if detected early, triggers advisory alerts to farmers, enabling preventive pesticide application and potentially saving entire harvests. The National Remote Sensing Centre in Hyderabad has operationalized such systems for kharif crops across multiple states.

At the supply chain and market stage, price forecasting models trained on decades of Agricultural Produce Market Committee (APMC) records help traders, exporters and government agencies anticipate price volatility. The infamous onion price spikes that recur periodically in India are now being studied through spectral analysis and wavelet decomposition - tools that decompose a time series into frequency components, revealing hidden cycles that simple moving averages would miss. Early detection of such cycles enables proactive buffer stock operations that can dampen price shocks before they cascade into a political crisis.

Challenges and the Road Ahead

Despite their promise, advanced time series models face significant challenges in agricultural deployment. Data quality remains a persistent issue many mandis and state agriculture departments maintain incomplete or inconsistently recorded datasets that undermine model performance. The interpretability of deep learning models is another concern; while a Transformer may outperform ARIMA statistically, a policymaker needs to understand why a particular forecast was generated to act on it confidently.

Hybrid approaches that combine the interpretability of classical econometric models with the predictive power of deep learning are emerging as a practical middle ground. Explainable AI (XAI) techniques such as SHAP (SHapley Additive exPlanations) are being applied to agricultural forecasting models, allowing analysts to decompose predictions and attribute specific forecast changes to identifiable drivers such as a rainfall deficit or a sudden spike in input costs.

Conclusion

The journey from ARIMA to Transformers in agricultural time series analysis reflects a broader maturation of data science as a field. Classical models provided the foundation - rigorous statistical thinking, attention to stationarity, and disciplined parameterisation. Machine learning expanded the scope by learning patterns without preconceived structural assumptions. Transformer architectures are now pushing the frontier further, enabling real-time, high-accuracy forecasting at scales previously unimaginable.

For Indian agriculture, which supports the livelihoods of hundreds of millions and accounts for approximately sixteen percent of GDP, these tools are not luxuries - they are necessities. Investment in data infrastructure, model transparency and capacity building among agricultural scientists will determine how effectively this technological revolution translates into tangible improvements in farm income, food security and climate resilience.

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No More Gambling: Monsoon is not a Coin Toss Anymore

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Raj Shekar M^{1,2}, Ramya Jagadish³, Sujith Arokia Swamy B^{1,2}, Bhavana Kabber⁴

¹The Graduate School, ICAR-Indian Agricultural Research Institute, New Delhi, India - 110012.

²ICAR-Indian Agricultural Statistics Research Institute, New Delhi, India - 110012.

³Tamil Nadu Agricultural University, Coimbatore, India- 641003.

⁴University of Agricultural Sciences, Raichur, Karnataka, India- 584104.

Summary

Predicting rainfall patterns and anticipating drought conditions are among the most consequential scientific challenges facing agricultural nations. This article examines how AI and machine learning techniques are advancing hydrometeorological forecasting, analyses their performance relative to conventional numerical weather prediction models and discusses their implications for water resource management and agricultural planning in monsoon-dependent economies.

Introduction

Water is the lifeblood of agriculture, and its spatial and temporal distribution - through rainfall, river flow, groundwater recharge, and evapotranspiration - determines crop production outcomes across the world. In India, where approximately fifty-five percent of agricultural land remains rain-fed and the Southwest Monsoon delivers seventy to ninety percent of annual precipitation in a four-month window, the predictability of rainfall is not an academic curiosity but a matter of national food security and economic stability. Conventional weather forecasting relies on Numerical Weather Prediction (NWP) - the simulation of atmospheric dynamics through massive systems of differential equations solved on supercomputers. Despite substantial advances, NWP systems struggle with sub-seasonal to seasonal forecasts beyond two weeks, particularly in complex orographic terrain and during transitional monsoon phases characterised by high atmospheric variability. Drought forecasting, which requires predicting the sustained absence of rainfall over months or seasons, is even more challenging.

Artificial intelligence offers a fundamentally different approach to these problems. Rather than simulating physical processes from first principles, AI models learn statistical relationships from historical data recognising patterns in sea surface temperatures, soil moisture anomalies, atmospheric pressure gradients, and vegetation indices that precede rainfall deficits or surpluses. Recent advances suggest that AI systems may be capable of forecasts that match or surpass operational NWP models on certain metrics, at a fraction of the computational cost.

AI Approaches to Rainfall Prediction

Several distinct AI methodologies have been applied to rainfall prediction. Artificial neural networks (ANNs) trained on historical monsoon data were among the first machine learning tools deployed in hydrology, establishing that statistical learning could capture non-linear relationships between atmospheric precursors and Indian Summer Monsoon Rainfall (ISMR). Subsequent decades saw the application of support vector machines, random forests, and gradient boosting algorithms, each offering improvements in handling high dimensional predictor spaces.

The most significant recent advance has been the application of deep learning architectures. Convolutional neural networks applied directly to gridded atmospheric data - treating three-dimensional atmospheric state variables as multi-channel spatial images have demonstrated the ability to detect spatially coherent patterns associated with monsoon onset and withdrawal. LSTM networks, sensitive to sequential dependencies, capture the temporal propagation of climate signals such as the Madden-Julian Oscillation (MJO), which is a primary driver of intraseasonal monsoon variability.

Google DeepMind's GraphCast model and Huawei's Pangu-Weather model, both released in 2023, represented landmark demonstrations that AI systems trained on the ERA5 global reanalysis dataset could produce ten-day weather forecasts at horizontal resolutions of 0.25 degrees approximately 28 kilometres with accuracy matching or exceeding the ECMWF (European Centre for Medium-Range Weather Forecasts) operational model, which has long been considered the gold standard of global NWP. The speed advantage was equally dramatic: GraphCast generated a ten-day forecast in under one minute, compared to several hours for operational NWP systems.

Drought Prediction and Early Warning

Drought prediction requires forecasting the sustained and widespread deficit of rainfall over periods spanning weeks to seasons. It is intrinsically more difficult than short-range precipitation prediction because it depends on slowly evolving

boundary conditions particularly sea surface temperature patterns such as El Nino-Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) that influence large-scale atmospheric circulation over extended time horizons.

AI models have shown particular promise in exploiting ENSO and IOD signals for seasonal drought prediction. Studies at the India Meteorological Department (IMD) and at various academic institutions have demonstrated that ensemble learning models combining multiple atmospheric teleconnection indices can produce categorical drought probability forecasts three to six months in advance with skill scores that exceed seasonal ensemble NWP forecasts for a majority of Indian agroclimatic zones.

The Drought Early Warning System (DEWS) developed by the National Drought Mitigation Centre in the United States, which has served as a model for similar initiatives globally, is increasingly incorporating machine learning components. In India, the National Remote Sensing Centre's drought monitoring platform integrates satellite-derived vegetation health indices, standardised precipitation indices, and soil moisture anomaly products all processed through machine learning pipelines that generate weekly drought severity maps at district resolution.

Limitations of AI in Weather and Drought Forecasting

The enthusiasm surrounding AI weather prediction must be tempered by an honest assessment of its limitations. AI models are fundamentally data-driven - they excel at recognising patterns that have appeared in their training data but may fail in novel conditions that fall outside historical experience. Climate change is systematically pushing weather systems into regimes with no historical precedent - intensifying extreme rainfall events, shifting monsoon onset and withdrawal dates, and creating unprecedented compound drought-flood sequences. An AI model trained on pre-climate-change data may be structurally ill-equipped to forecast these emergent patterns accurately.

Physical consistency is a further concern. NWP models are grounded in conservation laws - energy, mass, and momentum are conserved in their forecasts. AI models have no such guarantee; they can produce physically implausible outputs that a domain expert would immediately recognise as unrealistic. Hybrid physics-informed AI models that embed physical constraints into neural network architectures are an active research frontier that may resolve this tension.

Conclusion

Artificial intelligence is demonstrably advancing the science of rainfall and drought prediction. Deep learning systems trained on global reanalysis datasets are producing medium-range weather forecasts with accuracy that rival decades of NWP development. Seasonal drought prediction models exploiting ENSO and IOD teleconnections are generating early warnings that can inform agricultural planning and water resource management months in advance.

In India, where monsoon variability shapes the food security of hundreds of millions of people, investment in AI-based hydrometeorological forecasting infrastructure is a high-return public investment. Integrating AI forecast outputs into agricultural advisory systems, crop insurance products and drought relief trigger mechanisms can translate meteorological intelligence into tangible improvements in rural resilience and national food security.

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Nashik to New Delhi: How Onion Moves Markets and Ministries

Article ID: 73801

Raj Shekar M^{1,2}, Sujith Arokia Swamy B^{1,2}, Bhavana Kabber³, Ramya Jagadish⁴

¹The Graduate School, ICAR-Indian Agricultural Research Institute, New Delhi, India - 110012.

²ICAR-Indian Agricultural Statistics Research Institute, New Delhi, India - 110012.

³University of Agricultural Sciences, Raichur, Karnataka, India- 584104.

⁴Tamil Nadu Agricultural University, Coimbatore, India- 641003.

Summary

Sudden and severe onion price spikes are a recurrent feature of India's agricultural economy, triggering consumer distress, political controversy and export disruptions. This article applies a time series analytical framework to dissect the structural and stochastic drivers of onion price volatility, examines how predictive modelling tools can provide early warning and proposes an evidence-based policy architecture for price stabilisation.

Introduction

Among all agricultural commodities in India, few evoke as strong a public reaction as the onion. Price spikes have toppled state governments, forced emergency import orders and consumed acres of newspaper front pages. The onion is not merely a vegetable it is a political barometer. When onion prices double or triple within weeks, the ripple effects reach every household in the country, disproportionately burdening the urban poor who spend a larger share of their income on food.

Yet for all their political drama, onion price spikes are not random events. They are the cumulative outcome of predictable structural features a concentrated production geography, a highly perishable commodity with limited storage, a seasonal supply cycle and a market structure prone to intermediary rent extraction interacting with specific stochastic shocks such as unseasonal rainfall or a sudden export ban reversal. Understanding this interaction through the lens of time series analysis provides not only explanatory insight but a foundation for actionable prediction and policy intervention.

The Structural Anatomy of Onion Price Cycles

India produces approximately 26 million tonnes of onion annually, making it the world's second- largest producer. But production is highly geographically concentrated Maharashtra alone accounts for approximately forty percent of total output, with Nashik district at the epicentre. This concentration means that localised weather events a late-season hailstorm during rabi onion harvesting in Nashik, flooding in Solapur and Pune districts during the kharif season can instantaneously reduce national supply by twenty to thirty percent, with price consequences amplified by inelastic demand.

Onion supply in India follows a tri-seasonal pattern corresponding to three distinct crop cycles: kharif (harvested October-November), late kharif (harvested December-January) and rabi (harvested March-May). The rabi crop accounts for roughly sixty-five percent of annual production and is the critical buffer stock that stabilises prices through the lean June-October period. When rabi crop output falls below expectations whether due to excessive rainfall during sowing, pest damage, or premature post-harvest deterioration the supply shortfall accumulates through the calendar and manifests as a price spike during the subsequent lean season.

This structural feature makes onion price dynamics inherently lagged and seasonal precisely the kind of pattern that time series decomposition techniques such as seasonal-trend decomposition using LOESS (STL) and wavelet multiresolution analysis are designed to extract. Multiple studies have identified a dominant twelve-month seasonal cycle in wholesale onion prices at major APMC markets, superimposed on a lower-frequency three-to-four-year cycle plausibly linked to area expansion and contraction dynamics in response to previous price signals.

The Role of Stochastic Shocks

Overlaid on these structural cycles are stochastic shocks that generate the most dramatic price spikes the events that make newspaper headlines. Unseasonal rainfall during the rabi harvest delays harvesting, increases field losses due to fungal rots and deteriorates stored onion quality. A single high-magnitude rainfall event in Nashik in April or May can destroy fifteen to twenty percent of the standing rabi crop within days, instantly altering supply projections for the following lean season.

Export policy discontinuities represent a second class of shock. India periodically imposes minimum export prices or outright export bans on onions to protect domestic consumers. The abrupt reversal of export restrictions, conversely, rapidly drains domestic supply and triggers price escalation. These policy shocks are difficult to model econometrically

because they are discretionary decisions subject to political economy dynamics rather than systematic rules. However, the market-level price response to export policy announcements follows recognisable patterns that machine learning event-study models can learn to anticipate.

Forecasting Onion Prices

Nashik Onion Weekly Prices Over Time

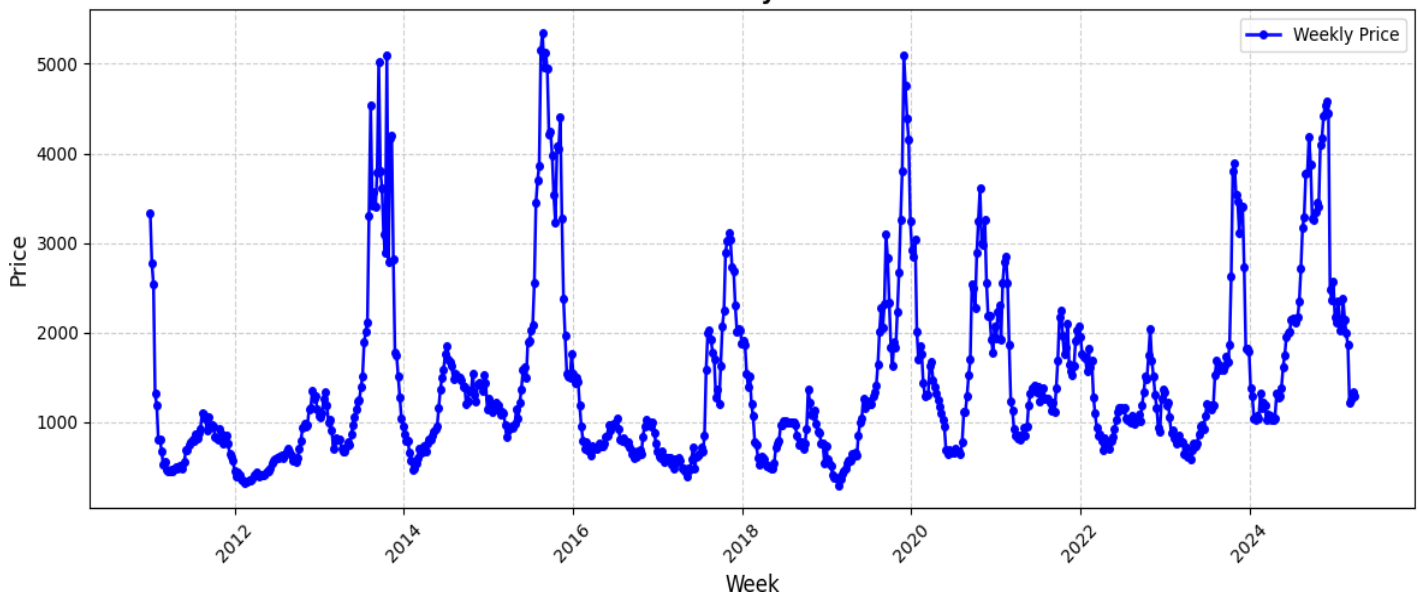


Figure 1: Time plot of weekly Onion price series (2011-2025)

Building a reliable onion price forecasting model requires integrating multiple data streams. The Agmarknet platform (<https://agmarknet.gov.in>), maintained by the Directorate of Marketing and Inspection, provides daily wholesale price data across several hundred APMC markets a rich dataset spanning more than two decades. Supplementary data sources include acreage estimates from the state agriculture departments, post-harvest loss assessments from the National Horticulture Research and Development Foundation (NHRDF), rainfall data from the IMD and cold storage occupancy figures.

Research groups at NHRDF and at academic institutions have demonstrated that ensemble machine learning models incorporating these data streams can produce thirty-day ahead price forecasts with mean absolute percentage errors in the range of 8-12% materially better than naive seasonal benchmarks. LSTM-based models that capture the sequential evolution of price dynamics across the crop calendar have performed particularly well in detecting the inflection points at which prices begin their upward trajectory, providing a critical early warning signal for government procurement agencies.

Policy Implications

The government's principal tool for managing onion price spikes has historically been reactive activating buffer stock releases from the Price Stabilisation Fund, imposing export restrictions, or authorising emergency imports from Egypt, Iran, or the Netherlands. Each of these interventions takes time to execute and by the time they become effective, prices may already have reached crisis levels. A proactive system grounded in AI-powered early warning could fundamentally alter this dynamic.

A thirty-day early warning triggered by an AI forecasting model could give the National Cooperative Exports Limited and the Department of Consumer Affairs sufficient lead time to initiate buffer stock procurement in surplus periods and plan logistics for targeted distribution in price-stressed markets. NHRDF's network of cold storage and irradiation facilities could be activated based on model-generated supply projections rather than emergency responses. Export policy decisions could be calibrated against projected domestic supply balances rather than reacting to market prices already in crisis territory.

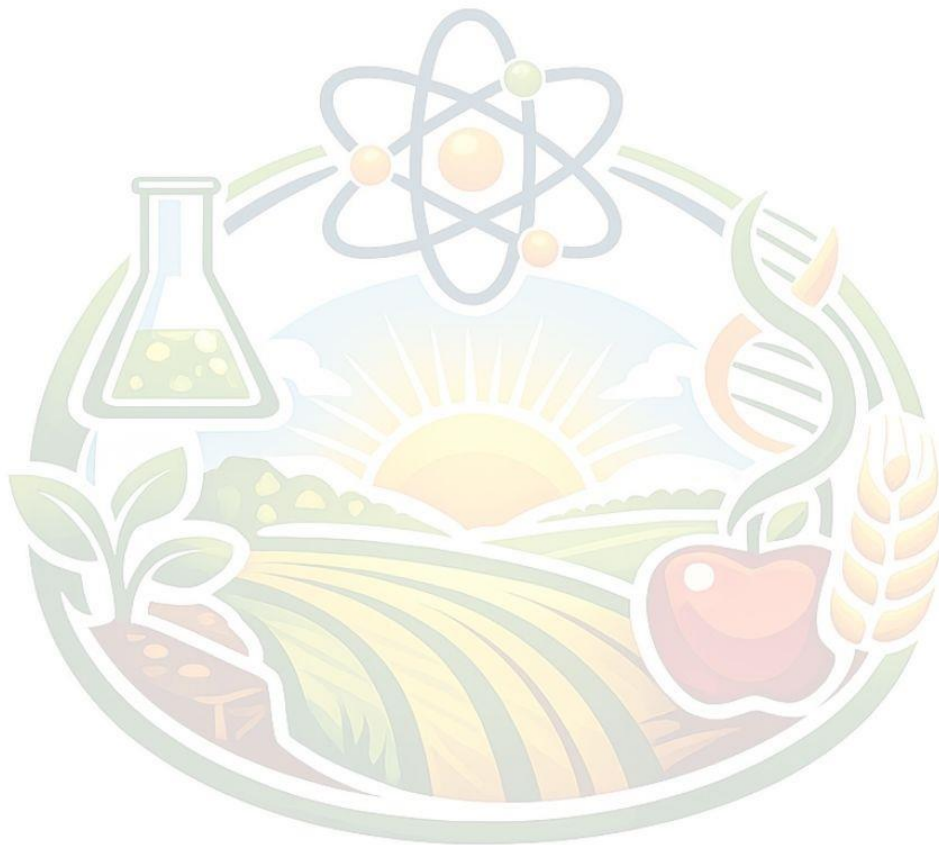
Conclusion

Onion price spikes are not mysteries they are the predictable outcomes of structural supply seasonality interacting with stochastic shocks in a market characterised by geographic concentration, limited storage and inelastic demand. Time series analysis provides both the diagnostic tools to understand these dynamics and the forecasting apparatus to anticipate them. Investment in a national onion market intelligence system integrating satellite-based crop condition monitoring, APMC price data analytics, storage inventory tracking and AI forecasting models offers the prospect of

transforming India's onion price crisis management from a cycle of costly reactive interventions to a regime of informed, proactive stabilisation.

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The Age of Alx: The Next Frontier of Smart Agriculture

Article ID: 73802

R Sujith Arokia Swamy B^{1,2}, Raj Shekar M^{1,2}, Bhavana Kabber³, Ramya Jagadish⁴

¹The Graduate School, ICAR-Indian Agricultural Research Institute, New Delhi, India - 110012.

²ICAR-Indian Agricultural Statistics Research Institute, New Delhi, India - 110012.

³University of Agricultural Sciences, Raichur, Karnataka, India- 584104.

⁴Tamil Nadu Agricultural University, Coimbatore, India- 641003.

Summary

Alx is the intersection of artificial intelligence, edge computing, extended reality and autonomous systems it's heralding a new era in agricultural practice. This article examines how these converging technologies are reshaping farm management, supply chain visibility, agri-finance, extension services and considers the governance frameworks needed to guide the transition toward responsible, inclusive smart agriculture.

Introduction

The agricultural world has witnessed several technological revolutions the mechanisation wave of the early twentieth century, the Green Revolution's seed-fertiliser-irrigation package in the 1960s and 70s and the biotechnology era that followed. A new wave, arguably more sweeping than any of its predecessors, is now gathering force. It is characterised not by any single breakthrough but by the convergence of multiple exponential technologies: artificial intelligence capable of processing complex multi-modal data, edge computing that brings analytical power to the field rather than requiring cloud connectivity, extended reality platforms that deliver immersive training and visualisation and autonomous robotic systems that can perform physical agricultural tasks with minimal human supervision.

The portmanteau Alx captures this convergence - AI extended and amplified by these complementary technologies. In agriculture, Alx is moving the frontier from advisory intelligence (models that recommend what a farmer should do) to autonomous intelligence (systems that act directly, monitoring and adjusting parameters in real time without waiting for human intervention). Understanding this shift, its potential benefits and the risks it creates is essential for scientists, policymakers and agricultural development practitioners navigating this rapidly evolving landscape.

Edge AI: Intelligence at the Field Boundary

A fundamental constraint of first-generation AI applications in agriculture was their dependence on reliable internet connectivity to upload sensor data to cloud servers for processing. In many rural agricultural contexts - particularly in hill districts, tribal areas and regions with underdeveloped digital infrastructure - this dependence was a severe bottleneck. Edge AI resolves this constraint by deploying trained machine learning models directly on low-power processors embedded in field devices, enabling real-time inference without cloud connectivity.

A solar-powered edge AI device mounted on a grain storage unit can continuously analyse temperature, humidity and carbon dioxide concentration readings, detect early signs of fungal infestation and trigger ventilation systems or alert the farmer - all without transmitting a single byte of data to a remote server. Similarly, an edge enabled camera trap on a farm boundary can identify crop-raiding wildlife, distinguish between species and trigger deterrent measures autonomously. These capabilities, previously available only to well-resourced commercial farms, are becoming accessible at price points compatible with cooperative ownership models in India.

Autonomous Systems and Agricultural Robotics

Autonomous agricultural robots represent perhaps the most visually dramatic manifestation of Alx in farming. Weeding robots guided by computer vision models trained to distinguish crop seedlings from weed species are being deployed in vegetable production systems in Europe and Japan and are beginning to appear in pilot programmes in India. Harvest-assist robots for strawberries and tomatoes combine robotic arms with force-sensitive grippers and real-time visual feedback loops to pick fruit at commercial speeds. Aerial drones equipped with multispectral cameras and AI-powered flight path optimisation software can survey several hundred hectares in a single flight, generating crop health maps that field agronomists once spent weeks assembling manually.

India has its own growing ecosystem of agricultural drone operators, supported by the Drone Rules 2021 framework and targeted subsidies under the sub-mission on agricultural mechanisation. Drone service providers are offering pay-per-acre crop spraying services to smallholder farmers, with AI-optimised spray planning that accounts for wind patterns, canopy geometry and pest hotspot maps. Early evaluations suggest pesticide use reductions of fifteen to twenty percent alongside measurable improvements in coverage uniformity.

Extended Reality in Agricultural Extension

Agricultural extension - the transmission of knowledge from research institutions to farmers - has long been a bottleneck in translating scientific advances into on-farm practice. Extended reality technologies, encompassing augmented reality (AR), virtual reality (VR) and mixed reality environments are creating qualitatively new channels for knowledge delivery. VR-based training modules allow farmers to practice operating precision agriculture equipment in simulated environments before deploying it in the field, reducing costly errors during adoption. AR applications that overlay crop health data onto a live camera feed allow extension workers to visualise invisible soil and plant stresses in real time during field visits.

The scalability of XR-based extension is particularly attractive. A single VR training module developed by an institution such as MANAGE (National Institute of Agricultural Extension Management) can be replicated and deployed across thousands of Krishi Vigyan Kendras simultaneously, overcoming the chronic shortage of trained extension personnel that has historically limited the reach of conventional extension programmes.

Governance, Data Rights and Digital Sovereignty

The proliferation of AIx systems in agriculture generates vast quantities of highly sensitive data - detailed records of farm productivity, soil health, irrigation practices, market transactions and financial status. The governance of this data is a matter of considerable importance. Farmers must retain meaningful ownership and control over data generated from their own land. Without appropriate legal protections, this data could be aggregated, analysed and commercially exploited by agri-tech platforms and multinational corporations in ways that undermine farmers' negotiating power and privacy. India's evolving digital personal data protection framework, combined with sector-specific provisions in the proposed AgriStack architecture, offers a potential governance model. However, its implementation requires robust enforcement mechanisms, farmer education about data rights and the development of community data trusts through which farmer collectives can negotiate the terms of data sharing collectively.

Conclusion

Smart agriculture in the age of AIx offers a genuinely transformative vision: farms that monitor themselves, supply chains that self-optimize, extension services that reach every corner of the country and financial products designed around real-time farm data. The convergence of AI with edge computing, autonomous robotics and extended reality is not a distant prospect - it is already beginning to reshape agricultural practice in pilot regions and at the vanguard of the commercial farming sector. The principal challenge is ensuring that this transformation is governed wisely and distributed equitably. The stakes for food security, rural livelihoods and environmental sustainability in a country of India's scale and complexity - demand nothing less than a coherent national strategy that places the interests of the farming community at its centre.

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From Fields to Fuel: India's Green Answer to Global Oil Wars

Article ID: 73803

Sujith Arokia Swamy B^{1,2}, Raj Shekar M^{1,2}, Bhavana Kabber³, Ramya Jagadish⁴

¹The Graduate School, ICAR-Indian Agricultural Research Institute, New Delhi, India - 110012.

²ICAR-Indian Agricultural Statistics Research Institute, New Delhi, India - 110012.

³University of Agricultural Sciences, Raichur, Karnataka, India- 584104.

⁴Tamil Nadu Agricultural University, Coimbatore, India- 641003.

Summary

Global ethanol demand is accelerating, driven by energy security concerns, decarbonisation mandates and fossil fuel price volatility intensified by geopolitical disruptions in western Asia and Eastern Europe. This article examines why ethanol demand is rising, how sugarcane-based ethanol positions India to buffer these shocks, the role of diversified feedstock deployment including maize and other crops and the policy architecture underpinning the government's ethanol blending programme and Prime Minister's sustainability commitments.

Introduction

The global energy landscape has been subjected to a series of convulsive shocks over the past several years. The conflict in Ukraine disrupted natural gas and petroleum product flows across Europe, driving energy prices to historic levels and forcing accelerated reassessment of fossil fuel dependence across the European Union. Simultaneously, sustained geopolitical instability across the Middle East historically the linchpin of global crude oil supply has introduced structural uncertainty into petroleum markets that even large strategic petroleum reserve releases have been unable to fully resolve.

Against this backdrop, ethanol a biofuel produced from agricultural feedstocks has assumed renewed strategic significance. Unlike petroleum, ethanol can be produced domestically from crops grown and monitored within national borders. Its production infrastructure is decentralised, creating supply chains with inherently lower geopolitical risk than those associated with imported fossil fuels. And when produced from sugarcane or other agricultural crops, its carbon footprint is substantially lower than that of petroleum-based fuels, aligning it with decarbonisation commitments made under the Paris Agreement and under India's own Nationally Determined Contributions (NDCs).

Why is Global Ethanol Demand Rising?

Several converging forces are driving the expansion of ethanol demand worldwide. The first and most immediate is energy security. Countries that previously accepted dependence on petroleum imports as a manageable cost of economic growth have discovered, through repeated geopolitical shocks, that this dependence constitutes a structural vulnerability. Ethanol blending programmes that substitute domestically produced biofuel for imported petroleum directly reduce this vulnerability, preserving foreign exchange, stabilising fuel prices and insulating economies from external supply disruptions.

The second driver is decarbonisation. Transport fuels account for roughly twenty percent of global greenhouse gas emissions and liquid biofuels such as ethanol represent one of the most practical near-term pathways to reducing the carbon intensity of the transport sector. Compared to petroleum-derived petrol, sugarcane ethanol produced in Brazil and India achieves lifecycle greenhouse gas emission reductions of sixty to seventy percent. As carbon pricing mechanisms tighten and fuel economy standards become more stringent globally, the relative attractiveness of ethanol strengthens.

The third driver is agricultural policy. Ethanol programmes create sustained and predictable demand for agricultural feedstocks, providing price support for sugarcane, maize and other crops that are prone to cyclical price collapses when supply outstrips food and feed demand. In India, the Ethanol Blended Petrol (EBP) programme has functioned partly as an agricultural income support mechanism, providing sugar mills with an additional offtake channel for excess sugarcane and helping to resolve the chronic payment arrear crisis that periodically afflicts cane farmers in Uttar Pradesh and Maharashtra.

Sugarcane Ethanol: India's Strategic Advantage

India is the world's largest sugarcane producer, cultivating approximately five million hectares of the crop annually and producing approximately 360-380 million tonnes of cane per year. Sugarcane's high sucrose content makes it an ideal ethanol feedstock the fermentation of cane juice or molasses to ethanol is a well-established industrial process with decades of operational experience in India's 700-plus sugar mills.

The geopolitical resilience of sugarcane-based ethanol stems from the geographic and climatic conditions of sugarcane cultivation. India's sugarcane belt spanning the subtropical plains of western Uttar Pradesh, the Deccan Plateau districts of Maharashtra and Karnataka and the coastal tracts of Andhra Pradesh and Tamil Nadu lies entirely within national territory and is not subject to disruption by any external actor. This stands in stark contrast to petroleum supply chains that traverse conflict zones, chokepoints such as the Strait of Hormuz and maritime routes vulnerable to geopolitical tensions.

The National Policy on Biofuels 2018, as revised in 2022, set a target of twenty percent blending of ethanol in petrol by 2025 a target that has been substantially advanced, with national blending levels reaching approximately fourteen to fifteen percent in 2023-24 against the earlier baseline of below one percent in 2013-14. This acceleration has been enabled by a combination of administered procurement prices for ethanol differentiated by feedstock (with higher prices for cane juice and B-heavy molasses ethanol incentivising diversion of sugarcane away from surplus sugar production), capital subsidies for distillery expansion and mandatory blending obligations on oil marketing companies.

Geopolitical Disruptions and the Ethanol Buffer

The Ukraine conflict demonstrated with brutal clarity how supply chain concentration in fossil fuels translates into economic and political vulnerability. European nations that had become dependent on Russian natural gas faced an acute energy crisis that compelled emergency diversification efforts accelerated renewable energy deployment, LNG terminal construction and enhanced efficiency mandates at enormous cost and with substantial economic disruption. For India, which imports approximately eighty-five percent of its petroleum requirements, the lesson was equally applicable.

Sustained crude oil price elevation driven by OPEC production restraint, Middle Eastern instability and reduced investment in new production capacity directly increases India's petroleum import bill. Each one-dollar increase in the price of crude oil adds approximately Rs. 10,000 crores to India's annual import expenditure. Against this backdrop, every percentage point of ethanol blending achieved represents a tangible reduction in petroleum import demand, a quantifiable saving in foreign exchange and an increment of energy sovereignty.

Diversified Feedstocks: Maize, Rice and Surplus Grains

Recognising that sugarcane availability is subject to its own cyclical production dynamics and competing demands from the food sugar market, India has actively promoted diversification of ethanol feedstocks. Maize has emerged as the most significant alternative, particularly for distilleries in states such as Bihar, Odisha and the northeastern region where sugarcane cultivation is limited. Maize based ethanol production requires starch-to-sugar conversion prior to fermentation an additional processing step but maize offers agronomic advantages including a shorter growing season and compatibility with a wider range of soil and climatic conditions.

The government has also permitted the use of surplus rice procured by the Food Corporation of India (FCI) for ethanol production a policy innovation that simultaneously addresses two chronic problems: the accumulation of excess grain stocks in central pool storage and the supply constraint on ethanol production during lean sugarcane seasons. Sweet sorghum, which can be grown as a rotational crop on sugarcane land during the off-season, is being evaluated as an additional feedstock that extends the crushing season of existing distillery infrastructure without requiring additional land.

Prime Minister's Sustainability Commitments and Progress

The Ethanol Blended Petrol programme aligns directly with India's commitments made under Prime Minister Narendra Modi's International Solar Alliance initiative, the LiFE (Lifestyle for Environment) movement and the Panchamrit pledges articulated at COP26. India committed to achieving fifty percent of its cumulative electric power installed capacity from non-fossil sources by 2030 and to reducing the carbon intensity of its economy by forty-five percent relative to 2005 levels. Biofuels, including ethanol, contribute to both objectives reducing petroleum consumption in the transport sector and creating an agricultural-industrial value chain that recycles atmospheric carbon through living plant biomass.

The monitoring of ethanol blending progress has been digitised through the Department of Food and Public Distribution's portal, which tracks procurement, despatch and blending performance at the level of individual oil marketing company depots. This digital monitoring architecture enables real-time identification of underperforming regions, targeted intervention by state government biofuel development boards and evidence-based adjustment of pricing and policy incentives.

Conclusion

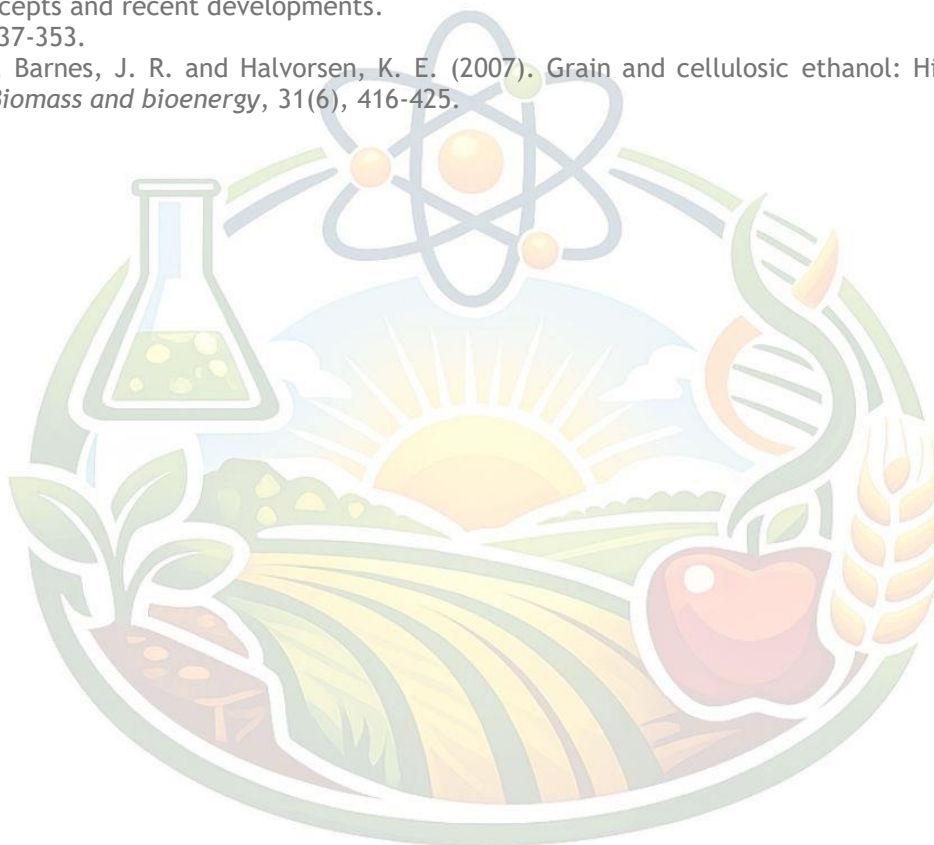
The convergence of energy security imperatives, decarbonisation commitments and agricultural income support objectives has made ethanol blending one of the most strategically significant policies in India's energy and agricultural landscape. Sugarcane ethanol, drawing on India's deep agronomic and industrial expertise in cane cultivation and sugar processing, provides the foundational supply capability for the programme. Diversification into maize, surplus grain and

emerging feedstocks such as sweet sorghum is building the resilience and geographic breadth needed to sustain blending targets through sugarcane production cycles.

As global geopolitical disruptions continue to underline the fragility of fossil fuel dependence, India's ethanol programme positions the country not as a passive recipient of energy market shocks but as a nation actively building the production, monitoring and policy infrastructure needed to meet Prime Minister Modi's vision of energy self-reliance and a sustainable agricultural economy. The road to twenty percent blending and beyond is ambitious, but the trajectory is clear and the institutional foundations are solidifying with each passing year.

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The Bitter Harvest: India's Tobacco Tax Storm and the Farmers Left Behind

Article ID: 73804

Sujith Arokia Swamy B^{1,2}, Bhavana Kabber³, Raj Shekar M^{1,2}, Ramya Jagadish⁴

¹The Graduate School, ICAR-Indian Agricultural Research Institute, New Delhi, India - 110012.

²ICAR-Indian Agricultural Statistics Research Institute, New Delhi, India - 110012.

³University of Agricultural Sciences, Raichur, Karnataka, India- 584104.

⁴Tamil Nadu Agricultural University, Coimbatore, India- 641003.

Summary

The Central Excise (Amendment) Act, 2025, passed by Parliament in December 2025 and effective from February 1, 2026, has triggered one of the steepest hikes in tobacco taxation in India's recent history raising cigarette duties from Rs. 200-735 to Rs. 2,700-11,000 per thousand sticks and imposing up to 100% excise on chewing tobacco. While aimed at health deterrence and revenue generation, the policy has set off a cascade of economic shocks. ITC Ltd., India's largest cigarette manufacturer, saw its stock fall nearly 10% within two trading sessions, wiping out approximately \$7 billion in market capitalisation. More alarmingly, the real cost is being borne silently by India's approximately 45 million tobacco dependent livelihoods, particularly the small and marginal farmers of Andhra Pradesh and Karnataka who anchor the country's flue-cured Virginia (FCV) tobacco economy. Stalled auction yards, unsold leaf stockpiles and reduced export competitiveness paint a picture of a rural crisis in the making.

Introduction

Tobacco has long occupied a paradoxical space in India's policy landscape simultaneously targeted by public health campaigns and quietly sustained by the rural economy it underpins. India is the world's second largest producer of tobacco, cultivating approximately 0.45 million hectares predominantly across the Godavari delta of Andhra Pradesh and parts of Karnataka, Gujarat and West Bengal (Tobacco Board of India, 2024). For the millions of small landholders who grow flue-cured Virginia (FCV) tobacco, it is not a lifestyle crop; it is often the single most remunerative agricultural commodity available to them on fragile, sandy loam soils unfit for rice or pulses.

The passage of the Central Excise (Amendment) Act, 2025 by Parliament on December 4, 2025 and its formal notification on December 12, has fundamentally altered this fragile equation. The amendment restores and dramatically scales up excise duty on all tobacco and tobacco products, a power the Union Government had effectively surrendered when GST was introduced in 2017, retaining only a token levy while routing the bulk of tobacco taxation through the compensation cess framework. Now, with the cess regime winding down, the government has moved swiftly to plug the revenue gap, but the scale of the increase has stunned industry, investors and farming communities alike.

Understanding the Scale of the Tax Shock

The magnitude of the new excise structure is extraordinary. Under the Central Excise Act, 1944, cigarette duties ranged from ₹200 to ₹735 per thousand sticks. The amended Act raises this to ₹2,700 to ₹11,000 per thousand cigarettes representing an increase of up to 1,400% on certain product categories. For chewing tobacco, jarda and gutkha, the excise duty leaps from 25% to as high as 100%. Smoking mixtures for pipes and hookahs will now attract an extraordinary 325% excise, up from 60%. All this is levied in addition to the existing 40% Goods and Services Tax on tobacco products, creating one of the most heavily taxed commodity regimes in the country (TaxTMI, January 2026).

Analysts at Jefferies Financial Group estimated the effective total tax hike at over 30% once the National Calamity Contingent Duty (NCCD) is layered in. Finance Minister Nirmala Sitharaman defended the measure by noting that India's total tax incidence on cigarettes stands at approximately 53% of retail price, compared to the World Health Organization's recommended benchmark of 75% (Tribune India, December 2025). The government's stated objectives are public health improvement and bringing India in line with international tobacco control norms under the Framework Convention on Tobacco Control (FCTC).

Market Reaction: ITC and the Wider Tobacco Sector

The equity market's verdict on the new tax regime was swift and severe. ITC Ltd., which commands the largest share of India's cigarette market and serves as the principal buyer of FCV tobacco from Indian farmers, saw its stock decline nearly 10% across two trading sessions immediately following the government notification. Shares touched ₹362.7, marking a 52-week low. The selloff erased approximately \$7 billion in market capitalisation in one of the sharpest single week reactions the company has witnessed in recent memory (Bloomberg, January 2026).

Godfrey Phillips India fared even worse, declining by approximately 19%, while VST Industries also recorded significant losses. The Tobacco Institute of India (TII), an industry body representing ITC, Godfrey Phillips, VST Industries, farmers

and ancillary businesses, described the duty hike as “unprecedented” and warned it would prove “revenue neutral” in practice arguing that extreme price increases would shift consumers toward illicit and contraband cigarettes, as observed in Australia and other countries with aggressive tobacco taxation (Upstox, January 2026).

The pricing implications for legal cigarettes are stark. If manufacturers pass even a portion of this tax burden to consumers, retail prices could rise sharply, compressing demand for domestic FCV leaf the primary raw material sourced from Indian farmers. ITC has historically procured a large share of its tobacco directly from growers in Andhra Pradesh, making the agricultural and corporate consequences deeply interlinked.

The Farmer at the End of the Chain: A Triple Crisis

While stock market commentary has dominated media coverage, the impact on tobacco cultivating farmers represents a deeper and less visible humanitarian concern. The Federation of All India Farmer Associations (FAIFA) has characterised the situation facing growers as a “triple crisis” encompassing: prolonged delays in auction commencement, reduced export competitiveness and a collapse of legal domestic demand (The Statesman, January 2026).

Tobacco auctions in Andhra Pradesh the epicentre of FCV tobacco cultivation ground to a halt as policy uncertainty caused buyers, both domestic and international, to hold back procurement. Farmers who had harvested and cured their crop in anticipation of the marketing season found themselves stranded with tonnes of unsold leaf, mounting storage costs and escalating debts to input suppliers. The human dimension of this is acute: many of these growers are smallholders cultivating under two acres on loamy soils in the Guntur and Krishna districts, with no alternative crop offering comparable returns in a single season.

Chief Ministers of both Andhra Pradesh and Karnataka acknowledged the distress publicly in early 2026 and assured farmers they would take up the issue with the Centre urgently. Opposition Members of Parliament were reportedly advised to raise the matter in Parliament, citing impacts on employment, export revenue and rural income (The Statesman, January 30, 2026). The warning from FAIFA was stark: without immediate policy intervention before January 30, 2026, the sector risked cascading into a national agricultural crisis.

Export Competitiveness and the Global Market Dimension

India is among the world’s top exporters of unmanufactured tobacco, with FCV leaf finding markets in Europe, the Middle East and Southeast Asia. The new excise regime, while primarily targeting manufactured tobacco products, has created collateral uncertainty for the entire value chain. International buyers, already concerned about supply chain disruptions and pricing unpredictability, have begun looking toward competing producers in Brazil, Zimbabwe and Malawi. Any sustained erosion of India’s global tobacco export share would directly reduce farm gate realisation prices and threaten the foreign exchange earnings the sector historically contributes.

The Tobacco Board of India faces the challenge of reassuring international buyers while simultaneously navigating domestically suppressed demand. The irony is that heightened excise duties, intended in part to deter domestic tobacco consumption, could paradoxically devastate farmers who are not tobacco consumers themselves but merely growers of a legally traded cash crop.

Government’s Position and Crop Diversification Programmes

Finance Minister Sitharaman has maintained that the excise restructuring will not harm tobacco farmers or beedi workers, pointing to existing support mechanisms including the crop diversification programme under the Rashtriya Krishi Vikas Yojana, which covers 10 major tobacco growing states. She noted that over 1.12 lakh acres of farmland had already transitioned from tobacco to alternative crops between 2017-18 and 2021-22 and that 49.82 lakh registered beedi workers are covered under labour welfare schemes (Tribune India, December 2025).

However, farmer groups and agricultural economists have countered that crop diversification is a longterm structural solution that offers no relief for growers who have already planted, tended and harvested their 2025-26 tobacco crop. The transition away from tobacco requires alternative crops that match or approximate the income potential of FCV leaf, adequate irrigation infrastructure, knowledge transfer and reliable markets none of which can be created in a single agricultural season. In the short run, rapid tax driven demand destruction therefore directly harms the very farmers the government claims to be protecting.

Personal Opinion Column

The tobacco taxation debate in India is not new, but the 2025 excise amendment represents a qualitative shift in policy aggression that demands more careful sequencing. There is no reasonable argument against the long term goal of reducing tobacco consumption for health reasons the evidence on tobacco’s harm is incontrovertible. The question is whether an abrupt, shock therapy approach to taxation, without concurrent robust income replacement programmes for farmers, constitutes sound agrarian governance. History suggests that punitive taxation of legally grown agricultural commodities, without structural alternatives for the growing community, transfers the cost of social policy reform

entirely onto the most economically vulnerable actors in the supply chain. India's tobacco farmer deserves better than to be the silent, invisible casualty of a well intentioned but poorly sequenced policy correction.

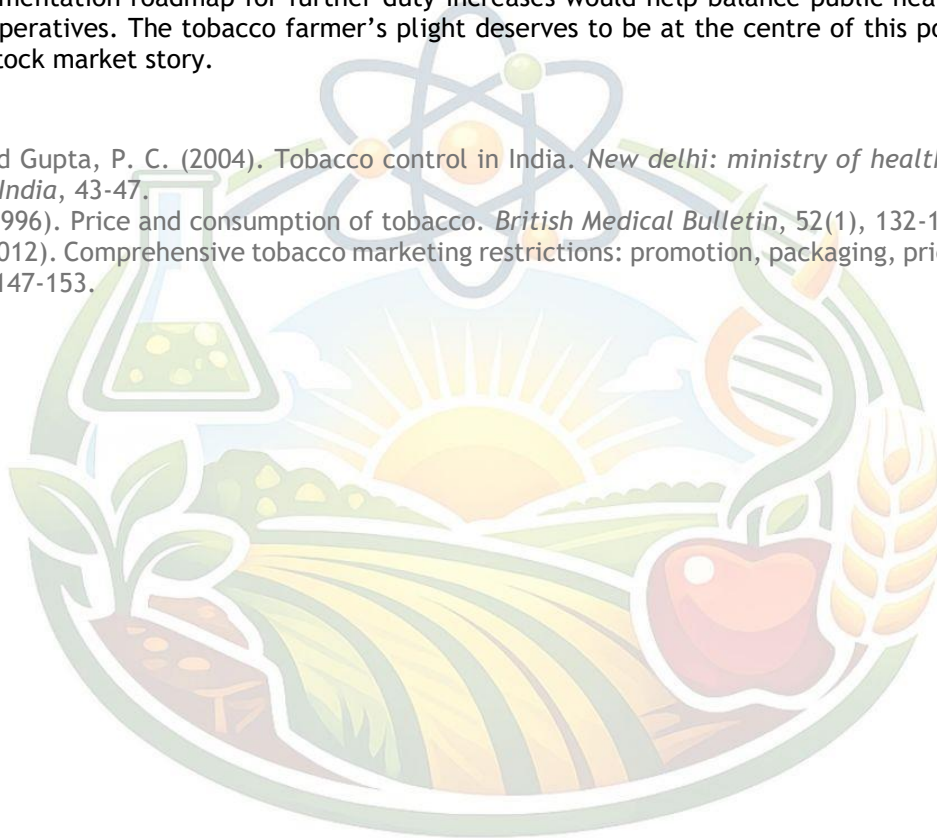
Conclusion

The Central Excise (Amendment) Act, 2025, represents India's most aggressive tobacco taxation move in decades, with excise duties on cigarettes rising by up to 1,400% in structural terms. The immediate market fallout a 10% collapse in ITC share price and \$7 billion in erased market capitalisation is significant, but the human cost borne by India's approximately 45 million tobacco dependent livelihoods is potentially far graver. Farmers in Andhra Pradesh and Karnataka face stalled auctions, depleted incomes and mounting debts while holding unsold leaf inventory. Export competitiveness is weakening as international buyers reassess India as a sourcing destination.

The government's reliance on long term diversification programmes as a buffer against immediate farmer distress reflects a structural mismatch between policy timeline and agricultural reality. An immediate relief package for the 2025-26 crop season, accelerated auction facilitation through the Tobacco Board, targeted price support mechanisms and a phased implementation roadmap for further duty increases would help balance public health objectives against agrarian welfare imperatives. The tobacco farmer's plight deserves to be at the centre of this policy conversation not as a footnote to a stock market story.

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Market Oracle: Smart Prices and Smarter Farms

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Bhavana Kabber¹, Sujith Arokia Swamy B^{2,3}, Raj Shekar M^{2,3}, Ramya Jagadish⁴

¹University of Agricultural Sciences, Raichur, Karnataka, India- 584104.

²The Graduate School, ICAR-Indian Agricultural Research Institute, New Delhi, India - 110012.

³ICAR-Indian Agricultural Statistics Research Institute, New Delhi, India - 110012.

⁴Tamil Nadu Agricultural University, Coimbatore, India- 641003.

Summary

Artificial intelligence is fundamentally transforming crop price forecasting in agricultural markets. This article examines how AI models - from gradient boosting to Recurrent Neural Networks - are being deployed to predict commodity prices, reduce market volatility, enable better income planning for farmers and support evidence-based government interventions in India and globally.

Introduction

Crop price volatility is among the most destabilising forces in agricultural economies. When prices collapse at harvest, farmers bear devastating income losses. When they spike unexpectedly, urban consumers and food processors face supply disruptions and inflationary pressures. For decades, agricultural economists attempted to model these dynamics using classical econometric tools - vector autoregression, error correction models and seasonal decomposition techniques. The results were often insightful but rarely actionable at the speed required by commodity traders, procurement agencies or farmers deciding whether to sell immediately or hold their stock.

Artificial intelligence has introduced a qualitatively different capability: the ability to simultaneously process structured price data, unstructured text from news sources, satellite-derived supply estimates and macroeconomic indicators - and synthesise them into a probabilistic price forecast updated in near real time. The implications for agricultural markets are profound, and India - home to one of the world's most complex and geographically dispersed agricultural market systems - stands to benefit enormously from this technological shift.

Why Crop Price Forecasting is Difficult

Agricultural commodity prices are among the most difficult economic variables to predict accurately. They are shaped by an intricate interplay of supply-side factors such as rainfall, pest incidence and area under cultivation; demand-side forces including population growth, income levels, and changes in dietary preferences; and policy interventions such as Minimum Support Price (MSP) revisions, export bans and public distribution system procurement targets. Superimposed on these are speculative dynamics in futures markets and global commodity price spillovers transmitted through trade channels.

Classical ARIMA and VAR models struggle with this complexity because they assume linear relationships and require the analyst to specify the model structure in advance. A sudden policy announcement - an export restriction on wheat, for instance - can fundamentally alter price dynamics in ways that are invisible to a model trained exclusively on historical price series. Incorporating such information requires a fundamentally different approach.

AI Architectures for Price Forecasting

Modern AI price forecasting systems typically employ an ensemble of complementary models. Gradient boosting algorithms such as XGBoost and LightGBM are well-suited for structured tabular data - APMC arrival volumes, rainfall deviations, MSP levels and lagged price series. These models learn non-linear relationships without manual specification and are relatively interpretable through feature importance metrics.

For capturing sequential dependencies in price data, LSTM networks and Gated Recurrent Units (GRUs) have demonstrated strong performance. More recently, Transformer-based architectures trained on multi-year commodity price histories have outperformed LSTM models on benchmarks involving complex seasonal patterns and structural breaks. Sentiment analysis models applied to agricultural news, APMC market bulletins, and social media feeds add a forward-looking dimension that historical price data alone cannot provide.

The National Commodity and Derivatives Exchange (NCDEX) and several agri-tech startups in India have begun deploying such multi-modal AI systems. Platforms such as DeHaat and Agriwatch use price forecasting models to deliver commodity-specific advisory messages to farmers through mobile applications, allowing even smallholders with limited market access to make more informed selling decisions.

Impact on Farmers and Market Efficiency

The most direct beneficiaries of accurate price forecasting are farmers. A reliable thirty-day price forecast enables a farmer to decide whether to store produce in a warehouse-receipt facility and wait for better prices or to sell immediately. Studies in Maharashtra found that farmers with access to mobile-delivered price forecasts earned, on average, eight to twelve percent more per quintal than those relying on trader estimates a significant income differential for households already operating on thin margins.

At the market level, better price forecasting reduces the information asymmetry between farmers and traders. Historically, traders with superior market intelligence extracted rents by purchasing produce at below-market prices from uninformed farmers. As AI-generated forecasts become widely accessible through farmer service centres, Krishi Vigyan Kendras (KVKs) and mobile platforms, this information gap is narrowing, contributing to more competitive and efficient markets. For government agencies, price forecasting models inform buffer stock management, import and export decisions and MSP revision calendars. The Department of Consumer Affairs uses commodity price dashboards drawing on AI models to monitor and respond to price spikes in essential commodities. Proactive buffer stock releases guided by AI forecasts have been credited with moderating tomato and onion price shocks in recent years.

Limitations and Ethical Considerations

AI price forecasting models are not infallible. They can fail spectacularly under conditions that have no historical precedent - a global pandemic, a once-in-a-century drought, or a sudden geopolitical rupture that closes export markets. Model confidence intervals are often underestimated, leading to false precision that can itself distort market behaviour if widely acted upon. There is also a risk that powerful AI forecasting tools become concentrated in the hands of large traders and corporate agribusinesses, potentially widening rather than narrowing the information advantage they hold over smallholder farmers.

Addressing these risks requires open-access data policies, publicly funded forecasting platforms accessible to all market participants and regulatory oversight to prevent AI-driven price manipulation. The design of these institutional safeguards is as important as the technical quality of the models themselves.

Conclusion

AI-powered crop price forecasting represents one of the most impactful applications of artificial intelligence in agriculture. By integrating diverse data streams, learning complex non-linear dynamics and updating forecasts in near real time, modern AI systems offer a qualitative leap over classical econometric approaches. The potential benefits higher farm incomes, greater market efficiency, more responsive government interventions - are substantial.

Realising these benefits equitably, however, requires deliberate effort to ensure that forecasting tools reach the millions of smallholder farmers who need them most. India's digital agriculture mission, combined with expanding mobile internet penetration in rural areas, creates a genuine opportunity to democratise market intelligence and transform the terms on which India's farmers engage with the market.

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The Intelligent Acre: AI Meets Indian Agriculture

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Bhavana Kabber¹, Raj Shekar M^{2,3}, Sujith Arokia Swamy B^{2,3}, Ramya Jagadish⁴

¹University of Agricultural Sciences, Raichur, Karnataka, India- 584104.

²The Graduate School, ICAR-Indian Agricultural Research Institute, New Delhi, India - 110012.

³ICAR-Indian Agricultural Statistics Research Institute, New Delhi, India - 110012.

⁴Tamil Nadu Agricultural University, Coimbatore, India- 641003.

Summary

Smart farming integrates artificial intelligence, Internet of Things sensors, satellite remote sensing, and predictive analytics to optimise agricultural decision-making. This article explores how these technologies combine to create intelligent farm management systems, analyses their impact on input efficiency and yield, and examines the pathways through which Indian smallholders can access and benefit from the smart farming revolution.

Introduction

The term smart farming describes a management concept in which agricultural practices are guided by real-time data collection, analysis, and predictive modelling rather than by tradition, intuition, or periodic expert consultation alone. It is, at its core, a shift from reactive to proactive farm management. Instead of responding to crop stress after it is visible, a smart farm detects the early precursors of stress a subtle shift in leaf reflectance, an anomaly in soil electrical conductivity, a deviation from expected transpiration rates and triggers a targeted intervention before yield losses occur.

Artificial intelligence is the integrating intelligence of smart farming systems. It processes the flood of data generated by field sensors, drones, satellite platforms and weather stations; identifies patterns that human analysts would miss; and generates recommendations that are specific to the spatial variability of individual fields. Predictive analytics, as a subset of AI, extends this capability into the future forecasting not just current field conditions but the likely evolution of those conditions over the coming days, weeks, or growing season. Together, these technologies are enabling a transformation in agricultural productivity and sustainability.

Core Technologies of Smart Farming

The smart farm rests on four technological pillars. The first is sensing the deployment of IoT soil moisture sensors, weather stations, crop canopy temperature sensors and aerial platforms that generate continuous streams of field data. India's government-funded Soil Health Card scheme has created a national database of soil health parameters, providing a foundation layer that AI models can draw upon for fertiliser recommendations.

The second pillar is connectivity the transmission of sensor data to cloud computing platforms for storage and processing. The expansion of 4G and 5G networks in rural India, combined with low- power wide-area network (LPWAN) technologies such as LoRaWAN, is progressively resolving the connectivity gap that previously limited smart farming deployment in remote agricultural areas.

The third pillar is analytics the application of machine learning models to derive insights from collected data. Convolutional Neural Networks (CNNs) trained on millions of crop disease images can now diagnose foliar diseases from smartphone photographs with accuracy matching or exceeding that of trained agronomists. Recurrent networks model the temporal progression of growing seasons and predict harvest dates and yield outcomes weeks in advance.

The fourth pillar is actuation the automated or advisory-driven response to analytical outputs. Variable-rate application equipment adjusts fertiliser or pesticide dosage dynamically as it traverses a field, guided by prescription maps generated by AI models. Drip irrigation controllers receive soil moisture forecasts and adjust irrigation schedules autonomously. Each of these actions reduces input waste, protects environmental quality and preserves farm profitability.

Predictive Analytics in Crop Management

Predictive analytics transforms farm management by shifting the decision-making horizon forward in time. Yield prediction models, trained on historical remote sensing data, in-situ measurements, and weather forecasts, can estimate final harvest outcomes with considerable accuracy as early as six weeks before harvest. This advance information is valuable not just for the farmer planning post-harvest logistics but for grain traders, processors, and government procurement agencies calibrating storage and transport capacity.

Pest and disease forecasting models represent another high-impact application. Locust swarm prediction, which integrates satellite-derived vegetation greenness, soil moisture levels, and atmospheric wind patterns, has been operationalised by the Food and Agriculture Organization (FAO) and national plant protection agencies. In India, brown

planthopper outbreak forecasting in rice-growing regions now draws on spatially explicit AI models that alert farmers and extension workers two to three weeks before projected infestations reach economic threshold levels. Early warning allows for targeted prophylactic interventions rather than emergency reactive spraying reducing pesticide use and preserving populations of beneficial insects.

Precision Irrigation and Water Management

Water is India's most critical and contested agricultural resource. With groundwater depletion accelerating across the Indo-Gangetic Plain and the Deccan Plateau, the optimisation of irrigation applying the right amount of water to the right location at the right time is not merely an efficiency objective but a long-term sustainability imperative.

AI-driven precision irrigation systems integrate soil moisture readings, evapotranspiration estimates derived from weather data, crop growth stage models, and seasonal rainfall forecasts to generate dynamic irrigation schedules. Studies in the cotton belt of Maharashtra documented water savings of twenty-five to thirty percent compared to conventional flood irrigation, without any reduction in yield. The financial savings from reduced pumping costs alone provided a return on investment for sensor deployment within a single growing season.

Accessibility for Small and Marginal Farmers

A persistent critique of smart farming is that its benefits disproportionately accrue to large commercial farms that can afford sensor networks, data subscriptions, and precision machinery. India's agricultural landscape, dominated by smallholders with average landholdings below 1.4 hectares, poses a particular challenge to this model. Addressing this equity dimension is essential if smart farming is to contribute to rural poverty reduction rather than simply intensifying existing inequalities. Several pathways are emerging like Farmer Producer Organisations (FPOs) are pooling resources to acquire shared drone and sensing infrastructure. Government-funded digital extension platforms such as the Unified Farmer Service Interface are delivering AI-generated advisories to farmers through simple mobile applications requiring only basic literacy. The integration of smart farming tools into the existing Krishi Vigyan Kendra network provides a trusted local intermediary through which technology adoption can be supported and monitored.

Conclusion

Smart farming, powered by AI and predictive analytics, offers a transformative pathway toward a more productive, efficient, and sustainable agriculture. The integration of sensing, connectivity, machine learning, and actuation creates a closed-loop system in which farm management decisions are continuously improved by real-world feedback. India's scale - both the scale of its agricultural challenge and the scale of its digital infrastructure investment - positions it as a potential global leader in the deployment of smart farming technologies.

The critical challenge is equitable diffusion. Ensuring that smallholders gain access to smart farming tools requires deliberate policy design, public investment in digital infrastructure and business models that reduce the cost of entry. When these conditions are met, AI-powered precision agriculture has the potential to simultaneously improve farm incomes, reduce environmental footprints and enhance India's food security.

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Agrivoltaics 2.0: Crop Performance, Microclimate Effects, and Economic Models Under Solar Panels

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Sima Kumari¹, Pavan Shukla¹, Ashutosh Singh¹, Amit Kumar Pandey¹

¹Bihar Agricultural University, Sabour, Bhagalpur, Bihar.

Abstract

Agrivoltaics, the co-location of agricultural production and photovoltaic energy generation on the same land area, has emerged as an innovative strategy for addressing the dual challenges of food security and renewable energy expansion. The concept has evolved significantly from its original form into what is increasingly referred to as Agrivoltaics 2.0, an advanced approach that integrates optimized solar panel designs, precision agriculture technologies, climate-smart crop management, and innovative economic models. Agrivoltaic systems create unique microclimatic conditions beneath solar panels that influence crop growth, water use, soil health, and overall agricultural productivity. These systems have demonstrated the potential to improve land-use efficiency, increase water-use efficiency, reduce heat stress, enhance resilience to climate change, and provide diversified income streams for farmers. Recent advances in panel configurations, dynamic tracking systems, artificial intelligence, and integrated farm-energy management have expanded opportunities for maximizing both crop and energy yields. This review examines the principles, technological evolution, crop performance responses, microclimate modifications, economic implications, environmental benefits, challenges, and future prospects of Agrivoltaics 2.0 in sustainable agricultural systems.

Introduction

The twenty-first century faces the interconnected challenges of ensuring food security, mitigating climate change, and meeting growing global energy demands. Rapid population growth, urbanization, land degradation, and increasing climatic variability place immense pressure on agricultural production systems. Simultaneously, nations worldwide are transitioning toward renewable energy sources to reduce greenhouse gas emissions and achieve climate goals. Traditionally, agricultural land and solar energy infrastructure have been viewed as competing land uses. Large-scale photovoltaic installations often occupy productive agricultural land, raising concerns about food production and rural livelihoods. Agrivoltaics emerged as a promising solution by integrating agricultural activities with solar energy generation on the same land area. The original concept of agrivoltaics was first proposed by Goetzberger and Zastrow in 1982, who suggested that agricultural land could simultaneously support crop cultivation and photovoltaic electricity production. Since then, advances in engineering, crop science, environmental monitoring, and renewable energy technologies have transformed agrivoltaics into a sophisticated multifunctional land-use system. Agrivoltaics 2.0 represents the next generation of integrated food-energy systems. Unlike early agrivoltaic installations that primarily focused on solar energy production, modern systems optimize both agricultural productivity and energy generation through intelligent design, precision management, crop selection, and economic integration. These systems are increasingly recognized as climate-smart solutions capable of enhancing sustainability, resilience, and profitability.

Evolution from Traditional Agrivoltaics to Agrivoltaics 2.0

The initial generation of agrivoltaic systems primarily involved elevated solar panels installed above agricultural fields. While these systems demonstrated the feasibility of dual land use, they often lacked optimization for crop growth and farm management. Agrivoltaics 2.0 incorporates substantial technological advancements. Modern systems employ adjustable panel heights, bifacial photovoltaic modules, dynamic solar tracking systems, precision irrigation technologies, sensor networks, artificial intelligence-based monitoring, and crop-specific panel configurations. These innovations allow real-time balancing of energy generation and agricultural productivity. The integration of digital agriculture tools enables continuous monitoring of solar radiation, soil moisture, temperature, humidity, crop growth, and energy production. Such data-driven approaches improve decision-making and maximize overall system performance. According to Barron-Gafford et al. (2019), agrivoltaic systems can substantially increase land productivity by simultaneously enhancing agricultural and energy outputs compared with separate land-use systems.

Principles of Agrivoltaic Systems

Agrivoltaics operates on the principle of dual land utilization, where crops and photovoltaic panels coexist within the same production landscape. Solar panels capture sunlight for electricity generation while allowing sufficient light penetration to support crop growth. The degree of shading varies depending on panel design, orientation, height, spacing, and tracking mechanisms. This controlled shading creates modified environmental conditions that can benefit certain crops, particularly under hot and arid climates. Agrivoltaic systems may be classified into several configurations including elevated fixed-panel systems, vertical solar arrays, dynamic tracking systems, greenhouse-integrated

photovoltaics, and livestock-integrated solar systems. Each design offers distinct advantages depending on climatic conditions, crop requirements, and economic objectives. The ultimate goal is to achieve synergy between agricultural productivity and renewable energy generation while minimizing trade-offs.

Microclimate Modifications Under Solar Panels

One of the most significant features of agrivoltaic systems is their ability to alter local microclimatic conditions. Solar panels partially intercept incoming solar radiation, resulting in modified temperature, humidity, wind patterns, and soil moisture dynamics beneath the panels. Reduced solar exposure often lowers daytime air temperatures and soil surface temperatures. This cooling effect becomes particularly beneficial during heat waves and periods of extreme temperature stress. Lower temperatures can reduce crop transpiration rates and mitigate heat-induced physiological damage.

Agrivoltaic systems frequently increase relative humidity within the crop canopy due to reduced evaporation and altered airflow. Enhanced humidity may contribute to improved plant water relations and reduced water stress under arid conditions. Soil moisture conservation is another important consequence of panel shading. Reduced evaporative losses often result in higher soil water availability, enabling crops to maintain growth during dry periods. These effects can significantly improve water-use efficiency and reduce irrigation requirements. Studies conducted in arid and semi-arid environments have demonstrated that agrivoltaic systems create more favorable microclimates for crop production, particularly under conditions of increasing climate variability.

Crop Performance Under Agrivoltaic Systems

Crop responses to agrivoltaic environments vary considerably depending on species, variety, climatic conditions, panel configuration, and management practices. While some crops may experience reduced yields due to lower light availability, many species demonstrate neutral or even positive responses under partial shading. Leafy vegetables such as lettuce, spinach, kale, and coriander often perform exceptionally well under agrivoltaic systems because excessive solar radiation and heat stress are reduced. Lower temperatures can improve photosynthetic efficiency, reduce leaf scorching, and enhance product quality. Root crops including potato, beetroot, carrot, radish, and sweet potato may also benefit from moderated soil temperatures and improved moisture retention. Several studies have reported improved tuber development and reduced drought stress under agrivoltaic conditions.

Leguminous crops such as beans, peas, and cowpea frequently demonstrate favorable responses to partial shading, particularly in hot climates where excessive solar radiation limits productivity. Fruit crops including strawberry, raspberry, blueberry, and certain orchard systems have shown promising performance under solar panels. Reduced heat stress and improved water conservation often enhance fruit quality and marketability. Research by Adeh et al. (2018) demonstrated that some crops grown beneath photovoltaic arrays exhibited increased water-use efficiency and maintained competitive yields compared with conventional systems.

Photosynthetic Responses and Light Dynamics

Light availability represents one of the most critical factors influencing crop performance under agrivoltaic systems. Solar panels reduce total incident radiation but also alter light quality and distribution. Partial shading can reduce photoinhibition, a condition in which excessive light damages photosynthetic machinery. Under high-temperature environments, moderated light levels may actually improve photosynthetic efficiency and carbon assimilation. Diffuse light generated through panel arrangements often penetrates crop canopies more effectively than direct sunlight. This improved light distribution can enhance photosynthesis throughout the canopy and increase overall productivity. Modern Agrivoltaics 2.0 systems increasingly employ dynamic tracking technologies that optimize light allocation between energy production and crop growth throughout the day and across seasons.

Water-Use Efficiency and Drought Adaptation

Water scarcity is becoming one of the most significant constraints to global agriculture. Agrivoltaic systems offer substantial advantages in improving water-use efficiency and enhancing drought resilience. Reduced evaporation from soil surfaces helps conserve water resources, while lower canopy temperatures decrease transpiration rates. These combined effects often result in significant water savings compared with conventional agricultural systems. Studies have reported reductions in irrigation requirements ranging from 15% to 40% depending on crop type and environmental conditions. Such improvements are particularly valuable in arid and semi-arid regions experiencing increasing water stress. Barron-Gafford et al. (2019) observed that agrivoltaic systems improved both crop productivity and water-use efficiency in desert agricultural environments. The ability to conserve water while maintaining productivity positions agrivoltaics as a powerful climate adaptation strategy.

Soil Health and Ecosystem Services

Agrivoltaic systems influence soil processes through modifications in temperature, moisture, and organic matter dynamics. Cooler soil conditions can support beneficial microbial activity and enhance nutrient cycling processes. Increased vegetation cover beneath solar panels often reduces soil erosion and protects soil surfaces from degradation.

Enhanced organic matter inputs from crop residues contribute to improved soil structure and fertility. The integration of pollinator habitats, cover crops, and biodiversity corridors within agrivoltaic landscapes can further enhance ecosystem services. Such multifunctional land-use systems support pollination, pest regulation, carbon sequestration, and biodiversity conservation. Agrivoltaics therefore contributes not only to agricultural productivity but also to broader ecological sustainability objectives.

Agrivoltaics and Climate Change Mitigation

Climate change mitigation requires substantial reductions in greenhouse gas emissions alongside increased renewable energy deployment. Agrivoltaics contributes directly to these goals by generating clean electricity while maintaining agricultural productivity. The dual-use approach reduces land-use conflicts associated with renewable energy expansion. Instead of converting agricultural land solely to energy production, agrivoltaics enables simultaneous achievement of food and energy objectives. Renewable electricity generated by photovoltaic systems offsets fossil fuel consumption and associated carbon emissions. Additionally, improved soil management and vegetation cover can contribute to carbon sequestration within agricultural landscapes. These combined benefits position agrivoltaics as an important component of sustainable climate mitigation strategies.

Economic Models and Financial Viability

Agrivoltaics 2.0 introduces innovative economic models that improve farm profitability and resilience. Traditional farming systems depend largely on agricultural revenues, which are often vulnerable to weather variability, market fluctuations, and production risks. The addition of solar energy production creates a secondary income stream that diversifies revenue sources and reduces financial uncertainty. Farmers can generate income through electricity sales, energy leasing agreements, power purchase contracts, and carbon credit programs.

Economic analyses frequently demonstrate higher land equivalent ratios and improved overall profitability compared with separate agricultural and solar operations. Revenue diversification enhances farm resilience and supports long-term economic sustainability. According to Dinesh and Pearce (2016), agrivoltaic systems can generate greater overall economic value per unit area than independent agricultural or photovoltaic land uses. Emerging business models include community-owned solar projects, farmer-energy cooperatives, agrivoltaic leasing arrangements, and public-private partnerships. These models create opportunities for broader participation and equitable benefit sharing.

Technological Innovations in Agrivoltaics 2.0

Recent technological advancements are accelerating the development of sophisticated agrivoltaic systems. Artificial intelligence and machine learning algorithms can optimize panel positioning, irrigation scheduling, crop management, and energy production simultaneously. Bifacial photovoltaic modules capture sunlight from both sides, increasing electricity generation efficiency. Dynamic solar tracking systems adjust panel angles throughout the day to maximize energy output while maintaining suitable light conditions for crops. Remote sensing technologies, drones, Internet of Things (IoT) sensors, and digital twin models enable continuous monitoring of environmental and agricultural variables. These tools support precision management and improve overall system performance. Future agrivoltaic systems may incorporate autonomous robots, smart irrigation networks, and predictive analytics to further enhance productivity and sustainability.

Challenges and Limitations

Despite significant promise, agrivoltaic systems face several challenges. Initial installation costs remain relatively high compared with conventional farming systems, potentially limiting adoption among resource-constrained farmers. Crop responses vary considerably, and not all species perform well under shaded conditions. Site-specific design and crop selection are therefore essential for achieving optimal outcomes. Technical complexity associated with panel installation, maintenance, machinery access, and farm operations can present practical challenges. Regulatory uncertainties, land-use policies, and grid connectivity issues may also affect project implementation. Long-term studies evaluating ecological, agronomic, and economic performance across diverse environments remain limited. Additional research is needed to develop region-specific recommendations and improve system optimization.

Future Prospects

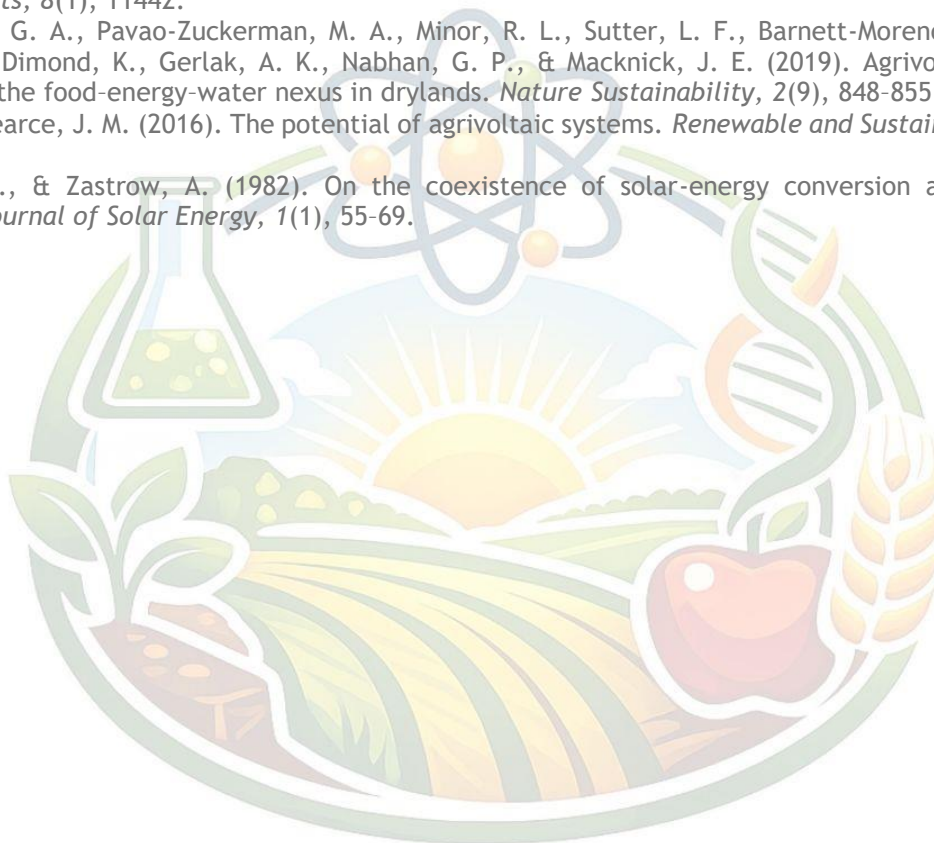
The future of Agrivoltaics 2.0 appears highly promising as governments, researchers, and industry stakeholders seek integrated solutions to food-energy-water challenges. Continued advances in photovoltaic technology, digital agriculture, and climate-smart farming are expected to improve system efficiency and accessibility. Future developments may include crop-specific solar designs, transparent photovoltaic materials, adaptive shading systems, and AI-driven management platforms. Integration with regenerative agriculture, carbon farming, and ecosystem restoration initiatives may further enhance sustainability outcomes. As climate change intensifies and competition for land resources increases, agrivoltaics offers a practical pathway toward multifunctional landscapes that simultaneously support food production, renewable energy generation, environmental conservation, and rural development.

Conclusion

Agrivoltaics 2.0 represents a transformative approach to sustainable land management that integrates agricultural production with renewable energy generation. Through strategic modification of microclimatic conditions, agrivoltaic systems can improve water-use efficiency, reduce heat stress, enhance crop resilience, and diversify farm incomes. Technological advancements including dynamic solar tracking, artificial intelligence, precision agriculture, and innovative economic models have significantly expanded the potential of modern agrivoltaic systems. While challenges related to cost, system design, crop compatibility, and policy frameworks remain, growing evidence suggests that Agrivoltaics 2.0 can play a critical role in climate-smart agriculture and sustainable development. By simultaneously addressing food security, energy transition, and climate resilience, agrivoltaics offers a promising pathway toward multifunctional and climate-resilient agricultural landscapes.

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Measurement, Reporting and Verification MRV of Soil Carbon Sequestration: Tech and Policy Gaps

Article ID: 73808

Amit Kumar Pandey¹, Ashutosh Singh¹, Pavan Shukla¹, Sima Kumari¹

¹Bihar Agricultural University, Sabour, Bhagalpur, Bihar.

Abstract

Soil carbon sequestration has emerged as a critical strategy for mitigating climate change while enhancing soil health, agricultural productivity, and ecosystem resilience. Accurate measurement, transparent reporting, and robust verification (MRV) systems are essential to quantify soil organic carbon (SOC) changes, ensure credibility in carbon markets, and support evidence-based policy decisions. This review provides an in-depth analysis of MRV frameworks for soil carbon sequestration, covering methodological approaches, technological advancements, uncertainties, and governance challenges. It highlights the integration of field-based measurements, remote sensing, modelling tools, and digital agriculture in improving MRV systems. Furthermore, the review discusses challenges related to spatial variability, permanence, leakage, and standardization, along with emerging solutions such as blockchain, machine learning, and harmonized protocols. The article concludes by emphasizing the need for scalable, cost-effective, and scientifically robust MRV systems to unlock the full potential of soil carbon sequestration in climate-smart agriculture.

Introduction

Soil represents one of the largest terrestrial carbon reservoirs, storing more carbon than the atmosphere and vegetation combined. Soil organic carbon (SOC) plays a crucial role in regulating climate, maintaining soil fertility, and supporting ecosystem services. Increasing SOC stocks through sustainable land management practices such as conservation agriculture, agroforestry, cover cropping, and organic amendments has been recognized as a viable climate mitigation pathway. However, quantifying SOC changes over time is complex due to inherent spatial variability, temporal dynamics, and methodological limitations. This necessitates the development of robust Measurement, Reporting, and Verification (MRV) systems that can ensure accuracy, transparency, consistency, and comparability. MRV frameworks are central to climate policy mechanisms, including carbon credit systems, nationally determined contributions (NDCs), and international climate agreements.

Conceptual Framework of MRV in Soil Carbon Sequestration

Measurement, reporting, and verification form an integrated system for quantifying greenhouse gas (GHG) emissions and removals. Measurement involves the estimation of SOC stocks and their changes over time. Reporting refers to the standardized documentation and communication of results, while verification ensures the credibility and reliability of reported data through independent assessment. The MRV framework for soil carbon sequestration is guided by principles such as transparency, accuracy, completeness, consistency, and comparability. These principles are aligned with international guidelines established by the Intergovernmental Panel on Climate Change (IPCC). The effectiveness of MRV systems depends on the integration of scientific methodologies, institutional arrangements, and technological innovations.

Measurement of Soil Carbon Sequestration

1. Direct Measurement Approaches: Direct measurement involves field sampling and laboratory analysis of soil organic carbon. Soil samples are typically collected at specified depths and analysed using methods such as dry combustion (e.g., elemental analysers) or wet oxidation techniques. Repeated sampling over time allows the estimation of SOC stock changes. Bulk density measurements are also required to convert carbon concentration into stock values. Despite being highly accurate, direct measurement is labour-intensive, time-consuming, and costly, particularly for large-scale applications.

2. Indirect and Modelling Approaches: Process-based and empirical models are widely used to estimate SOC dynamics. Models such as RothC, Century, and DNDC simulate carbon turnover processes based on inputs such as climate, soil properties, and management practices. These models enable extrapolation across spatial and temporal scales and are integral to MRV frameworks. Remote sensing technologies provide indirect estimates of SOC through proxies such as vegetation indices, land use patterns, and soil reflectance characteristics. Advances in hyperspectral imaging and satellite data have improved the accuracy of SOC prediction models.

3. Emerging Technologies in Measurement: Recent advancements have introduced innovative tools such as in situ soil sensors, spectroscopy (near-infrared and mid-infrared), and portable soil carbon analysers. These technologies enable rapid, non-destructive, and cost-effective measurement of SOC. Machine learning algorithms are increasingly used to

integrate diverse datasets and improve SOC prediction accuracy. Digital soil mapping techniques combine field observations with environmental covariates to generate high-resolution SOC maps.

Reporting of Soil Carbon Sequestration

Reporting is a critical component of MRV systems, ensuring that SOC data are communicated in a standardized and transparent manner. Reporting frameworks are typically aligned with IPCC guidelines and national greenhouse gas inventories. SOC changes are reported in terms of carbon stock changes or CO₂ equivalents, considering factors such as land use, management practices, and emission factors. Tiered approaches (Tier 1, Tier 2, and Tier 3) are used to represent increasing levels of methodological complexity and accuracy. Digital platforms and databases play a significant role in reporting, enabling real-time data sharing and integration. Standardized protocols and reporting templates enhance comparability across regions and projects.

Verification of Soil Carbon Sequestration

Verification ensures the credibility and reliability of reported SOC data. It involves independent assessment by third-party auditors who evaluate methodologies, data quality, and compliance with standards. Verification processes include field inspections, data audits, and cross-validation with independent datasets. Statistical methods are used to assess uncertainties and ensure that reported SOC changes are significant and not due to measurement errors. Certification standards such as Verified Carbon Standard (VCS) and Gold Standard provide guidelines for verification in carbon offset projects. Robust verification mechanisms are essential for building trust in carbon markets and ensuring environmental integrity.

Uncertainty and Challenges in MRV Systems

- 1. Spatial and Temporal Variability:** SOC is highly heterogeneous, varying across soil types, land uses, and climatic conditions. This variability introduces significant uncertainty in measurement and modelling. Long-term monitoring is required to capture meaningful changes in SOC stocks.
- 2. Permanence and Reversibility:** Carbon sequestered in soils can be released back into the atmosphere due to land use changes, climate variability, or management practices. Ensuring permanence is a major challenge in soil carbon projects.
- 3. Leakage:** Leakage refers to unintended increases in emissions outside the project boundary as a result of project activities. MRV systems must account for such effects to ensure accurate estimation of net carbon benefits.
- 4. Cost and Scalability:** High costs associated with soil sampling, laboratory analysis, and verification limit the scalability of MRV systems. Developing cost-effective approaches is crucial for widespread adoption.
- 5. Standardization and Harmonization:** Lack of standardized methodologies and protocols hampers comparability across studies and regions. Harmonization of MRV frameworks is necessary for global implementation.

Advances and Innovations in MRV Systems

- 1. Integration of Digital Technologies:** Digital agriculture tools, including geographic information systems (GIS), remote sensing, and big data analytics, have significantly enhanced MRV capabilities. These tools enable large-scale monitoring and improve data accuracy.
- 2. Role of Blockchain in MRV:** Blockchain technology offers a decentralized and transparent platform for recording and verifying carbon transactions. It enhances traceability, reduces fraud, and improves trust in carbon markets.
- 3. Machine Learning and Artificial Intelligence:** AI and machine learning algorithms are increasingly used to analyze complex datasets, improve SOC predictions, and reduce uncertainties. These technologies enable the integration of diverse data sources, including soil, climate, and management data.
- 4. Participatory and Community-Based Approaches:** Engaging farmers and local communities in data collection and reporting can enhance the scalability and effectiveness of MRV systems. Participatory approaches also improve data ownership and transparency.

Policy and Institutional Frameworks

MRV systems are integral to climate policies and international agreements such as the Paris Agreement. National governments play a key role in developing MRV frameworks, supported by international organizations and research institutions. Policies promoting sustainable land management and incentivizing carbon sequestration are essential for the success of MRV systems. Capacity building, institutional support, and financial mechanisms are critical components of effective MRV implementation.

Future Perspectives

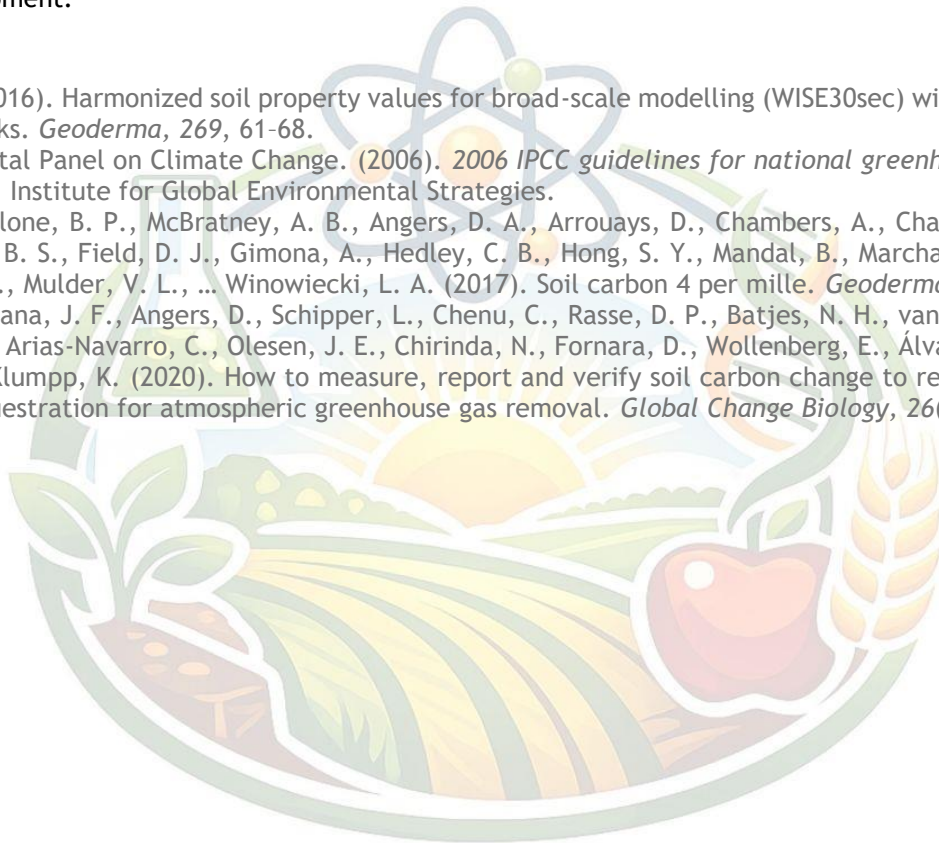
The future of MRV in soil carbon sequestration lies in the development of integrated, scalable, and cost-effective systems. Advances in sensor technologies, remote sensing, and data analytics will continue to improve measurement accuracy and reduce costs. Harmonization of methodologies and the establishment of global standards will enhance comparability and facilitate international collaboration. Integration of MRV systems with carbon markets and climate policies will unlock new opportunities for sustainable agriculture and climate mitigation.

Conclusion

Measurement, reporting, and verification systems are fundamental to the success of soil carbon sequestration initiatives. While significant progress has been made in developing MRV frameworks, challenges related to uncertainty, cost, and standardization remain. The integration of advanced technologies, standardized protocols, and supportive policies can enhance the effectiveness and scalability of MRV systems. Strengthening MRV frameworks will not only ensure the credibility of soil carbon sequestration efforts but also contribute to global climate mitigation and sustainable agricultural development.

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Neglected and Underutilized Crops for Climate-Proof Food Systems: A Review of Millets, Quinoa, and Amaranth

Article ID: 73809

Pavan Shukla¹, Ashutosh Singh¹, Sima Kumari¹, Amit Kumar Pandey¹

¹Bihar Agricultural University, Sabour, Bhagalpur, Bihar.

Abstract

Global agriculture is increasingly challenged by climate change, environmental degradation, shrinking natural resources, and the growing demand for nutritious food. Conventional food systems rely heavily on a few staple crops such as rice, wheat, and maize, making global food security vulnerable to climatic shocks, pest outbreaks, and resource scarcity. Neglected and underutilized crops (NUCs) have emerged as promising alternatives capable of enhancing agricultural resilience, nutritional security, and sustainability. Among these, millets, quinoa, and amaranth possess remarkable adaptability to marginal environments, drought tolerance, low input requirements, and superior nutritional profiles. These crops have been cultivated for centuries by indigenous communities but have received limited scientific, commercial, and policy attention compared to major cereals. In recent years, however, increasing recognition of their climate resilience and nutritional value has renewed global interest in their cultivation and utilization. This review examines the role of millets, quinoa, and amaranth in developing climate-proof food systems. The article discusses their agronomic characteristics, climate resilience mechanisms, nutritional significance, contribution to sustainable agriculture, economic potential, challenges to wider adoption, and future prospects. The review highlights how these crops can contribute significantly to diversified, resilient, and sustainable food systems capable of addressing the intertwined challenges of climate change, malnutrition, and food insecurity.

Introduction

Agriculture is at the forefront of climate change impacts. Rising temperatures, altered precipitation patterns, increasing frequency of droughts and floods, salinity intrusion, land degradation, and biodiversity loss are threatening global food production. Modern agricultural systems are heavily dependent on a limited number of crop species. Approximately 60–70% of global caloric intake is derived from rice, wheat, and maize, creating a high degree of vulnerability to environmental stresses and market fluctuations. Such dependence on a narrow genetic base reduces the resilience of food systems and limits adaptation opportunities under changing climatic conditions.

The Food and Agriculture Organization has emphasized the importance of agricultural diversification to ensure future food security. One promising strategy involves the promotion of neglected and underutilized crops (NUCs), which are species that have historically played important roles in local food systems but have received limited research, policy, and commercial attention compared with major staple crops. These crops are often adapted to marginal environments and possess unique traits that enable them to withstand harsh climatic conditions while providing nutritious food.

Millets, quinoa, and amaranth are among the most important NUCs attracting global attention. Their exceptional adaptability, low water requirements, high nutritional quality, and ability to thrive under adverse environmental conditions position them as strategic crops for climate-resilient agriculture. The increasing global recognition of these crops is reflected in initiatives such as the declaration of 2023 as the International Year of Millets by the United Nations. These crops offer opportunities to improve dietary diversity, enhance farmer livelihoods, conserve agrobiodiversity, and strengthen food system resilience in the face of climate change.

Concept and Significance of Neglected and Underutilized Crops

Neglected and underutilized crops represent plant species that are locally important but globally overlooked. They often possess significant genetic diversity and have evolved under diverse environmental conditions over centuries. These crops are generally cultivated by smallholder farmers in marginal environments where major crops perform poorly.

The importance of NUCs extends beyond agricultural production. They contribute to food sovereignty, nutritional security, cultural heritage preservation, biodiversity conservation, and climate adaptation. Their cultivation supports resilient farming systems by reducing dependence on a limited number of crops and enhancing ecosystem stability. According to Padulosi et al. (2013), neglected crops can play a crucial role in addressing food insecurity, poverty alleviation, and sustainable agricultural development, particularly in vulnerable regions. Climate-resilient agriculture increasingly recognizes NUCs as valuable genetic resources capable of supporting adaptation strategies. Their resilience to drought, heat, poor soils, and other environmental stresses makes them particularly suitable for future climate scenarios.

MILLETS



QUINOA



AMARANTH



Millets: Ancient Grains for Future Food Security

Millets comprise a diverse group of small-seeded cereal crops belonging primarily to the Poaceae family. Important millet species include pearl millet (*Pennisetum glaucum*), finger millet (*Eleusine coracana*), foxtail millet (*Setaria italica*), proso millet (*Panicum miliaceum*), barnyard millet (*Echinochloa frumentacea*), kodo millet (*Paspalum scrobiculatum*), and little millet (*Panicum sumatrense*).

Millets have been cultivated for thousands of years across Asia and Africa and are among the earliest domesticated cereal crops. They are particularly important in arid and semi-arid regions where rainfall is limited and environmental conditions are challenging. One of the most remarkable characteristics of millets is their exceptional tolerance to drought. Their efficient root systems, short growth cycles, and ability to maintain productivity under water stress make them highly suitable for climate-affected regions. Millets require significantly less water compared to rice and wheat. Many millet species can produce satisfactory yields with annual rainfall ranging between 250 and 500 mm.

Millets also exhibit high tolerance to elevated temperatures. Their C4 photosynthetic pathway allows efficient carbon fixation under high-temperature conditions, enhancing water-use efficiency and reducing photorespiration losses. This physiological advantage enables them to maintain productivity under heat stress conditions increasingly prevalent due to global warming. Another important advantage is their adaptability to poor soils. Millets can grow successfully in nutrient-deficient, acidic, alkaline, and degraded soils where conventional cereals often fail. Their low input requirements make them particularly suitable for resource-constrained farmers.

Nutritionally, millets are rich sources of dietary fiber, protein, minerals, vitamins, antioxidants, and phytochemicals. Finger millet is particularly notable for its exceptionally high calcium content, while pearl millet contains significant levels of iron and zinc. Research by Saleh et al. (2013) demonstrated that millets provide superior nutritional quality compared to many conventional cereals and can contribute substantially to combating micronutrient deficiencies.

Quinoa: The Golden Grain of the Andes

Quinoa (*Chenopodium quinoa* Willd.) is a pseudo-cereal originating from the Andean region of South America. Historically cultivated by indigenous communities for over 7,000 years, quinoa has gained worldwide recognition due to its exceptional nutritional composition and remarkable environmental adaptability. Quinoa possesses extraordinary genetic diversity, allowing cultivation across a wide range of environmental conditions. It can grow from sea level to elevations exceeding 4,000 meters and tolerates diverse climatic conditions including drought, frost, salinity, and poor soil fertility.

One of the most important characteristics of quinoa is its exceptional drought tolerance. The crop possesses deep rooting systems, osmotic adjustment mechanisms, and efficient water-use strategies that enable survival under prolonged moisture stress. Quinoa can produce acceptable yields under rainfall levels considerably lower than those required by many conventional crops.

Salinity tolerance represents another unique feature of quinoa. The crop can withstand saline conditions that severely limit the productivity of most staple cereals. Studies by Jacobsen et al. (2003) highlighted quinoa's ability to maintain growth and productivity under high salinity environments, making it particularly valuable in regions affected by soil salinization. Quinoa is nutritionally exceptional because it contains all nine essential amino acids in balanced proportions. Unlike most cereals, quinoa provides complete protein comparable in quality to animal protein. The crop is also rich in dietary fiber, vitamins, minerals, antioxidants, and bioactive compounds.

The grain contains substantial amounts of magnesium, phosphorus, iron, potassium, calcium, zinc, and vitamin E. Additionally, quinoa is gluten-free, making it suitable for individuals suffering from celiac disease and gluten intolerance. The crop's adaptability to diverse agroecological conditions has led to successful introduction into more than 100 countries. Its cultivation is expanding rapidly as nations seek climate-resilient and nutritious alternatives to conventional crops.

Amaranth: A Resilient Nutritional Powerhouse

Amaranth belongs to the genus *Amaranthus*, which includes approximately 70 species. Grain amaranths such as *Amaranthus hypochondriacus*, *Amaranthus cruentus*, and *Amaranthus caudatus* are particularly important for food production. Amaranth has a long history of cultivation dating back thousands of years in Central and South America. Despite its ancient importance, the crop remained largely neglected during the expansion of modern agricultural systems.

Amaranth possesses remarkable adaptability to adverse environmental conditions. It demonstrates excellent tolerance to drought, heat stress, and poor soil fertility. The crop's C4 photosynthetic pathway contributes to efficient carbon assimilation and superior water-use efficiency. The deep and extensive root system of amaranth enables effective extraction of soil moisture under drought conditions. Furthermore, its rapid growth rate allows completion of the life cycle within relatively short periods, reducing exposure to prolonged environmental stresses. Amaranth exhibits impressive resilience to high temperatures. Studies have shown that it can maintain physiological activity and productivity under temperatures that significantly reduce yields in conventional cereal crops.

Nutritionally, amaranth is considered one of the most valuable pseudo-cereals. The grain contains high-quality protein with elevated levels of lysine, an essential amino acid often deficient in cereals. According to Rastogi and Shukla (2013), amaranth grain contains approximately 13-18% protein and possesses an amino acid composition superior to many conventional cereals. Amaranth is also rich in dietary fiber, calcium, iron, magnesium, phosphorus, potassium, and vitamins. Additionally, it contains bioactive compounds such as squalene, tocopherols, phenolic compounds, and flavonoids that contribute to antioxidant activity and potential health benefits.

Climate Resilience Mechanisms in Millets, Quinoa, and Amaranth

The climate resilience of these crops results from a combination of physiological, morphological, biochemical, and genetic adaptations. Efficient water-use mechanisms enable survival under drought conditions. Deep root systems facilitate access to moisture stored in deeper soil layers. Osmotic adjustment mechanisms help maintain cellular function during water stress.

Heat tolerance is enhanced through efficient photosynthetic pathways, particularly in millets and amaranth, which utilize C4 photosynthesis. These pathways reduce photorespiration and maintain productivity under elevated temperatures. Salinity tolerance, especially pronounced in quinoa, involves ion compartmentalization, osmotic regulation, and specialized physiological adaptations that minimize salt-induced damage. Genetic diversity within these crops provides a broad reservoir of adaptive traits that can be utilized in breeding programs aimed at developing climate-resilient varieties.

Contribution to Sustainable and Climate-Proof Food Systems

The incorporation of millets, quinoa, and amaranth into agricultural systems can significantly enhance sustainability and resilience. Diversification reduces production risks associated with climatic variability and pest outbreaks. Mixed cropping systems involving these crops improve ecosystem stability and resource-use efficiency. These crops contribute to sustainable intensification by maintaining productivity with lower external inputs. Reduced requirements for irrigation, fertilizers, and pesticides decrease environmental impacts while lowering production costs.

The cultivation of NUCs also promotes agrobiodiversity conservation. Preserving diverse crop species and varieties enhances ecosystem resilience and maintains valuable genetic resources essential for future breeding efforts. Climate-proof food systems require both production resilience and nutritional adequacy. Millets, quinoa, and amaranth contribute

to both objectives by providing stable yields under adverse conditions and delivering nutrient-dense foods capable of addressing hidden hunger and malnutrition.

Nutritional Security and Human Health Benefits

Malnutrition remains a major global challenge despite increases in food production. Micronutrient deficiencies affect billions of people worldwide, particularly in developing countries. Diversification of diets through nutrient-rich crops is increasingly recognized as a critical strategy for improving nutritional outcomes.

Millets provide substantial amounts of iron, zinc, calcium, magnesium, and dietary fiber. Their low glycemic index contributes to improved blood glucose regulation and reduced risk of metabolic disorders. Quinoa offers complete protein, making it particularly valuable for vegetarian and vegan diets. Its rich mineral and antioxidant content supports overall health and disease prevention. Amaranth provides high-quality protein, essential amino acids, minerals, and bioactive compounds with antioxidant properties. Regular consumption may contribute to improved cardiovascular health, immune function, and nutritional status. The integration of these crops into food systems can enhance dietary diversity and support healthier populations while simultaneously strengthening agricultural resilience.

Economic Potential and Livelihood Opportunities

The growing global demand for healthy and sustainable foods has created new market opportunities for NUCs. Millets, quinoa, and amaranth are increasingly incorporated into functional foods, health products, gluten-free foods, bakery products, beverages, and nutraceuticals. Expansion of value chains can generate income opportunities for smallholder farmers, particularly in marginal regions where conventional crop production is constrained. Processing industries based on these crops can create employment and stimulate rural economic development. International recognition of millets and growing consumer awareness regarding nutritious foods are driving market expansion. Similarly, quinoa has transformed from a traditional Andean crop into a globally traded commodity, demonstrating the economic potential of underutilized crops.

Constraints to Wider Adoption

Despite their numerous advantages, several barriers limit large-scale adoption of millets, quinoa, and amaranth. Limited research investment has resulted in slower genetic improvement compared to major cereals. Yield potential remains relatively lower under optimal conditions, reducing competitiveness in intensive production systems. Weak seed systems often restrict access to improved varieties. Inadequate processing technologies, limited value addition infrastructure, poor market development, and low consumer awareness further constrain expansion.

Policy support remains insufficient in many countries where agricultural programs continue to prioritize major staple crops. Investment in research, extension services, marketing infrastructure, and value chain development is essential for overcoming these challenges. Consumer perceptions also influence adoption. In some regions, traditional crops are viewed as "poor people's foods," reducing demand despite their nutritional superiority. Educational campaigns and product innovation are necessary to improve market acceptance.

Future Perspectives

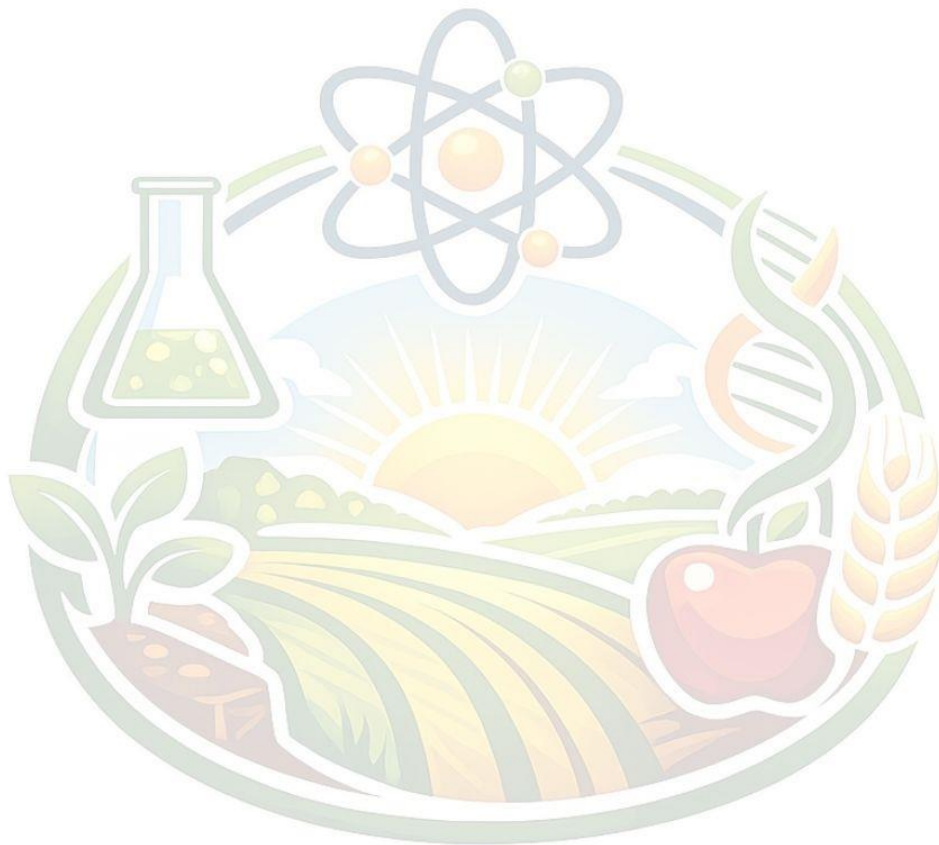
Future agricultural development must increasingly focus on diversification and resilience. Advances in genomics, molecular breeding, and biotechnology offer opportunities for improving productivity, stress tolerance, and nutritional quality of NUCs. Climate-smart agricultural policies should integrate millets, quinoa, and amaranth into national food security strategies. Public investment in breeding programs, seed systems, processing technologies, and market development will be crucial for unlocking their full potential. Research should prioritize understanding adaptive mechanisms, improving agronomic practices, developing climate-resilient varieties, and enhancing value chains. Greater collaboration among researchers, policymakers, farmers, and private sector stakeholders will accelerate adoption. Educational initiatives promoting awareness of nutritional and environmental benefits can stimulate consumer demand and support market growth. Integrating these crops into school feeding programs, public food procurement systems, and nutrition interventions can further enhance their impact.

Conclusion

Neglected and underutilized crops such as millets, quinoa, and amaranth represent valuable resources for building climate-proof food systems. Their remarkable resilience to drought, heat, salinity, and poor soil conditions positions them as strategic crops for climate adaptation. Simultaneously, their superior nutritional profiles contribute to addressing malnutrition and promoting human health. These crops support agricultural diversification, biodiversity conservation, sustainable resource use, and rural livelihood development. Although significant challenges remain regarding research investment, market development, consumer awareness, and policy support, the growing recognition of their importance presents unprecedented opportunities. Harnessing the full potential of millets, quinoa, and amaranth can contribute substantially to resilient, sustainable, and nutritionally secure food systems capable of meeting future global challenges.

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Soil Microbiome Engineering for Regenerative Farming: Meta-Omics Insights and Field Applications

Article ID: 73810

Ashutosh Singh¹, Amit Kumar Pandey¹, Pavan Shukla¹, Sima Kumari¹

¹Bihar Agricultural University, Sabour, Bhagalpur, Bihar.

Abstract

Regenerative farming has emerged as a transformative agricultural approach aimed at restoring soil health, enhancing biodiversity, improving ecosystem resilience, and promoting sustainable food production. Central to this paradigm is the soil microbiome, a highly complex community of bacteria, fungi, archaea, protozoa, algae, viruses, and other microorganisms that regulate nutrient cycling, organic matter decomposition, plant growth, and ecosystem stability. Soil microbiome engineering refers to the deliberate manipulation, enhancement, or management of microbial communities to improve soil functionality and agricultural sustainability. Recent advances in molecular biology, metagenomics, synthetic biology, microbial ecology, and precision agriculture have expanded opportunities to engineer soil microbiomes for regenerative farming systems. These approaches include microbial inoculation, synthetic microbial consortia, host-mediated microbiome selection, biofertilizers, biostimulants, conservation agriculture, organic amendments, and microbiome-guided crop management. Engineered soil microbiomes contribute to carbon sequestration, nutrient-use efficiency, disease suppression, drought tolerance, climate resilience, and restoration of degraded lands. Despite significant progress, challenges related to microbial establishment, ecological stability, environmental variability, scalability, and regulatory concerns remain. This review comprehensively examines the principles, mechanisms, technologies, applications, opportunities, and future prospects of soil microbiome engineering in regenerative farming while highlighting its role in developing climate-resilient and sustainable agricultural systems.

Introduction

Modern agriculture has significantly increased global food production through intensive cultivation practices, mechanization, synthetic fertilizers, pesticides, and irrigation systems. However, these achievements have been accompanied by severe ecological consequences, including soil degradation, loss of biodiversity, nutrient imbalance, greenhouse gas emissions, declining soil organic matter, and reduced ecosystem resilience. The growing recognition of these challenges has stimulated interest in regenerative farming, an agricultural philosophy focused on restoring ecological processes while maintaining productivity. Regenerative farming emphasizes soil regeneration, biodiversity enhancement, reduced external inputs, improved water retention, carbon sequestration, and ecosystem restoration. At the centre of these processes lies the soil microbiome, which acts as a biological engine driving nutrient transformations, soil aggregation, plant health, and ecosystem functioning. The soil microbiome represents one of the most diverse biological systems on Earth, containing billions of microorganisms and thousands of species within a single gram of soil.

Recent advances in microbiome science have transformed our understanding of plant-soil-microbe interactions. High-throughput sequencing technologies, metagenomics, metatranscriptomics, metabolomics, and systems biology approaches have revealed intricate microbial networks that influence crop productivity and ecosystem sustainability. Consequently, soil microbiome engineering has emerged as a promising strategy for regenerative farming by actively managing microbial communities to enhance beneficial functions and suppress detrimental processes.

Concept of Soil Microbiome Engineering

Soil microbiome engineering refers to the intentional manipulation of soil microbial communities to achieve desired agricultural and ecological outcomes. Unlike traditional soil management approaches that primarily focus on chemical and physical properties, microbiome engineering directly targets biological processes within the soil ecosystem. The concept involves modifying microbial composition, diversity, abundance, interactions, and functionality through biological, ecological, genetic, and agronomic interventions. The ultimate objective is to establish resilient microbial communities capable of supporting sustainable crop production while restoring ecosystem health.

Microbiome engineering encompasses various approaches including microbial inoculants, synthetic microbial communities, microbiome transplantation, host-mediated microbial selection, genomic engineering of beneficial microorganisms, and agricultural management practices that promote beneficial microbial assemblages. These interventions aim to enhance nutrient acquisition, stress tolerance, disease suppression, carbon sequestration, and soil regeneration. According to Trivedi et al. (2020), plant-associated microbiomes function as dynamic biological networks that mediate interactions between plants and their environment, thereby influencing plant growth, health, and productivity. Understanding these interactions forms the foundation of microbiome engineering strategies.

Soil Microbiome Composition and Diversity

The soil microbiome consists of a vast array of microorganisms occupying diverse ecological niches within soil aggregates, rhizospheres, root surfaces, and plant tissues. Bacteria represent the most abundant members of soil microbial communities. Dominant bacterial phyla include Proteobacteria, Actinobacteria, Acidobacteria, Firmicutes, and Bacteroidetes. These microorganisms participate in nutrient cycling, decomposition, nitrogen fixation, and pathogen suppression.

Fungi constitute another major component of the soil microbiome. Mycorrhizal fungi establish symbiotic relationships with plant roots, facilitating nutrient uptake and improving stress tolerance. Saprophytic fungi contribute significantly to organic matter decomposition and carbon cycling. Archaea are increasingly recognized for their role in nitrogen transformations and adaptation to extreme environmental conditions. Protozoa regulate bacterial populations through predation, thereby influencing nutrient availability. Soil viruses, particularly bacteriophages, shape microbial community dynamics by controlling bacterial abundance and genetic exchange. The interactions among these organisms create highly interconnected ecological networks that determine soil functionality and ecosystem resilience.

Role of Soil Microbiomes in Regenerative Farming

The success of regenerative farming largely depends on the restoration and maintenance of healthy soil microbial communities. Soil microorganisms perform numerous ecosystem services essential for sustainable agricultural production. One of the most important functions is nutrient cycling. Microorganisms decompose organic residues and convert complex organic compounds into plant-available nutrients. Nitrogen-fixing bacteria transform atmospheric nitrogen into biologically usable forms, while phosphate-solubilizing microorganisms mobilize unavailable phosphorus.

Microbial communities also contribute to soil aggregation through the production of extracellular polymeric substances and fungal hyphae. Stable soil aggregates improve soil structure, aeration, water infiltration, and erosion resistance. Disease suppression represents another critical service provided by soil microbiomes. Beneficial microorganisms compete with pathogens for resources and space, produce antimicrobial compounds, and induce systemic resistance in plants. Diverse microbial communities often enhance ecosystem stability and reduce pathogen outbreaks.

Furthermore, soil microbiomes regulate carbon sequestration by influencing decomposition rates and stabilization of soil organic matter. These processes are particularly important in regenerative farming systems aimed at mitigating climate change. Banerjee and van der Heijden (2022) emphasized that soil microbiomes are fundamental drivers of sustainable agriculture because they regulate nutrient cycling, plant health, and ecosystem multifunctionality.

Rhizosphere Engineering and Plant-Microbe Interactions

The rhizosphere is a highly dynamic zone surrounding plant roots where intense interactions occur between plants and microorganisms. Plant roots release exudates containing sugars, amino acids, organic acids, flavonoids, and signalling molecules that shape microbial community composition. Rhizosphere engineering involves manipulating root-associated microbial communities to enhance beneficial interactions. Plants selectively recruit microorganisms capable of promoting growth, suppressing diseases, and improving stress tolerance. This recruitment process provides opportunities for targeted microbiome engineering.

Beneficial rhizosphere microorganisms known as plant growth-promoting rhizobacteria (PGPR) stimulate plant growth through multiple mechanisms. These include nitrogen fixation, phosphate solubilization, phytohormone production, siderophore synthesis, and pathogen antagonism. Mycorrhizal fungi significantly expand the effective root surface area, improving nutrient and water uptake. Arbuscular mycorrhizal fungi also contribute to soil aggregation and carbon stabilization. Understanding the molecular communication between plants and microbes has enabled researchers to develop strategies for enhancing beneficial associations through microbiome engineering.

Microbial Inoculants and Biofertilizers

Microbial inoculants represent one of the most widely adopted microbiome engineering tools in regenerative agriculture. These products contain beneficial microorganisms introduced into soil or plant systems to improve crop performance. Biofertilizers typically include nitrogen-fixing bacteria such as *Rhizobium*, *Azotobacter*, and *Azospirillum*, phosphate-solubilizing bacteria including *Bacillus* and *Pseudomonas* species, and potassium-mobilizing microorganisms. The application of microbial inoculants can reduce dependence on synthetic fertilizers while enhancing nutrient-use efficiency. Additionally, many inoculants improve plant resilience against environmental stresses.

Recent developments have shifted from single-strain inoculants toward multi-species microbial consortia capable of providing complementary functions. These consortia often demonstrate greater ecological stability and effectiveness under field conditions. However, successful establishment of introduced microorganisms remains a major challenge due to competition with native microbial communities and environmental variability.

Synthetic Microbial Communities

Synthetic microbial communities, commonly known as SynComs, represent an advanced form of microbiome engineering. These communities consist of carefully selected microbial species assembled to perform specific ecological functions. SynComs are designed based on ecological principles, functional complementarity, and microbial interaction networks. Researchers select microorganisms capable of working synergistically to enhance nutrient acquisition, disease resistance, stress tolerance, and soil restoration.

Compared with single-strain inoculants, synthetic communities often exhibit greater stability, resilience, and functionality. Functional redundancy within SynComs can ensure ecosystem services even when certain species decline. The design of SynComs increasingly relies on metagenomic data, ecological modelling, and machine learning approaches that identify keystone species and beneficial microbial interactions. According to Toju et al. (2022), identifying and managing core microbiomes may provide a foundation for developing sustainable agroecosystems capable of maintaining productivity while enhancing ecological resilience.

Host-Mediated Microbiome Selection

Host-mediated microbiome selection is an emerging strategy that utilizes plants themselves as agents for selecting beneficial microbial communities. This approach exploits the natural ability of plants to recruit and shape microbiomes through root exudates and immune signalling mechanisms. Repeated selection cycles can gradually enrich microbial communities that enhance desired plant traits such as drought tolerance, nutrient efficiency, disease resistance, and productivity. This technique mirrors traditional plant breeding but focuses on microbial communities rather than plant genetics alone. Host-mediated selection may provide a sustainable and low-cost method for engineering microbiomes adapted to local environmental conditions. The approach has shown promising results in improving plant performance under abiotic stresses and may play a major role in future regenerative farming systems.

Organic Amendments and Microbiome Engineering

Organic amendments significantly influence soil microbial communities and are widely used in regenerative agriculture. Compost, farmyard manure, biochar, vermicompost, green manure, crop residues, and cover crops provide substrates that stimulate microbial growth and activity. Compost introduces diverse microbial populations while increasing organic matter content. Biochar creates favourable habitats for microbial colonization and improves nutrient retention. Cover crops support microbial diversity through continuous root exudation and organic matter inputs. Organic amendments enhance microbial biomass, enzymatic activities, nutrient cycling, and soil aggregation. Long-term application often results in more stable and resilient microbial communities compared with conventional agricultural systems. The integration of organic amendments with microbial inoculants may produce synergistic effects that accelerate soil regeneration and ecosystem restoration.

Soil Microbiome Engineering for Carbon Sequestration

Carbon sequestration is a major objective of regenerative farming because of its potential to mitigate climate change. Soil microorganisms play a critical role in carbon storage through decomposition, humification, and stabilization processes. Microbial communities influence the formation of soil organic matter and stable carbon pools. Certain microorganisms produce extracellular compounds that contribute to aggregate formation and protection of organic carbon from decomposition.

Fungal networks, particularly mycorrhizal fungi, facilitate carbon transfer within soil ecosystems and contribute to long-term carbon stabilization. Regenerative practices such as reduced tillage, cover cropping, and organic amendments promote microbial-mediated carbon sequestration. Enhanced microbial diversity often increases ecosystem resilience and improves the capacity of soils to store carbon under changing climatic conditions.

Disease Suppression through Microbiome Manipulation

Soil-borne diseases are major constraints to agricultural productivity worldwide. Microbiome engineering offers sustainable alternatives to chemical pesticides by harnessing naturally occurring microbial antagonists. Beneficial microorganisms suppress pathogens through competition, antibiosis, parasitism, niche exclusion, and induction of plant immune responses. Diverse microbial communities can create suppressive soils where pathogens fail to establish or cause disease. Engineering disease-suppressive microbiomes involves introducing beneficial microorganisms, promoting native antagonists, and enhancing microbial diversity through regenerative management practices. These strategies contribute to long-term ecosystem stability while reducing environmental impacts associated with pesticide use.

Climate Resilience and Abiotic Stress Tolerance

Climate change is increasing the frequency and intensity of droughts, heat waves, salinity stress, and extreme weather events. Soil microbiomes play crucial roles in helping plants adapt to these environmental challenges. Beneficial microorganisms enhance plant tolerance through phytohormone regulation, osmolyte production, antioxidant activation,

nutrient acquisition, and improved water-use efficiency. Certain microbial communities can alter root architecture and improve plant resilience under adverse conditions.

Engineered microbiomes capable of supporting crop performance under climate stress are becoming increasingly important for sustainable food production. Recent studies indicate that microbiome-based interventions can significantly improve crop survival and productivity under drought and salinity conditions, making them valuable tools for climate-resilient regenerative agriculture.

Advanced Technologies in Soil Microbiome Engineering

Rapid technological advances have accelerated the development of soil microbiome engineering. High-throughput sequencing technologies allow comprehensive characterization of microbial communities and their functional capabilities. Metagenomics reveals microbial genetic diversity, while metatranscriptomics provides insights into active biological processes. Metabolomics identifies biochemical interactions among plants, microbes, and the environment.

Artificial intelligence and machine learning increasingly support predictive modelling of microbiome behaviour and ecosystem responses. These technologies facilitate identification of keystone species, functional networks, and optimal microbial combinations. Synthetic biology has further expanded opportunities for engineering microorganisms with enhanced functional capabilities. Genetic modification can improve nutrient acquisition, stress tolerance, pathogen suppression, and environmental adaptation. Walter et al. (2021) highlighted the growing potential of microbiome editing technologies for manipulating complex microbial communities and improving ecosystem functionality.

Challenges in Soil Microbiome Engineering

Despite considerable progress, several challenges hinder large-scale implementation of microbiome engineering in regenerative farming. One major limitation is the complexity of soil ecosystems. Microbial communities are influenced by numerous interacting factors including soil type, climate, crop species, management practices, and environmental conditions. Introduced microorganisms often fail to establish stable populations because of competition with native microbiota. Ecological unpredictability may reduce the consistency of microbiome-based interventions across locations and seasons.

Technical limitations in microbial cultivation, formulation, delivery systems, and long-term monitoring further complicate implementation. Economic constraints, regulatory requirements, and farmer adoption barriers also influence commercialization and field deployment. Addressing these challenges requires interdisciplinary collaboration among microbiologists, soil scientists, agronomists, ecologists, data scientists, and policymakers.

Future Prospects

The future of soil microbiome engineering is closely linked to advances in systems biology, artificial intelligence, synthetic biology, and precision agriculture. Emerging technologies may enable the development of customized microbiome solutions tailored to specific crops, soils, and environmental conditions. Integration of microbiome engineering with regenerative farming practices has the potential to transform agricultural systems from input-intensive models toward biologically driven and self-sustaining ecosystems. Future research will likely focus on identifying core microbiomes, developing resilient synthetic communities, enhancing microbial persistence, and improving predictive models for ecosystem management. Precision microbiome management may become a cornerstone of next-generation regenerative agriculture. As global challenges related to food security, climate change, and environmental degradation intensify, microbiome engineering offers promising pathways for restoring ecosystem functionality while maintaining agricultural productivity.

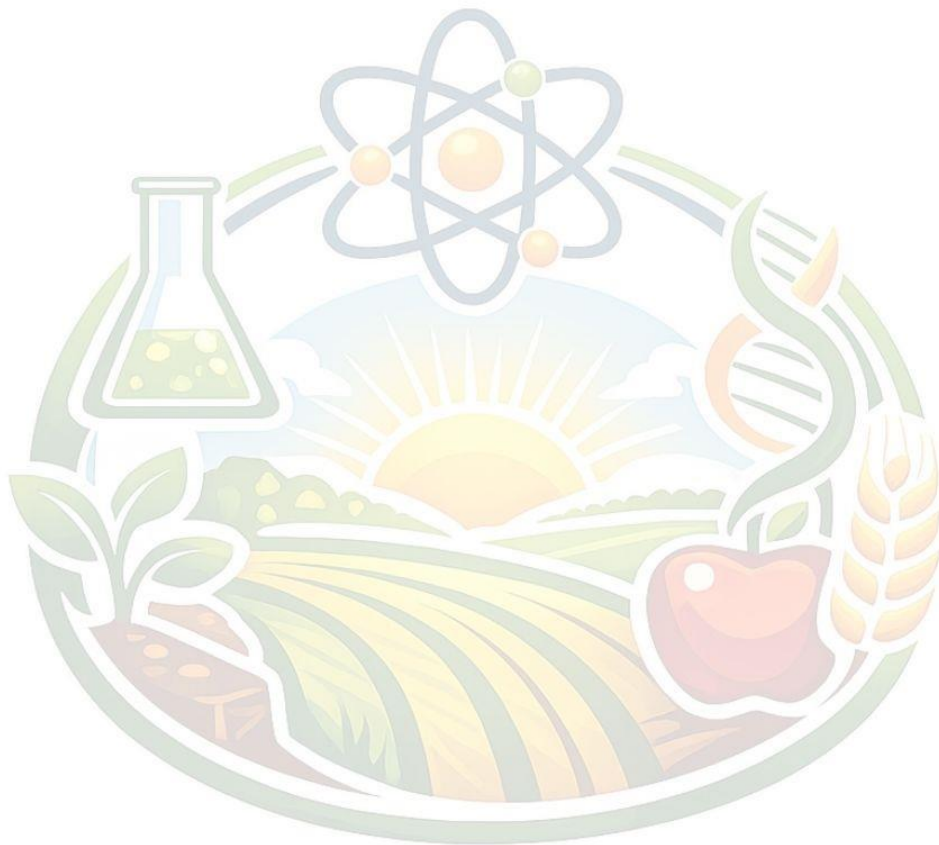
Conclusion

Soil microbiome engineering represents one of the most promising frontiers in regenerative farming and sustainable agriculture. By intentionally managing microbial communities, it becomes possible to enhance nutrient cycling, improve soil structure, suppress diseases, increase carbon sequestration, and strengthen climate resilience. Advances in omics technologies, synthetic biology, and ecological modeling have greatly expanded our capacity to understand and manipulate complex soil microbial systems. Although significant challenges remain regarding ecological stability, field performance, and large-scale adoption, the integration of microbiome engineering with regenerative farming principles provides a powerful framework for restoring degraded ecosystems and developing resilient agricultural systems. Continued research and innovation will be essential for translating scientific discoveries into practical solutions capable of supporting global food security while safeguarding environmental sustainability.

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Drones Over Mulberry Gardens: Innovation in Indian Sericulture

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Samreen¹, B. Samuel Naik²

¹CSB-Central Sericultural Research and Training Institute, Berhampore, West Bengal-742101, India.

²CSB-Central Sericultural Research and Training Institute, Mysuru, Karnataka-570008, India.

Abstract

Sericulture is an important agro-based industry in India, supporting rural livelihoods and silk production, but it faces challenges such as climate variability, pests, labour shortages, and high production costs. This study reviews the role of smart farming technologies, particularly drones, IoT, and AI, in modernizing sericulture. Drone-based systems enable efficient mulberry monitoring, pest and disease detection, precision spraying, and irrigation management, leading to improved crop health and productivity. Case studies from India show that adoption of these technologies enhances cocoon yield, reduces input costs, and improves farmer income. Government initiatives supporting drone use, digital agriculture, and skill development further promote technology adoption in the sector. However, high costs, lack of technical knowledge, and limited rural infrastructure remain key barriers. The study concludes that smart sericulture technologies can significantly improve productivity and sustainability, provided adequate policy support, training, and infrastructure development are ensured.

Introduction

Sericulture is an important agro-based industry in India that supports rural livelihoods, employment, and silk production. India is one of the leading silk-producing countries, with millions of farmers engaged in mulberry cultivation and silkworm rearing. Traditionally, sericulture depends on manual labour and conventional management practices, but challenges such as climate change, pest and disease outbreaks, labour shortages and rising costs have created the need for modern technologies. In recent years, precision agriculture tools have gained importance, with drones (UAVs) emerging as key innovations. Equipped with advanced cameras, multispectral sensors, thermal imaging, and GPS, drones are widely used for crop monitoring, pest and disease detection, irrigation management, and precision spraying. Their application in sericulture offers strong potential to improve mulberry productivity and overall silk production efficiency.

Successful Case Studies and Emerging Innovations in Smart Sericulture

1. Drone-Based Monitoring in Indian Sericulture: A recent study highlighted the potential of drones in Indian sericulture for monitoring mulberry plantations, detecting pest and disease incidence, and improving precision input management. UAVs equipped with multispectral sensors can identify stressed mulberry areas at an early stage, enabling timely corrective measures and improving leaf quality for silkworm feeding. This approach supports precision agriculture and enhances overall productivity in sericulture systems.

2. Technology Adoption in Chittoor Sericulture Farmers: A case study conducted in Chittoor District evaluated the adoption of improved sericulture technologies among farmers. The study revealed that farmers adopting scientific mulberry cultivation practices, improved silkworm rearing methods, and modern management technologies achieved significantly higher cocoon yield and better economic returns than conventional farmers.

3. Smart Sericulture Using IoT and Automation: Researchers developed an IoT-based smart sericulture framework called the SeriFarm Automation System (SFAS), integrating sensors for monitoring temperature and humidity in silkworm rearing houses. The study found that IoT-based automation significantly reduced manual monitoring efforts, improved silkworm survival rates, stabilized rearing conditions, and enhanced overall cocoon quality and yield.

4. Eco-Friendly Pest Management in Karnataka: A field-level case study in Kolar District evaluated eco-friendly management practices against uzi fly infestation in silkworm rearing. The study found that farmers adopting integrated pest management strategies experienced significantly reduced infestation levels and lower crop losses compared to conventional practices.

5. Drought Management Technologies in South Indian Sericulture: A study involving 300 sericulture farmers in South India examined drought perception and technological interventions in mulberry cultivation. The findings showed that farmers adopting drought mitigation practices such as drip irrigation and improved mulberry management were able to maintain better leaf yield and sustain silkworm productivity during water-stress conditions. The study concluded that such technologies significantly improved drought resilience, stabilized cocoon production, and enhanced overall farm sustainability.

6. Integrated Farming System in Sericulture: An integrated farming system combining sericulture with livestock, aquaculture, and horticulture was implemented in Karnataka to assess livelihood improvement. The study found that integrated systems significantly enhanced farm profitability, improved resource recycling efficiency, and provided

diversified income sources to farmers. It also demonstrated that such systems increase sustainability, reduce production risks, and strengthen overall livelihood security in sericulture-based farming communities.

Government Initiatives Supporting Drone Adoption in India

Initiative Scheme	Subsidy / Financial Support	Eligible Groups	Major Key Points	Relevance to Smart Sericulture
Sub-Mission on Agricultural Mechanization (SMAM)	Up to 40-100% assistance depending on category and institution	Farmers, FPOs, SHGs, cooperatives, agricultural institutions	Promotes agricultural mechanization and drone purchase for farming activities	Useful for mulberry crop monitoring, precision spraying, and nutrient management
Namo Drone Didi Scheme	Financial support for providing drones to SHGs	Women Self-Help Groups (SHGs)	Aims to empower rural women through drone-based agricultural services	Supports drone spraying and surveillance in sericulture farming areas
Kisan Drone Initiative	Subsidies and operational support for agricultural drones	Farmers, FPOs, custom centres, hiring agri-startups	Encourages drone use for spraying, crop assessment, and digital agriculture	Helps in monitoring mulberry fields and pest management
Startup India Initiative	Financial incentives and startup support	Agri-tech startups and entrepreneurs	Encourages innovation in drones, AI, and smart farming technologies	Promotes development of sericulture-focused drone solutions
Digital Agriculture Mission	Government-supported digital infrastructure and pilot projects	Farmers, research institutions, agri-tech companies	Promotes AI, GIS, remote sensing, and drone integration in agriculture	Enables precision sericulture and data-driven farm management
Drone Rules 2021	Simplified licensing and reduced compliance burden	Drone operators, startups, training institutes	Liberalized drone regulations to encourage wider adoption	Facilitates easier deployment of drones in sericulture regions
Skill Development and Drone Training Programs	Free or subsidized drone pilot training	Rural youth, farmers, agri-graduates	Builds technical skills in drone operation and maintenance	Creates skilled manpower for smart sericulture practices
SVAMITVA Scheme	Government-funded drone mapping activities	Rural communities and village administrations	Uses drones for land mapping and rural digitization	Enhances awareness and acceptance of drone technologies in rural areas
AI for Agriculture Programs	Research grants and innovation funding	Research institutes, universities, startups	Supports AI-enabled agricultural technologies and decision systems	Useful for disease prediction and smart mulberry monitoring

Major Benefits of Drones in Indian Sericulture

1. Rapid monitoring of mulberry crop health and field conditions
2. Early detection of pests, diseases, and nutrient deficiencies
3. Precision spraying with reduced chemical and water usage
4. Reduction in labour requirement and time-saving farm operations
5. Improved mulberry leaf quality and cocoon productivity.

Major Challenges in Adopting Drone Technology in Sericulture

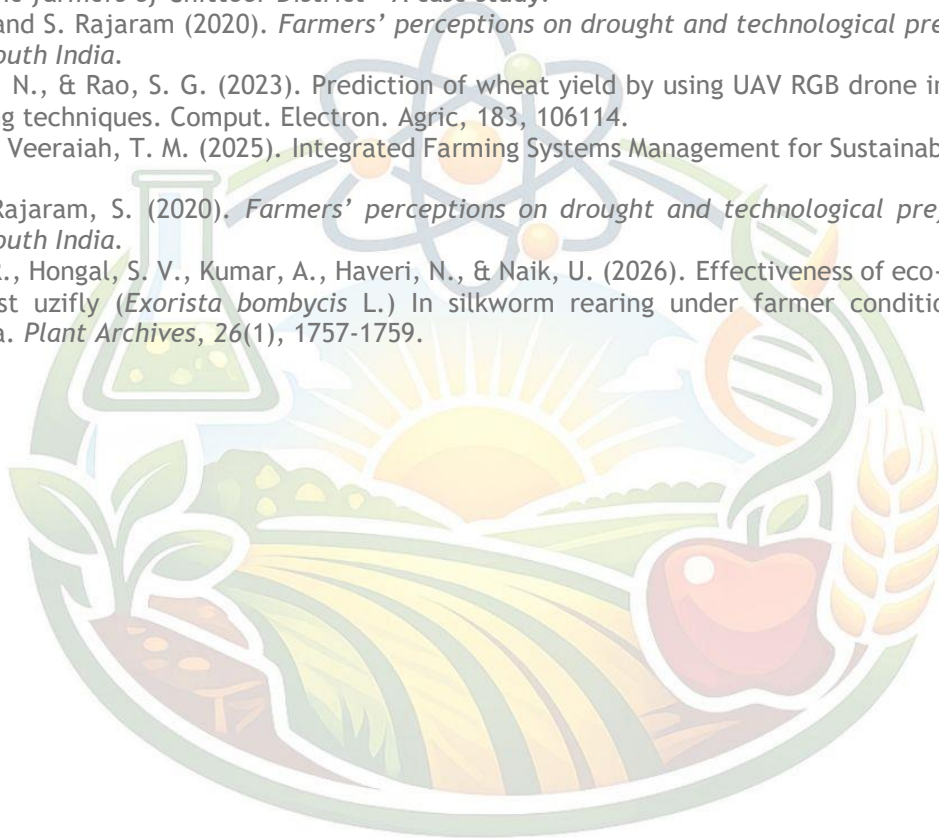
1. High initial investment cost of drones and equipment
2. Lack of technical knowledge and trained operators
3. Limited awareness among sericulture farmers
4. Small landholdings reducing operational efficiency
5. Maintenance and battery limitations of drones
6. Regulatory restrictions and licensing procedures
7. Poor digital infrastructure in rural areas

Conclusion

The integration of drones and smart farming technologies is transforming sericulture into a more efficient and technology-driven system. Applications like crop monitoring, precision spraying, pest detection, and environmental management improve mulberry growth and silkworm productivity. Case studies show that drones, IoT, and precision agriculture increase cocoon yield, reduce costs, and improve farmer income. Government support along with advances in AI, remote sensing, and digital agriculture is accelerating modernization. However, high costs, limited skills, and weak rural infrastructure still limit large-scale adoption. With proper training, research, and policy support, smart sericulture can ensure more sustainable silk production in India.

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Artificial Intelligence in Food Processing: Innovations, Applications and Future Prospects

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A. Vishnu Charan¹, Sugunya rao Y², R V Jaybhaye³

¹M. Tech, Processing and Food Engineering, Dept. of Agricultural Process Engineering CAET, VNMKV, Parbhani.

²Phd Scholar, Dept. of Food Processing Technology, College of Food Processing Technology and bio energy, AAU, Anand, Gujarat.

³Professor and Head, Dept. of Agricultural Process Engineering, CAET, VNMKV, Parbahni.

Summary

Artificial Intelligence (AI) has become a revolutionary force in the food processing sector by enhancing operational efficiency, food quality, safety measures, sustainability, and product innovation. Technologies including machine learning, deep learning, computer vision, robotics, and predictive analytics are being increasingly incorporated into food manufacturing systems for purposes such as automated inspection, process optimization, contamination detection, and intelligent decision-making. AI-powered systems facilitate swift quality assessments, predictive maintenance, resource optimization, and traceability throughout food supply chains. Emerging technologies like Digital Twins and Generative Artificial Intelligence are further propelling the advancement of intelligent and autonomous food manufacturing systems.

Keywords: Artificial intelligence (AI), Digital Twins, Predictive Analytics, Sustainable Food Systems.

Introduction

The food processing sector is crucial in guaranteeing food quality, safety, and accessibility for the expanding global population. The rising demand for nutritious, convenient, and safe food items has hastened the implementation of advanced technologies within food manufacturing sectors. Conventional food processing methods are frequently labor-intensive, time-consuming, and susceptible to human error. In recent times, Artificial Intelligence (AI) has surfaced as a significant technology for enhancing automation, efficiency, and decision-making in the food industry. AI technologies such as machine learning (ML), deep learning (DL), computer vision, robotics, and predictive analytics are increasingly integrated into modern food processing industries for quality control, process optimization, and predictive maintenance (Chhetri, 2024; Song *et al.*, 2025). The food industry's shift toward Industry 4.0 is defined by the synergy of AI, cloud computing, and sensor technology, which together optimize manufacturing outputs and sustainability (Hassoun *et al.*, 2024). Recent advances in deep learning and computer vision have enabled automated inspection systems capable of detecting food defects, contamination, bruises, and spoilage with high accuracy (Liakos *et al.*, 2025). AI-assisted predictive analytics also supports demand forecasting, resource optimization, and reduction of food waste (Agrawal *et al.*, 2025). Furthermore, emerging technologies such as Digital Twins are improving real-time monitoring and optimization of food manufacturing processes (Abdurrahman & Ferrari, 2025).

This article discusses the application of AI in food processing industries, including food quality control, food safety, process optimization, industrial automation, and future prospects.

Application of Artificial Intelligence in Food Processing

1. Food Quality Control and Safety: The quality and safety of food are paramount concerns within the food processing sector. AI-driven quality inspection systems utilize computer vision, machine learning, and deep learning algorithms to automate the monitoring and assessment of food products. In contrast, conventional food inspection techniques depend significantly on manual observation and human expertise, frequently leading to inconsistencies and reduced processing speeds. AI-based inspection systems overcome these limitations by providing rapid, automated, and highly accurate inspection capabilities (Liakos *et al.*, 2025). Computer vision systems integrated with Convolutional Neural Networks (CNNs) can identify defects, contamination, discoloration, bruises, and foreign materials in food products. Deep learning architectures such as YOLO (You Only Look Once) are widely used for real-time object detection in food manufacturing systems. Jarkas *et al.*, (2023) reported that YOLOv5 and ResNet-101 models achieved high accuracy in meat classification and industrial inspection applications. AI technologies combined with hyperspectral imaging and Near-Infrared (NIR) spectroscopy are increasingly applied for non-destructive food quality evaluation. These systems rapidly analyze chemical composition, moisture content, protein levels, and internal defects of food materials.

Table: Performance of AI Models Used in Food Quality Control and Safety Applications

Model	Application	Performance	Reference
ResNet-101	Meat box classification	99% accuracy	Jarkas <i>et al.</i> , (2023)

YOLOv5m	Meat cut detection	High real-time detection efficiency	Jarkas <i>et al.</i> , (2023)
YOLOv8	Plant stress detection	98.2% mAP	Daraghmi <i>et al.</i> , (2025)
CNN + DeiT	Vegetable classification	98% F1-score	Touvron <i>et al.</i> , (2021)
Gradient Boosting	Pathogen identification	69% accuracy	Wang <i>et al.</i> , (2021)

Food safety monitoring is another important application of AI technology. Machine learning algorithms can rapidly identify foodborne pathogens such as *Salmonella* and *Escherichia coli*. AI-assisted sensing systems significantly reduce detection time compared to conventional microbiological techniques (Sharma *et al.*, 2024). AI also enhances food traceability systems through integration of blockchain, IoT, and predictive analytics. These systems improve transparency across food supply chains and enable rapid identification of contaminated food batches.

2. Process Optimization and Industrial Automation: Artificial Intelligence is revolutionizing the creation of food products by speeding up the processes of formulation, sensory evaluation, and forecasting consumer likes. Generative AI systems examine extensive datasets concerning ingredient makeup, nutritional content, flavor elements, and consumer tastes to generate novel food formulations. AI-assisted sensory evaluation systems predict taste, aroma, texture, and mouthfeel characteristics of food products (Jo *et al.*, 2025). Personalized nutrition is another rapidly growing field supported by AI technologies. Machine learning algorithms analyze dietary habits, metabolic profiles, and health data to recommend customized diets and functional food products. Digital Twin (DT) technology is an emerging innovation in food processing industries. Digital Twins are virtual replicas of physical manufacturing systems continuously updated using real-time operational data. DT systems enable process simulation, predictive maintenance, process optimization, and production monitoring (Abdurrahman & Ferrari, 2025).

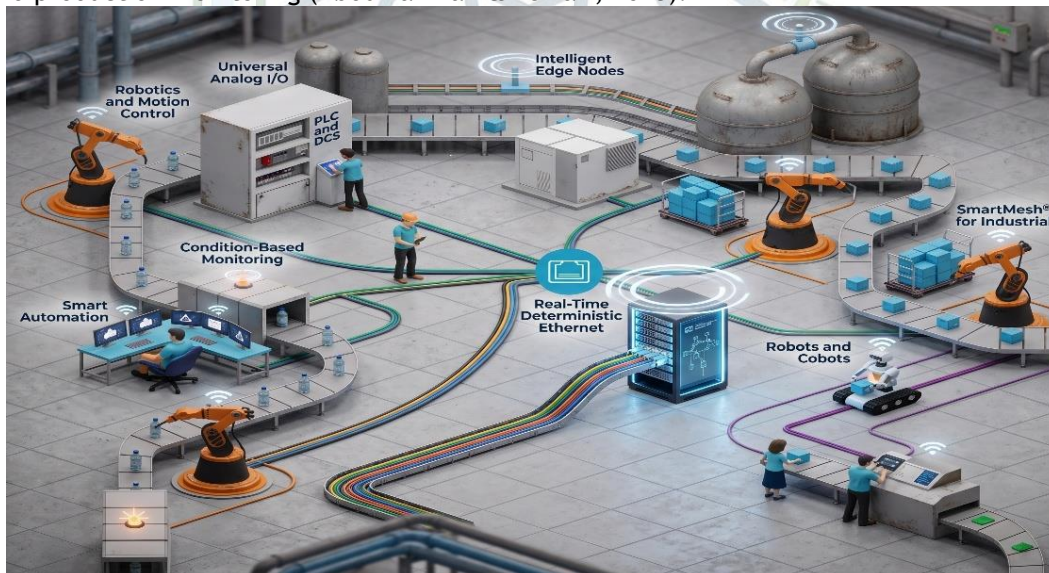


Fig. Digital twin technology to connect all operations from beginning to end (Image Source: Analog Devices)

Explainable Artificial Intelligence (XAI) is also gaining importance because many deep learning systems operate as “black-box” models. XAI improves transparency and interpretability of AI-generated decisions, particularly in food safety and quality assurance applications. The future of AI in food processing points toward highly automated, intelligent, and sustainable food manufacturing systems. Integration of AI with robotics, IoT, cloud computing, and blockchain technologies will further improve traceability, productivity, and operational efficiency.

Conclusion

Artificial Intelligence is rapidly transforming the food processing industry by enhancing food quality, safety, efficiency, and sustainability through intelligent automation and data-driven technologies. Applications of machine learning, deep learning, robotics, computer vision, and predictive analytics have significantly improved quality control, process optimization, and predictive maintenance in food manufacturing systems. Furthermore, emerging technologies such as Digital Twins, Generative AI, collaborative robotics, and explainable AI are expected to accelerate the development of smart and autonomous food industries. Despite challenges related to implementation, data management, and workforce adaptation, continuous advancements in AI technologies will play a crucial role in building sustainable, efficient, and innovative food processing systems capable of meeting future global food demands.

Despite several advantages, challenges related to data quality, cybersecurity, implementation costs, and workforce adaptation must be addressed for successful large-scale implementation of AI technologies. Continuous advancements in AI and interdisciplinary collaboration among researchers, industries, and policymakers will further strengthen the role of AI in creating safer, smarter, and more sustainable food processing systems.

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