

The background of the entire page is a close-up photograph of several ripe, red strawberries. The strawberries are in sharp focus in the foreground, showing their characteristic seeds and texture, while others in the background are slightly blurred. The lighting is soft, highlighting the natural colors of the fruit.

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Physiological Disorders and their Management in Onion

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Introduction

Onion is an important vegetable, condiment and spice crop grown commercially in different parts of the country for domestic consumption as well as export market. Onion is known for its flavour, pungency and medicinal value. It is used as salad or cooked in various ways like curries, soup and preserved as pickle. India stands as a global leader in onion production, with an estimated 31.6 million tonnes harvested from 1.941 million hectares. The major onion producing states are Maharashtra, Gujarat, Madhya Pradesh, Karnataka, Andhra Pradesh Rajasthan, Haryana, Uttar Pradesh, Bihar, West Bengal, Odisha and Tamil Nadu. Maharashtra has highest share both in area and production.

A key challenge in onion cultivation is the occurrence of physiological disorders refer to abnormalities or irregularities in the normal physiological processes that can affect their growth, development, and overall health. These disorders are often non-infectious and result from internal factors, environmental conditions, or a combination of both. Unlike diseases caused by pathogens, physiological disorders do not involve infectious agents such as bacteria, viruses, or fungi. Physiological disorders constitute a significant, yet often overlooked, economic threat to onion and garlic production. These disorders pose a significant yet often overlooked threat to onion and garlic production, with yield losses estimated between 10% and 50%. Moreover, the impact extends beyond the field, as affected bulbs are more prone to spoilage during storage, leading to substantial post-harvest losses.

In India, onion cultivation spans three main seasons: *Kharif*, Late *Kharif*, and *Rabi*. The extent of physiological disorders and resulting losses varies by season and variety. In the *kharif* season, the highest losses are attributed to post-harvest sprouting (up to 54%) and bulb doubling (up to 17%). During the Late *Kharif*, bolting (up to 23%) and bulb doubling (up to 25%) are more prominent. In contrast, *Rabi* season onions generally experience fewer physiological disorders, making it the most favourable season in terms of quality and storage potential.

Important Physiological Disorders

The important physiological disorders and biological factors acting as constraint in onion cultivation are described below along with their management practices.

1. Bolting: It is serious disorder of onion bulb crops. It refers to the emergence of seed stalk prior to time of their formation and adversely affects the formation and development of bulbs. Bolting is undesirable character as the further development of onion bulbs stops, and bulbs of such plants are light in weight, fibrous, and have a lower shelf life ultimately directly affects the bulb yield of onion. In India, 5-80% bolting is reported in early *Rabi* and late *Kharif* seasons, which leads to an annual loss of approximately 11 to 50 hundred thousand tonnes of onion bulbs.

Causes:

- Low temperature (10-15 °C)
- In Indian conditions, the incidence of bolting was higher during early *rabi* or late-*kharif* (0-77%) than *rabi* season (0-25%).
- Plants were grown from large sets, more bolting was observed than those from smaller sets.
- Transplanting of over-aged seedlings.
- Poor supply of nitrogen in nursery and field induces premature bolting.
- Cold storage offsets leads to more bolting than sets stored at 20°C.

Management:

- Adjust the time of transplanting in such a way that crop may be exposed to moderate temperature at bulbing.
- Seedlings of the age of 45 days should be used to avoid bolting.
- Use resistant varieties like NHRDF Red 4, NHRDF K-883, Bhima Super, Early Grano etc.
- Use of recommended dose of nitrogenous fertilizer.
- Application of PGRs like Ethephon @ 5000 ppm and Paclobutrazol @ 20 to 40 ppm reduces bolting and enhances onion bulb yield by increasing the bulb size.



Bolter

2. Sprouting: It is one of the most important disorders in the storage and causes a huge loss to the growers. Sprouting can alter the flavour and texture of the onion, making it less desirable for the market. Several factors are involved in the sprouting of onions such as genotype, soil moisture at the time of harvest as well as pre-harvest operations like manuring, dose and time of fertilizer, irrigation and physiological maturity at harvest, curing, etc.

Causes:

- Application of excessive nitrogen to onion crops.
- Excessive soil moisture at maturity.
- Improper drying and curing before neck cutting.

Management:

- Application of recommended dose of nitrogenous fertilizer as well as time of application.
- Withhold irrigation 15 days before harvesting bulbs.
- Preharvest spray of 2500 ppm maleic hydrazide inhibits sprouting upto 5 months of storage
- Properly curing onion (4-5 days in field and 8-10 days under shade set) can reduce post-harvest losses.



Sprouted onions

3. Bulb splitting/Doubling: Bulb splitting also referred to as bulb doubling or twinning is a physiological disorder in onions where a single bulb divides into two or more segments. These segments grow from a common root system but develop into separate, distinct bulbs. While this may appear harmless, it is generally considered undesirable in commercial onion production, as market preference is for single, uniform, and well-formed bulbs that are easier to handle, store, and sell.

Causes:

- The higher doubling was observed in plants developing from the larger sets than smaller ones.
- Application of higher nitrogenous fertilizers
- Wider Spacing
- Mechanical injury to developing bulbs during intercultural operations may lead to the emergence of outgrowth,
- Excess irrigation at the maturity time and delay in crop harvesting.

Management:

- Onion crop should be planted at recommended spacing (15x10 cm)
- The onion crop should be fertilized with recommended dose (N:P:K:S – 100:50:50:30) before 60 days.
- Application of potassium fertilizers resulted in the least occurrence of double bulbs.
- Optimum irrigation should be given at recommended interval during crop growth stage and should be stopped 7-15 days before harvesting.
- Crop should be harvested at proper maturity stage i.e. Neckfall stage.



Double

4. Thick Neck: The thick neck in onion occurs when the bulbs fail to mature and there is continuous production of leaves; this leads to the thickening of the neck. It is also called incomplete bulbing. Thick-necked bulbs have poor storage qualities and are prone to early sprouting and rotting.

Causes:

- Late application of nitrogenous fertilizers, especially urea, increases pseudo-stem diameter, contributing to thick-neck formation.
- Transplanting seedlings earlier than the recommended schedule.
- It is also influenced by variety, location, transplant size, and season of planting.

Management:

- Use of recommended nitrogenous fertilizer application and avoid use of urea.
- Recommended spacing, i.e. low plant density.
- Use varieties known to be less prone to thick-neck development and follow the recommended transplanting schedule.



Thick - Neck

5. Poor seed germination: Seed germination of onion is, in general, poor and this problem is severe in case of old seedstock. Seeds lost viability very soon in ordinary storage condition. However, cold storage condition somewhat extends the seed viability.

Management:

- Store the seeds in cold storage at a temperature of 2–5 °C and relative humidity 65%.
- Use healthy fresh seed for sowing.
- Soak the seeds in water and sodium phosphate solution for 2-6 hours followed by drying which is beneficial for vigour and viability of the seeds.



Onion Nursery

6. Watery/leathery scale in storage: Watery scale is a significant physiological disorder affecting onions during storage, leading to considerable economic losses. This condition often arises when onions are exposed to elevated levels of carbon dioxide, either internally within the scales or externally in controlled atmosphere (CA) storage environments. High CO₂ concentrations disrupt the physiological balance of the onion, resulting in the development of watery or leathery scales. These symptoms compromise the quality and marketability of the stored bulbs, making proper storage management crucial.

Conclusion

Onion is primarily a valuable cash crop, offering farmers the potential for substantial profits. However, its cultivation and storage are often challenged by various issues. Successful onion farming requires addressing these challenges effectively, making it possible to cultivate the crop under diverse environmental conditions. In particular, physiological disorders in both onion and garlic can significantly reduce the quality of the produce. To mitigate these issues, it is essential to adopt good agricultural practices, choose appropriate varieties, plant during the recommended seasons, and follow proper post-harvest management techniques. By implementing these strategies, farmers can enhance yield quality and ensure better profitability.

Modern Tools and Technologies Shaping the Future of Horticulture

Article ID: 72201

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Abstract

The global challenge of feeding a burgeoning population, projected to reach nearly 10 billion by 2050, demands a paradigm shift in how we grow our food. Horticulture the cultivation of fruits, vegetables and ornamental plants is at the forefront of this transformation. Faced with limited arable land, climate change and post-harvest losses, the sector is turning to a suite of revolutionary technologies to boost productivity, efficiency and sustainability. This article explores the integration of cutting-edge tools such as Artificial Intelligence (AI), the Internet of Things (IoT), blockchain, remote sensing and vertical farming into modern horticulture. We delve into how AI and computer vision are enabling automated harvesting and disease detection, how IoT sensors are creating smart, responsive farms and how blockchain is ensuring transparency from farm to fork. Furthermore, we examine the role of nuclear technology in developing resilient crop varieties and the potential of soilless vertical farms to revolutionize urban agriculture. While challenges in cost, technical literacy and interoperability remain, the convergence of these technologies promises a more productive, sustainable and intelligent future for horticulture, ensuring food security for generations to come.

Keywords: Artificial Intelligence, Internet of Things (IoT), Remote Sensing, Vertical Farming, Precision Agriculture, Automation, Sustainable Horticulture.

Introduction

Global agricultural systems face unprecedented pressure to meet the nutritional demands of a rapidly expanding population, projected to exceed 9 billion by 2050 (Cazzola *et al.*, 2020). This challenge is exacerbated by finite arable land, climate change and post-harvest losses. Enhancing the productivity and sustainability of the horticultural sector encompassing fruits, vegetables and ornamental plants is therefore critical. As a vital economic component in countries like India, horticulture significantly contributes to farm output and employment.

However, horticultural crops are inherently vulnerable. They are perishable, labor-intensive and susceptible to pests, diseases and extreme weather. Conventional practices, relying on uniform applications of water and agrochemicals, are increasingly unsustainable, leading to resource depletion and environmental degradation.

The convergence of digital technologies, termed Agriculture 4.0, offers a transformative pathway. The integration of Artificial Intelligence (AI), the Internet of Things (IoT) and robotics is facilitating a shift towards precision horticulture. This data-driven paradigm optimizes resource use and enhances crop management. For instance, AI-powered computer vision enables automated pest monitoring and harvesting, while IoT sensor networks allow for real-time, site-specific irrigation and fertilization (Kale *et al.*, 2024).

The Intelligent Farm: Artificial Intelligence Takes Root

At the heart of the high-tech farm is Artificial Intelligence (AI), the ability of machines to learn, reason and act. In horticulture, AI acts as a super-human farm manager, processing vast amounts of data to make intelligent decisions.

From Pest Control to Perfect Harvests: One of the most promising applications is in pest management. Instead of relying on periodic manual checks of sticky traps, farmers can now use digital insect traps. These smart traps are equipped with cameras that automatically count and identify pests, sending real-time

alerts to a farmer's smartphone. This allows for targeted pesticide application only when and where it is needed, dramatically reducing chemical use.

When it comes to harvesting, AI is tackling one of the sector's biggest costs and challenges: labor. Fruit harvesting robots are being trained to see and pick with care. Using advanced computer vision, these robots can distinguish a ripe apple from a leaf, orient a robotic gripper and apply just the right amount of pressure to detach the fruit without bruising it (Zhou *et al.*, 2022). This not only addresses labor shortages but also ensures that harvesting happens at the perfect moment of maturity.

Predicting the Future of the Field: AI's predictive capabilities are perhaps its most powerful asset. Machine learning models can analyse historical and real-time data on weather, soil conditions and plant health to forecast yields with remarkable accuracy. This helps farmers plan their logistics and market their produce more effectively. Furthermore, AI can provide early warnings for environmental threats like frost, allowing farmers to take proactive measures, such as activating heaters in a greenhouse, to save their crops.

The Connected Crop: The Internet of Things (IoT)

If AI is the brain of the smart farm, the Internet of Things (IoT) is its nervous system. IoT refers to a network of physical devices viz., sensors, drones, actuators embedded with software and connected to the internet, enabling them to collect and exchange data.

Sensing the Unseen: In a connected orchard or greenhouse, a multitude of sensors constantly monitor the micro-environment. Soil moisture sensors tell irrigation systems exactly when and how much to water, conserving a precious resource. Nutrient sensors can analyse soil composition, allowing for precise fertilizer application that meets the crop's exact needs, minimizing runoff and pollution. This is the essence of precision agriculture: applying inputs in the right amount, at the right time, in the right place.

The Rise of the Agricultural Drone: Drones, or Unmanned Aerial Vehicles (UAVs), have become invaluable eyes in the sky. Equipped with multispectral and thermal cameras, they can quickly survey vast areas of land. They can identify areas of water stress, detect nutrient deficiencies before they are visible to the human eye and even spot the early signs of pest infestation or disease (Ahirwar *et al.*, 2019). Some drones are also used for targeted spraying, applying pesticides or fertilizers with pinpoint accuracy, thereby reducing the quantity of chemicals used and protecting the health of farmworkers.

Trust from Farm to Fork: The Power of Blockchain

While AI and IoT optimize the growing process, blockchain technology is revolutionizing what happens after the harvest. Blockchain is a secure, decentralized digital ledger that records transactions in a way that is transparent and tamper-proof. In the complex, global supply chain for horticultural produce, traceability is a major issue. Where did this mango come from? When was it harvested? Were any pesticides used? Blockchain can answer these questions confidently. Each step of the journey from the farm, to the packer, to the distributor, to the retailer can be recorded as a "block" in the chain (Kamilaris *et al.*, 2019). This creates an immutable record that builds consumer trust. In the event of a food safety scare, like an *E. coli* outbreak linked to lettuce, a blockchain record can instantly identify the affected batch, enabling a swift and precise recall instead of a costly industry-wide shut down. For farmers, this transparency can lead to fairer compensation, as the value of their high-quality produce can be verified and recognized throughout the chain.

A Bird's-Eye View: The Scope of Remote Sensing

Scaling up from the individual plant or field, remote sensing technology uses satellites and aircraft to monitor horticultural landscapes on a regional scale. By analyzing the light reflected from crops (their spectral signature), specialists can glean a wealth of information without setting foot on the ground.

Key applications include orchard mapping and area estimation, providing governments and industries with accurate data on crop planting areas. It is also instrumental in detecting abiotic stresses like drought. For instance, researchers have used thermal and multispectral imagery to monitor water stress in peach orchards by measuring subtle changes in canopy temperature and reflectance, allowing for optimized irrigation schedules (Khanal *et al.*, 2020). Furthermore, remote sensing can help detect pest infestations

and disease outbreaks over large areas, enabling a coordinated regional response instead of isolated farm-level actions.

Breeding Better Plants: The Unsung Role of Nuclear Technology

Often associated solely with energy, nuclear technology has quietly been driving progress in horticulture for decades, primarily through mutation breeding. By exposing seeds or plant cuttings to low doses of gamma radiation or X-rays, scientists can accelerate the natural process of mutation.

This technique has been used to develop hundreds of improved crop varieties. As highlighted in the research, these "mutant" crops boast traits highly beneficial for farmers and consumers alike. For example, radiation was used to develop the 'Pusa Nanha' papaya, a dwarf variety that is easier to harvest and seedless oranges that are more appealing to consumers (Rimberia *et al.*, 2018). This technology provides a powerful, non-GMO tool for creating plants that are more productive, resilient to disease and adaptable to changing climates.

Farming Upwards: The Vertical Farming Revolution

For the ultimate in controlled-environment agriculture, look no further than vertical farming. This method involves growing crops in vertically stacked layers, often in repurposed warehouses or shipping containers, using artificial lighting and soilless cultivation techniques.

Hydroponics, Aeroponics and Aquaponics: The bedrock of vertical farming is soilless culture. Hydroponics, the most common method, involves growing plants with their roots submerged in a nutrient-rich water solution. Systems like the Nutrient Film Technique (NFT) constantly flow a thin film of water past the roots, providing optimal oxygen and nutrient uptake (Palmitessa *et al.*, 2024). Aeroponics, a more advanced method, suspends roots in the air and mists them with a nutrient solution, leading to even faster growth and water savings of up to 95% compared to traditional farming. Aquaponics combines this with aquaculture, creating a symbiotic ecosystem where fish waste fertilizes the plants and the plants, in turn, purify the water for the fish. These systems are increasingly automated and integrated with IoT sensors, creating a perfectly tuned environment for plant growth, free from pests and unpredictable weather. While currently best suited for high-value leafy greens and herbs, vertical farming represents a critical step towards decentralizing food production and bringing fresh produce closer to urban consumers.

Conclusion

The integration of AI, IoT, blockchain, remote sensing and advanced cultivation techniques is transforming horticulture into a more data-driven, efficient and resilient system. These innovations offer benefits such as reduced resource use, improved yields, better quality and enhanced traceability. Challenges like high costs, the need for digital skills and connectivity issues must be addressed through supportive policies and accessible solutions. The aim is to empower farmers, creating a new generation of "agri-technologists" capable of making informed decisions for a sustainable horticultural future.

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Food Waste: The Quiet Shame of the Kitchen Bin from Landfill to Leggings and Garbage to Gas

Article ID: 72202

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Abstract

Food waste is major problem in the modern world. The food, which is consumable but is not used for consumption is known as food waste. Food waste causes economic loss, resources loss, methane effect, social injustice. According to some data, 1.05 million tonnes of food waste are produced. The food waste is recycled into fabric and biofuels, on a large scale. In small scale composting techniques are used. Food waste reduction can only be achieved if we reduce the waste.

Keywords: Food waste, recycle, fabric, biofuels, composting.

Introduction

Imagine this, 'every day, enough food to feed over a billion people ends up in garbage bins — while nearly 800 million go hungry. Food waste isn't just about spoiled produce or leftovers; it's about lost resources, lost money, and a worsening climate crisis. Turning the tide on food waste is one of the most powerful things we can do to help people and the planet. Food is vital for survival, providing essential nutrients and energy for growth, body repair, and daily functions of the living organisms. FSSAI defines food as any substance, processed, partially processed, or unprocessed, intended for human consumption. The Food and Agriculture Organization (FAO) defines food waste as "food appropriate for human consumption being discarded, whether it's kept beyond its expiry date or left to spoil". Food is an essential commodity, as it is one of the major sources of our survival, hence factors like "food loss" or "food waste" should be brought under serious consideration and addressed in order to minimize their occurrence and the impact that they happen to incur on not just humans but the overall balance of the ecosystem and the environment (Lin et al., 2022). Food wastes could be solid, semi-solid, or in liquid forms; solid wastes mainly include the food items themselves, parts of the food items, or other parts or items associated with particular food items, which are usually rich in starch, cellulose, lignin, and monosaccharides (Yahiya et al., 2019). Food waste management is an important one in the modern world. It helps in reducing food waste and also turn the food waste into valuable fuels.

Effects of Food Waste

Food waste leads to various problems such as economic loss, social injustices, resource losses, methane production. In case of economic loss, a yearly wastage of food of a family leads to loss of many dollars, and for the business entities such as Hotels, restaurants it becomes some lakh dollars. In the scenario of methane production, waste food produces the most dangerous greenhouse gases, which are more dangerous than carbon dioxide in the heat trapping effect. Food waste leads to loss of resources used for food production such as land and water. It indirectly affects wildlife, because forests are being brought under cultivation to feed the population. Due to waste of food in the plate of some people leads to keeping people in hunger, thereby it creates a social injustice.

Food Waste Index & Food Security

Around 1.05 billion tons of food was wasted at the retail, food service, and household levels. The Food Waste Index is developed by the United Nations Environment Programme (UNEP) to measure how much food is wasted at the consumer level across households, retail, and food services. It is a global benchmark used to track progress towards SDG 12.3, which aims to halve per-capita global food waste by 2030. The second United Nations Sustainable Development Goal calls for global food security and the end of world hunger by 2030 (United Nations, 2015). Various definitions are arrived for food security such as, Achieving food security means that all individuals will have access, at all times, to enough nutritious food to live a healthy

life (Stringer 2016). According to the FAO, food security is composed of four components: availability of food, access to food, utilization of food, and stability of food supply (Barrett 2010; FAO 2014).

Food Waste into Potential Products

Food waste is managed by reducing the wastages by various techniques such as proper post-harvest technologies, quality checking, proper packing with suitable packing materials. Food waste are recycled into fabric and biofuels. Many fruits are used in fabric production. Orange is a citrus fruit. According to some studies, a approximately value of 51.8 million metric tonnes of orange were produced from which 15-25 million tonnes of peels waste are thrown in landfills/incinerated without proper recycling alternatives (Sachidhanandham, 2020).

A variety of methods such as wet, dry, melting and spinning techniques could be employed for the formulation of fabric from orange peel waste. (Sarah et al., 2018).

Pineapple is cultivated for its high nutritional value. It has high fiber content; hence it is used in textile manufacturing industry. In 2016, the annual production of pineapple was 51 million metric tonnes. (Pandit et al., 2020). Pina clothing refers to clothes that are manufactured from pineapple leaves. Due to the increased demand of pineapple, the leaves production increases to meet out the demand. Thereby increases the raw materials for the production of fabric from the pineapple leaves is used in the manufacturing of clothes, table linens, bags etc...

Bananas are widely cultivated in tropical and subtropical counties. It has many reasons for wide cultivation and one of the reasons is its different parts such as Flowers, stems, peels, and leaves are used for different purposes. Fabric from a banana plant is a sustainable textile called banana fiber fabric. It is ecofriendly and biodegradable. It is suitable for clothing, home textiles and accessories.

Food waste is also recycled into biofuels. Food waste such as oils, brewery effluents and other food contains proteins, lipids, minerals and Vitamins had the capabilities of initiating microbial activities. By using microbial action food waste is recycled into biofuels. Vegetable matter, crop residues, farm waste are capable of Bioethanol production. (Prasoulas et al., 2020). Biofuels such as biogas, biodiesel, bio hydrogen, are produced through various methods such as anaerobic digestion, fermentation, pyrolysis etc... From the waste of food. These biofuels are alternatives for fossil fuels. It reduces environmental pollution. It is a renewable energy production.

Conclusion

Food is a vital one for living organisms to survive. Hence food is travel in proper chain from production to plate. By reducing food waste, we can feed the hunger people. Food loss is reduced by keeping the food from contamination. Food wastes are recycled on a large scale by converting into fabric, biofuels. In small scale it is recycled by composting techniques. Save food, save lives, save world.

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Lac Cultivation: A Growing Source of Income for Tribal Farmers in Chhattisgarh

Article ID: 72203

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Introduction

Lac, often known as the “golden gift of the forest,” is becoming an important source of income for tribal farmers in Chhattisgarh. Traditionally, tribal families have depended on forests for their livelihood, collecting minor forest produce such as tendu leaves, mahua, and sal seeds. But in recent years, lac cultivation has gained attention as a profitable and sustainable practice. It not only supports tribal households financially but also promotes eco-friendly farming and forest conservation.

What is Lac?

Lac is a natural resin secreted by tiny insects known as *Kerria lacca*. These insects live on host trees like palash, kusum, and ber, covering twigs and branches with a protective resin. After harvesting and processing, lac is used in making bangles, varnishes, polishes, paints, cosmetics, medicines, and even food products. India is one of the largest producers of lac in the world, and Chhattisgarh plays a key role in this production.



Fig.1: Close-up view of lac insects covering tree branches with golden resin

Why Tribal Farmers Prefer Lac Cultivation

For tribal farmers, lac cultivation offers several advantages. It requires very little investment, as farmers only need a few host trees and broodlac sticks to begin the process. It also provides returns within a short period, usually six to eight months, making it a seasonal income source twice a year. Since many tribal households already live close to forests where host trees naturally grow, they do not have to clear new land or buy fertilizers and pesticides. Another major benefit is that lac cultivation is eco-friendly, as it does not harm trees but instead motivates farmers to preserve them.



Fig.2: Lac cultivation is a natural, low-cost practice suited to tribal communities

The Process of Cultivation

The journey of lac from forest to market follows a simple but well-planned process. Farmers first select suitable host trees such as kusum, palash, or ber. During specific seasons, usually June–July and November–December, they tie broodlac sticks containing living lac insects onto the branches. These insects multiply and begin covering the twigs with resin. The farmers then carefully look after the trees, protecting them from pests and ensuring the branches remain healthy. After about six to eight months, the resin encrustations are harvested by scraping the branches. The raw lac is later cleaned and processed into shellac or other value-added products.

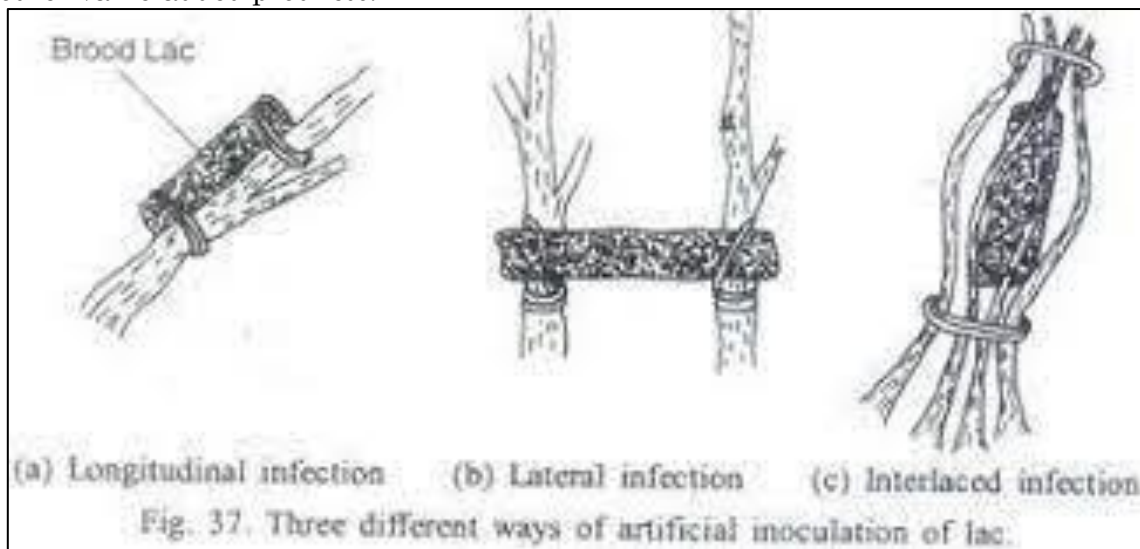


Fig.3: From inoculation to harvesting, every stage of lac cultivation requires care and patience

Income and Economic Opportunities

Lac cultivation has opened new economic opportunities for tribal farmers in Chhattisgarh. On average, a small farmer can earn between ₹20,000 and ₹50,000 annually from just 15 to 20 host trees. With larger plantations and better practices, incomes can rise further. Government departments and cooperatives are actively supporting farmers by providing training, distributing broodlac at subsidized rates, and purchasing lac directly to eliminate middlemen. In addition, many programs are encouraging value addition, where farmers process lac into bangles, decorative items, or shellac, which fetch a much higher price in the market.



Fig.4: Farmers selling raw lac in village markets, turning forest produce into income

Women and Lac-Based Enterprises

A special feature of lac cultivation in Chhattisgarh is the involvement of women. Women not only participate in inoculating and harvesting lac but are also leading in lac-based enterprises. Many self-help groups run by women now produce lac bangles, ornaments, and handicrafts. These activities not only add to household income but also empower women economically and socially, giving them a greater role in decision-making within their families and communities.



Fig.5: Women in rural Chhattisgarh crafting colourful lac bangles to support their families

Support and Schemes

To make lac cultivation more profitable and sustainable, both government and research institutions are extending support. The Indian Institute of Natural Resins and Gums (IINRG) provides scientific training, while the state government offers subsidies and market linkages. Cooperative societies have also been formed to help tribal farmers collectively bargain for fair prices. Through such initiatives, farmers are not only learning improved techniques but also finding access to national and international markets.



Fig.6: Training programs help farmers learn modern lac cultivation techniques

Challenges in Lac Cultivation

Despite its growing popularity, lac cultivation faces certain hurdles. Pests often damage the resin, reducing yield. Many farmers are still unaware of modern methods of cultivation and depend solely on traditional practices. Market prices can fluctuate, making incomes unstable. Moreover, the entire process relies heavily on the availability of host trees, which may decline if forests are degraded. To overcome these challenges, continuous training, scientific research, and strong forest protection measures are essential.

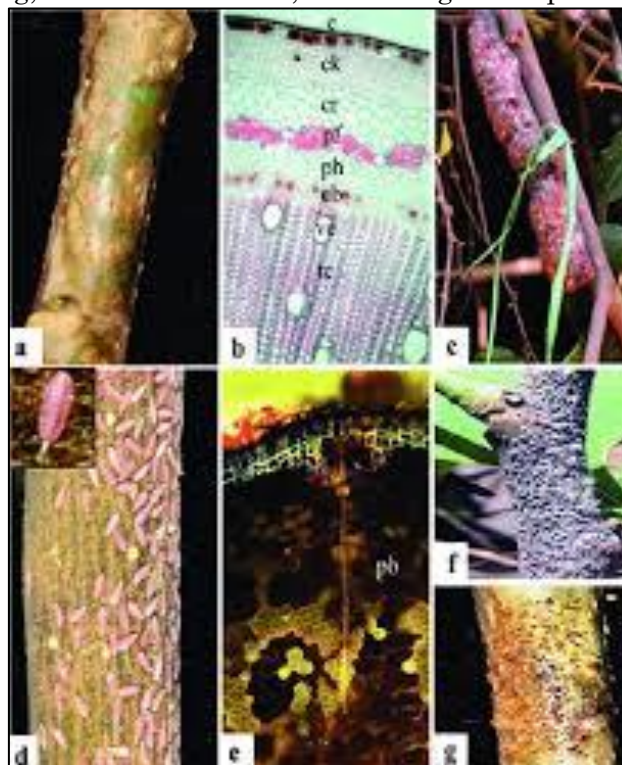


Fig.7: Pest attacks remain one of the biggest challenges for lac farmers

Future of Lac Cultivation in Chhattisgarh

Looking ahead, the future of lac cultivation in Chhattisgarh seems very bright. With the rising demand for eco-friendly and natural products worldwide, lac has strong export potential. At the same time, it is perfectly suited to tribal lifestyles, as it blends traditional knowledge with modern opportunities. If

supported with training, technology, and better marketing, lac cultivation can become a pillar of sustainable rural development in the state. It has the power to transform tribal lives by ensuring steady income while protecting the environment.



Fig.8: A hopeful tribal family with their lac host trees, the future of eco-friendly farming

Conclusion

Lac cultivation is not just about resin; it is about resilience. For tribal farmers in Chhattisgarh, it represents a livelihood that is low-cost, eco-friendly, and sustainable. It ties their economic future to the health of forests, creating a win-win situation for both people and nature. With proper guidance and support, this golden gift of the forest has the potential to shine even brighter in the lives of Chhattisgarh's tribal communities.

The Rise of Jackfruit Cultivation in Kerala

Article ID: 72204

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Introduction

In the green heartlands of Kerala, the jackfruit tree has always been a familiar sight. Its enormous, spiky fruits hang from tree trunks and branches, filling courtyards, roadsides, and farmland edges. For generations, these fruits were treated as everyday food. Families enjoyed tender jackfruit cooked as curry, ate ripe bulbs as a seasonal delight, and roasted the seeds for simple snacks. But despite its abundance, much of the harvest went to waste every year, left to rot under trees or fed to cattle. That old story has started to change. Today, Kerala is reimagining jackfruit as more than just a backyard fruit. It is now recognised as the official state fruit, a growing source of income, and a symbol of cultural pride. With farmers, entrepreneurs, and women's self-help groups stepping in, the fruit has found new life as chips, flour, jams, frozen pulp, and even vegan-friendly meat alternatives. The rise of jackfruit cultivation reflects a deeper transformation: a move towards valuing traditional crops, reducing food waste, and tapping into global markets that now see jackfruit as a superfood.



Fig. 1: A jackfruit tree in full bloom, its heavy fruits hanging close to the trunk

Jackfruit in Kerala's Culture

Long before economic possibilities were explored, jackfruit held a secure place in Kerala's kitchens and traditions. It was a dependable food during lean times, filling stomachs when rice was scarce. Its versatility meant that every part of the fruit was used. Tender jackfruit became a curry or stir-fry, ripe bulbs were eaten fresh, seeds were boiled or roasted, and even the fibrous parts went into homemade dishes. Cultural references to jackfruit are found in folk sayings, songs, and family customs. In villages, neighbours exchanged fruits during the harvest season as a gesture of goodwill. Traditional feasts often included dishes

made from jackfruit, especially during the summer months when the fruit was plentiful. Despite this cultural presence, jackfruit never entered mainstream markets in a big way. Unlike cash crops such as coconut, rubber, or pepper, it remained a household resource, growing quietly in courtyards and farmland.



Fig. 2: Traditional Kerala dish made from tender jackfruit, showing its deep roots in local cuisine

The Turning Point

The shift began in 2018 when the Kerala government declared jackfruit as the official state fruit. This move was more than symbolic. It gave the fruit a new identity and encouraged systematic efforts to promote it. Around the same time, discussions on food security, organic farming, and reducing food waste were gaining attention. Jackfruit, with its organic and sustainable nature, fit perfectly into these conversations. Local entrepreneurs and women's self-help groups began experimenting with jackfruit-based products. What was once eaten fresh at home started appearing in packets as chips, flour, or preserved pulp in supermarkets. Farmers saw that the fruit had untapped value, and small processing units sprang up across districts. This marked the beginning of jackfruit's journey from neglected surplus to organised cultivation and marketing.



Fig. 3: Packets of jackfruit chips and flour displayed in a shop

Scale of Cultivation

Kerala today produces millions of jackfruits annually. The trees cover more than 90,000 hectares across the state, making it one of the largest producers in India. Districts like Idukki, Kannur, Thiruvananthapuram, and Malappuram lead the way, thanks to their favourable climate and widespread presence of backyard trees. Most cultivation is still semi-traditional, with trees growing in courtyards and mixed farmlands rather than large plantations. This has a unique advantage: the fruits are often organic by default, free from heavy use of chemicals. In addition, the seasonal glut means that during peak months, entire markets overflow with jackfruit, attracting traders from neighbouring states.



Fig. 4: Stacks of jackfruits at a busy local market in Kerala, attracting traders from nearby states

From Waste to Wealth

Perhaps the most remarkable change in Kerala's jackfruit story is the rise of value-added products. In earlier times, nearly half the harvest would go to waste. Now, much of it is being processed into forms that can travel far beyond the local market. Chips are the most popular, sold widely across Kerala and in other states. Flour made from raw jackfruit is promoted as a healthy, diabetic-friendly food. Frozen pulp and preserved tender jackfruit are finding customers in cities and even abroad. Small industries, many of them run by women's collectives, have become part of this chain, adding jobs and income in rural areas. These innovations are helping farmers and entrepreneurs earn steady incomes while reducing the shocking levels of wastage that once defined the fruit's story. What was once seen as excess is now seen as opportunity.



Fig. 5: Women's self-help group members processing jackfruit into chips and flour in a small-scale unit

Human Stories Behind the Change

Behind the statistics lie stories of individuals who embraced jackfruit cultivation and processing. Farmers who once left fruits to fall are now carefully harvesting them to sell to traders. Women's groups that began with home experiments are running successful cottage industries today. Entrepreneurs with small investments have turned local produce into brands with loyal customers. These stories highlight the social impact of the jackfruit boom. They show how an overlooked fruit can become a source of empowerment, not only adding to family income but also building confidence and independence, especially among women in rural areas.



Fig. 6: A farmer proudly holding freshly harvested jackfruits, representing the people behind the state's jackfruit success

Challenges Along the Way

The growth of jackfruit cultivation has not been without challenges. The fruit is seasonal, leading to gluts during certain months and scarcity in others. Without proper cold storage or transportation facilities, much of the produce still risks being wasted. Farmers often struggle with fluctuating prices, as the value drops sharply when the markets are flooded. Another hurdle is limited processing infrastructure. Although small units are spreading, many regions still lack access to efficient facilities, which means farmers cannot fully benefit from the fruit's commercial potential. Awareness about jackfruit products outside Kerala also remains limited, making it harder to build steady demand.



Fig. 7: Overripe jackfruits lying wasted on the ground

Opportunities for the Future

Despite the challenges, the opportunities are vast. The global trend toward plant-based foods has put jackfruit in the spotlight as a natural meat substitute. Kerala can tap into this demand with better processing and export systems. At the same time, domestic consumers are becoming more health-conscious, creating a growing market for jackfruit flour, snacks, and preserved products. Government support, research into new products, and improved storage and marketing systems can push jackfruit cultivation to new heights. More importantly, promoting jackfruit as part of nutrition programs in schools and communities could make it a tool for improving food security at home.



Fig. 8: Packaged jackfruit-based products marketed as healthy, plant-based alternatives for a modern audience

Wider Impact

Beyond economics, jackfruit cultivation brings environmental and social benefits. The trees are hardy, require little care, and contribute to biodiversity in home gardens. They provide shade, enrich the soil, and help reduce carbon footprint compared to other intensive crops. For households, they offer a reliable source of nutrition rich in fibre, vitamins, and minerals. The fruit's revival also shows how traditional crops can adapt to modern needs without losing their cultural roots. It has given Kerala a new sense of pride in a fruit that has always been part of its identity.



Fig. 9: A Kerala home garden with jackfruit trees, showing how cultivation blends with sustainable living

Conclusion

The rise of jackfruit cultivation in Kerala is a story of rediscovery. From a neglected fruit left to rot in backyards, it has become a celebrated state symbol and a growing economic resource. Farmers, entrepreneurs, and communities are rewriting its story by reducing waste, adding value, and reaching new markets. Kerala's journey with jackfruit shows that sometimes the greatest opportunities lie in what we have always had around us. With continued effort and innovation, the humble jackfruit has the potential not only to transform local economies but also to win hearts and plates across the world.

Emerging Flowering Culture as a Livelihood in Himachal Pradesh

Article ID: 72205

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Introduction

Nestled in the lap of the Himalayas, Himachal Pradesh has always been celebrated as the “Land of Gods” and the “Fruit Bowl of India.” Agriculture and horticulture have remained the backbone of its rural economy for centuries, shaping the lifestyle, culture, and livelihood of its people. From lush apple orchards in Shimla and Kinnaur to off-season vegetable cultivation in Solan and Mandi, farming has never been just an occupation; it has been a way of life. In recent decades, however, changing climate conditions, small landholdings, and rising market uncertainties have pushed farmers to explore new opportunities that offer both sustainability and profitability. One such emerging avenue is the cultivation of flowers, popularly known as floriculture. Floriculture in Himachal Pradesh is not only about the beauty of blossoms but is gradually becoming a serious livelihood option. The state’s diverse agro-climatic zones, ranging from temperate to sub-tropical, create ideal conditions for growing a wide variety of flowers throughout the year. Carnations thrive in polyhouses, gladiolus blooms sway in open valleys, and marigolds brighten local festivals and markets. The increasing demand for fresh flowers in urban centers for weddings, festivals, decorations, and exports has encouraged farmers to shift from low-return cereal crops to high-value flowers. The rise of flowering culture in Himachal Pradesh is a story of resilience, innovation, and adaptation. It reflects the ability of farmers to embrace change, adopt modern technology, and respond to the ever-growing demand of a globalized market. As we explore this journey further, it becomes clear that floriculture is more than just farming practice. It is an emerging livelihood revolution that has the potential to redefine Himachal’s rural landscape in the years to come.



Fig 1: Flower fields blooming in the valleys of Himachal Pradesh

Background: Agriculture and Horticulture in Himachal Pradesh

Agriculture has always been the lifeline of Himachal Pradesh, engaging nearly two-thirds of the state’s population. The mountainous terrain and varied climatic conditions have shaped the nature of farming here, making it very different from the plains of North India. The majority of farmers cultivate small and fragmented landholdings, often located on terraced fields carved out of steep slopes. Despite these challenges, agriculture remains central to the state’s economy, social life, and cultural traditions. Historically, farming in Himachal was centered on cereals such as maize, wheat, and barley, along with

pulses and millets. These crops were primarily grown for subsistence rather than commercial purposes. Limited returns from such farming made it difficult for rural households to sustain themselves. Over time, as infrastructure improved and market linkages developed, farmers diversified into horticulture. This marked a turning point in the agricultural story of the state. Horticulture, especially apple cultivation, transformed the rural economy and brought prosperity to many hill districts. Popularly called the “apple revolution,” it boosted incomes, created employment, and strengthened Himachal’s identity as the fruit hub of India. Alongside apples, crops like plums, apricots, pears, and peaches gained importance, while off-season vegetables such as peas and capsicum found markets in neighboring states. The introduction of horticulture showed farmers the potential of shifting from traditional cereals to high-value crops that could thrive in the state’s unique climate. Yet, even horticulture began facing challenges in recent years. Climate change, erratic rainfall, increasing temperatures, and pest attacks started to affect yields. Small and marginal farmers often struggled with fluctuating prices and limited storage facilities. These issues created a strong need for further diversification within the agricultural sector. It is against this backdrop that floriculture has emerged as a promising alternative, offering better returns and year-round demand.

The Rise of Floriculture in Himachal Pradesh

The journey of floriculture in Himachal Pradesh is relatively recent compared to traditional agriculture and horticulture, yet it has shown remarkable growth in a short span of time. What started as an experiment by a few progressive farmers has now taken the shape of a promising livelihood option for many households.

Growing awareness about the economic potential of flowers, combined with government support and market demand, has encouraged more farmers to adopt this new avenue. The state’s agro-climatic conditions provide a natural advantage. From the lower hills to higher regions, Himachal offers an environment suitable for cultivating a wide variety of flowers. Carnations, roses, marigolds, gladiolus, lilies, and chrysanthemums flourish across districts.

Farmers realized that flowers could generate higher returns compared to cereals, particularly when cultivated under controlled conditions like polyhouses. Government schemes and training programs have played a big role. Subsidies for polyhouses, improved seed varieties, and technical guidance from Krishi Vigyan Kendras have made floriculture more accessible. Universities like Dr. Y.S. Parmar University of Horticulture and Forestry have provided training in modern practices, pest control, and post-harvest management.

This support system has reduced risks and given farmers the confidence to invest in flowers. Another reason behind this rise is the consistent demand for flowers. Weddings, religious ceremonies, cultural festivals, and events in cities like Delhi, Chandigarh, and even export hubs ensure that farmers have markets throughout the year. This demand has turned floriculture into a reliable source of income. At the same time, younger farmers and rural entrepreneurs see it as a business opportunity where they can combine modern farming with innovative marketing strategies.

Major Flowers Cultivated in Himachal Pradesh

Himachal Pradesh is today home to a range of commercially important flowers.

- 1. Carnations:** Grown widely in polyhouses, they are in high demand across India.
- 2. Gladiolus:** Known for its long spikes and vibrant colors, gladiolus thrives in open fields and has become one of the most popular flowers of the state.
- 3. Marigold:** A traditional favorite for religious and cultural functions, marigolds ensure steady income, especially during festivals.
- 4. Chrysanthemums:** Popular for decoration and bouquets, they add diversity to the floriculture portfolio.
- 5. Roses and Lilies:** With polyhouse technology, roses and lilies are also gaining ground, particularly in districts closer to urban markets.

This mix of traditional and exotic flowers allows farmers to target both local and national markets. The variety also ensures that income is not dependent on a single crop, making flower cultivation more sustainable.



Fig 2: A vibrant display of colorful gladiolus blooms

Economic and Social Impact

Floriculture is bringing visible changes to rural life in Himachal Pradesh. Farmers earn better returns from small plots of land, which is vital in a state where holdings are fragmented. Youth who once migrated to cities for jobs are now finding opportunities in their own villages. Women are also playing a key role, especially in nursery work, harvesting, and bouquet preparation, making floriculture an important tool for empowerment.



Fig 3: Women and youth shaping Himachal's floriculture

Beyond income, floriculture is encouraging entrepreneurship. Farmers are exploring packaging, branding, and direct marketing to urban buyers. Some are even forming cooperatives or joining self-help groups to collectively sell their produce. These steps are turning simple farmers into business-minded individuals who think beyond production and focus on the entire value chain.

Challenges Ahead

Despite its promise, floriculture faces challenges in Himachal. The high initial investment in polyhouses and planting material can discourage small farmers. Lack of cold storage, transportation facilities, and assured markets often lead to price fluctuations. Competition from imported flowers also poses risks. To overcome these hurdles, stronger infrastructure, better logistics, and organized farmer groups are needed.

Future Prospects

The future of floriculture in Himachal Pradesh looks bright. With increasing urbanization, rising disposable incomes, and the popularity of grand celebrations, demand for flowers will only grow. Export opportunities, eco-tourism linkages, and value addition through bouquet making or essential oils add further scope. If supported with proper policies and infrastructure, floriculture can stand alongside apples and vegetables as a key pillar of the state's rural economy.



Fig 4: Himachal flowers reaching local markets

Conclusion

The emerging flowering culture in Himachal Pradesh is more than a trend; it is a livelihood revolution. It has the potential to transform rural life by providing sustainable incomes, empowering women, and creating opportunities for youth. By embracing flowers, farmers are not only adding color to their fields but also hope to their lives. With continued support, innovation, and determination, Himachal Pradesh can soon be known not just for its apples but also as the flower capital of northern India.

Cultivation of Apple in Himachal Pradesh

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Introduction

Himachal Pradesh is a land of towering mountains, winding rivers, and green valleys. But beyond its natural beauty, the state is also famous for something sweet, crisp, and refreshing apples. Over the years, Himachal has proudly earned the name “*Apple State of India*.” The cool orchards. For farmers in Himachal, growing apples is not just a profession. It is a tradition, a source of pride, and a lifeline that supports their families. From the time of planting to the joy of harvest, apples bring both economic stability and cultural identity to the region. This article looks at how apple cultivation began in Himachal, the conditions that make it possible, the varieties grown, and the challenges and future of this much-loved fruit.



Fig 1: Flower fields blooming in the valleys of Himachal Pradesh

Historical Background

Apple cultivation in Himachal Pradesh has an inspiring story. Although the land and climate were suitable for apples, the fruit was not grown here until the early 20th century. The credit for introducing apples goes to Samuel Evans Stokes, an American missionary who settled in Kotgarh, near Shimla. Around 1916, he brought high-quality apple saplings from the United States and planted them in the hills.

At first, it was just an experiment. But soon, the orchards flourished and proved to be more profitable than traditional crops. Other farmers in the region began following the same path, and slowly, apple orchards spread from Kotgarh to Shimla, Kullu, Mandi, and later Kinnaur. By the mid-20th century, apples had become the backbone of the rural economy. Today, it is impossible to imagine Himachal without thinking of its apple orchards.

Geographical and Climatic Conditions

The success of apple cultivation in Himachal is linked directly to its natural environment. Apples need cool temperatures, well-drained soil, and a certain altitude to grow well. In Himachal, the ideal altitude for apples is between 1,500 and 3,000 meters above sea level. The winters are cold enough to provide the chilling hours that apple trees require, while summers are mild and pleasant.

The soil in these regions is rich in organic matter and has good drainage, which prevents waterlogging. Together, these factors create the perfect environment for apple orchards to thrive.

Major Apple Growing Regions

Apples are grown in many districts of Himachal Pradesh. Some of the most famous regions include:

1. **Shimla:** The heart of apple production, with areas like Kotgarh and Rohru.
2. **Kullu Valley:** Known for its scenic orchards and high-quality varieties.
3. **Kinnaur:** Famous for late-season apples that are very sweet and juicy.
4. **Mandi and Chamba:** Smaller regions but still significant contributors.

Each of these regions has built its reputation on the quality of apples they produce, and together they make Himachal the apple hub of India.

Popular Varieties of Apples

Over time, many different apple varieties have been introduced and cultivated in Himachal. Some of the most popular ones are:

1. **Royal Delicious:** The most famous and widely grown variety.
2. **Red Delicious:** Deep red in color with a crisp bite.
3. **Golden Delicious:** Yellow-green apples with a sweet taste.
4. **Rich Red and Red Chief:** Known for their attractive color.
5. **Granny Smith:** Green apples with a tangy flavor, often used for baking.



Fig 2: Different apple varieties in baskets

Each variety has its own season, taste, and market demand, making apple farming diverse and profitable.

The Cultivation Process

Apple farming is not an easy task; it requires patience, skill, and proper care. The process usually begins with land preparation and planting of saplings in winter or early spring. Trees are given proper spacing, so they get enough sunlight and air.

Pruning and training of the trees are done regularly to shape them and ensure healthy growth. Pollination is very important, and honeybees play a major role in transferring pollen from one flower to another. Farmers also use irrigation methods like drip systems to save water and keep the soil moist.

Apples are vulnerable to pests and diseases, so farmers spend a lot of time on plant protection. Finally, the harvesting season, which usually starts in July and lasts till October, brings joy to farmers. Apples are carefully plucked, sorted, and packed in boxes before being sent to markets across India.



Fig 3: Farmer harvesting apples

Role of Technology and Innovation

In recent years, technology has become a big part of apple farming. Farmers are adopting high-density plantations, where more trees are planted in smaller areas using dwarf rootstocks. This gives higher yields and quicker returns.

Cold storage and controlled atmosphere units are being set up to keep apples fresh for longer. Digital platforms and mobile apps are helping farmers connect directly with buyers, reducing dependence on middlemen. All these innovations are making apple cultivation more modern and efficient.



Fig 4: Modern high-density plantation photo

Economic Importance

Apple farming is the backbone of Himachal's rural economy. It provides livelihood to thousands of families and generates crores of rupees every year. Many small farmers depend entirely on their orchards for income.

Beyond farming, apples also create jobs in transport, packaging, cold storage, and marketing. The orchards have even become a part of tourism, as visitors love to see and experience apple-picking during the harvest season. In this way, apples not only feed people but also fuel the economy.

Challenges in Apple Cultivation

Despite its success, apple cultivation in Himachal faces several challenges. Climate change is the biggest threat, with unpredictable rain, hailstorms, and rising temperatures affecting harvests. Farmers also struggle with high input costs, such as pesticides and fertilizers, which reduce their profits.

Storage and transport are another issue. Many orchards are in remote villages, making it hard to get the fruit to markets in time. Middlemen often take a large share of the profit, leaving farmers with less income.

Government Support and Future Prospects

The government has taken several steps to support apple growers. Subsidies for high-density plantations, schemes for cold storage, and crop insurance programs are being introduced to help farmers. Projects like the Himachal Pradesh Horticulture Development Project are aimed at improving infrastructure and training farmers in modern techniques.

Looking ahead, the future of apple cultivation lies in adopting climate-resilient varieties, organic farming practices, and better market linkages. With the right support, Himachal can continue to hold its place as the Apple State of India for generations to come.

Conclusion

Apple cultivation in Himachal Pradesh is more than agriculture it is a story of transformation, culture, and resilience. From the first orchards planted by Samuel Evans Stokes to the modern high-density farms of today, apples have changed the lives of countless farmers and given Himachal a special identity. The crisp, juicy apples that reach our markets are not just fruits; they are the result of hard work, tradition, and a deep connection between the land and its people. Protecting and strengthening this tradition is not only important for the economy but also for preserving the heritage of the beautiful hill state of Himachal Pradesh.

Unlocking the Insect World: Application of Omics in Entomology

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Introduction

Insects are the most diverse and adaptable group of animals on Earth. From pollinators like bees and butterflies to notorious pests like mosquitoes and locusts, they influence agriculture, ecosystems, human health, and even global economies. Understanding insects has therefore been at the heart of entomology for centuries. However, conventional approaches such as morphological identification, behavioral studies, and classical genetics often provided only a partial picture of their biology.

In recent decades, the rise of omics technologies—including genomics, transcriptomics, proteomics, metabolomics, and epigenomics—has revolutionized the study of insects. Collectively referred to as “omics,” these approaches allow scientists to explore the complex molecular networks that drive insect growth, development, adaptation, and interactions with their environment. Omics is essentially about capturing the “big picture” of biological systems, making it a powerful tool for solving entomological challenges in agriculture, medicine, biodiversity, and conservation.

This article highlights the application of omics in entomology, emphasizing how these cutting-edge technologies are transforming pest management, pollinator health, vector-borne disease control, and ecological research.

The Omics Revolution in Entomology

Omics refers to large-scale approaches that aim to map and analyze the complete set of molecules in living organisms. Each omics field focuses on a specific level of biological information:

1. Genomics – study of the complete DNA sequence of an organism.
2. Transcriptomics – analysis of RNA transcripts that reflect gene activity.
3. Proteomics – profiling of proteins expressed in cells or tissues.
4. Metabolomics – identification of small molecules and metabolites involved in physiology.
5. Epigenomics – study of heritable changes in gene expression not coded in DNA sequence.
6. Microbiomics – exploration of microbial communities associated with insects.

By combining these approaches (integrative omics), entomologists can move beyond studying single genes or traits to understanding entire biological systems.

Genomics: Decoding the Blueprint of Insects

Genomics has been the cornerstone of modern entomology. With the advent of next-generation sequencing (NGS), insect genomes can be sequenced faster and cheaper than ever before.

Pest management: Sequencing of pest genomes like the fall armyworm (*Spodoptera frugiperda*) or cotton bollworm (*Helicoverpa armigera*) has revealed genes linked to insecticide resistance. This information helps in designing novel pesticides and monitoring resistance evolution.

Disease vectors: The genomes of mosquitoes (*Anopheles gambiae*, *Aedes aegypti*) and sandflies have been sequenced to identify genes responsible for transmitting malaria, dengue, and leishmaniasis. Genome editing tools like CRISPR-Cas9, informed by genomic data, are now being used to engineer sterile or resistant mosquito strains for vector control.

Pollinator health: The sequencing of the honeybee (*Apis mellifera*) genome has provided insights into immunity, social behavior, and responses to environmental stressors, supporting conservation strategies.

Thus, genomics provides the foundational “blueprint” to understand insect biology and apply it to practical challenges.

Transcriptomics: Listening to the Voices of Genes

While genomics tells us what could happen, transcriptomics reveals what is actually happening inside insect cells at a given moment. By sequencing RNA, scientists can study gene expression under different conditions.

Stress and adaptation: Transcriptomic studies have shown how insects respond to heat, drought, or pesticide exposure by switching on or off specific genes. This helps in predicting pest outbreaks under climate change scenarios.

Host–pathogen interactions: In mosquitoes, transcriptomics has revealed how immune genes are activated when they ingest malaria parasites. Such findings pave the way for blocking parasite development inside the insect.

Development and metamorphosis: The transformation of a caterpillar into a butterfly is guided by complex gene expression changes. Transcriptomics maps these changes, giving clues to hormonal control and developmental biology.

By capturing the dynamic “voices” of genes, transcriptomics provides a real-time snapshot of insect physiology.

Proteomics: Mapping the Workhorses of Life

Proteins are the functional molecules that carry out cellular activities. Proteomics, the large-scale study of proteins, helps entomologists understand the biochemical machinery of insects.

Insecticide targets: Proteomic studies identify detoxification enzymes such as cytochrome P450s, esterases, and glutathione-S-transferases that allow insects to survive pesticide exposure.

Venom and saliva analysis: The saliva of mosquitoes or the venom of parasitoid wasps contains proteins that suppress host defenses. Proteomics reveals their structure and function, aiding in medical entomology and drug discovery.

Pollinator nutrition: Proteomic analysis of bee hemolymph (insect blood) and royal jelly has provided information on nutrition and immune health in pollinators, vital for their conservation.

Proteomics therefore connects genes with their biological functions, serving as a bridge between genetic information and observable traits.

Metabolomics: The Chemical Fingerprint of Insects

Metabolomics focuses on small molecules such as amino acids, sugars, lipids, and secondary metabolites. These molecules directly influence insect survival, reproduction, and ecological interactions.

Insect–plant interactions: Metabolomics helps unravel how herbivorous insects detoxify plant toxins or how plants alter their chemistry to defend against insect attacks.

Insect communication: Many insects rely on pheromones and chemical signals. Metabolomic profiling identifies these compounds, aiding in the development of eco-friendly pest management strategies like pheromone traps.

Disease vectors: In mosquitoes, metabolomics has shown how malaria parasites alter host metabolism, offering new intervention points.

Through metabolomics, entomologists gain insights into the “chemical language” of insects.

Epigenomics: Beyond the Genetic Code

Epigenomics examines how environmental factors modify gene expression without changing the DNA sequence itself. In insects, epigenetic modifications like DNA methylation or histone modification influence behavior, caste differentiation, and adaptation.

Social insects: In honeybees, epigenomic changes decide whether a larva develops into a worker or a queen, despite having the same genetic code.

Insecticide resistance: Epigenetic regulation can turn on detoxification genes, enabling pests to adapt quickly to new chemicals.

Transgenerational effects: Epigenomic studies show how parental exposure to stress or toxins can influence offspring traits, relevant for predicting pest resilience.

Epigenomics adds another layer of complexity, showing that genes are not destiny but are regulated by flexible molecular switches.

Microbiomics: The Hidden Allies and Enemies

Insects harbor diverse microbial communities—bacteria, fungi, and viruses—that influence their health, development, and ecological roles.

Symbionts in pests: Endosymbiotic bacteria like *Wolbachia* manipulate insect reproduction and reduce vector competence in mosquitoes, offering a biological control strategy.

Gut microbiota: In termites, gut microbes digest cellulose, while in mosquitoes they influence pathogen transmission. Manipulating gut microbiota is an emerging area in pest and vector management.

Pollinator health: Microbiome studies in bees have identified beneficial bacteria that enhance immunity and digestion, highlighting the role of microbial balance in pollinator decline.

Microbiomics reminds us that insect biology is not just about the insect itself but also its invisible microbial partners.

Applications of Omics in Entomology

1. Pest Management: Omics tools provide insights into resistance mechanisms, pest population genetics, and novel control targets. For example, transcriptomic markers can detect early signs of insecticide resistance, while metabolomic studies aid in pheromone-based integrated pest management (IPM).

2. Vector Biology and Disease Control: Genomic and transcriptomic data are being used to design genetically modified mosquitoes that are resistant to malaria parasites. Microbiome manipulation through *Wolbachia* is already being field-tested in dengue control programs.

3. Pollinator Conservation: Honeybee genomics and proteomics have revealed stress responses to pesticides, pathogens, and nutrition deficits. These findings inform sustainable agricultural practices that protect pollinators.

4. Biodiversity and Evolution: Comparative genomics across insect species sheds light on evolutionary adaptation, speciation, and biodiversity conservation. DNA barcoding, based on genomics, allows rapid insect identification for ecological studies.

5. Climate Change Studies: Transcriptomic and metabolomic analyses reveal how insects cope with heat stress, drought, or changing host plants, helping predict shifts in pest ranges under global warming.

Future Prospects

The integration of multiple omics—so-called systems biology—is the future of entomology. By combining genomics, proteomics, metabolomics, and epigenomics, researchers can build holistic models of insect biology. Artificial intelligence and machine learning will further accelerate data analysis, turning omics into predictive tools.

However, challenges remain, including high costs, complex data interpretation, and ethical considerations in releasing genetically modified insects.

Conclusion

Omics has opened a new era in entomology, enabling scientists to move from descriptive studies to predictive and applied sciences. From decoding insect genomes to profiling their microbiomes, these approaches provide unprecedented insights into insect biology. The applications in pest management, pollinator protection, and vector control demonstrate how omics is not only advancing fundamental knowledge but also addressing global challenges in agriculture, health, and the environment.

As omics technologies continue to evolve, the tiny world of insects will no longer remain hidden. Instead, it will be illuminated at molecular detail, offering innovative solutions for a sustainable future.

Natural Farming: A Systems-Based Agroecological Paradigm for Sustainable Agriculture

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Abstract

Natural Farming (NF) represents a paradigm shift in agronomic practice, emphasizing ecological harmony, endogenous input systems, and the regeneration of agroecosystems. Rooted in both traditional knowledge systems and contemporary agroecological science, NF challenges the industrial, input-intensive model that dominates global agriculture. This paper critically examines the theoretical foundations, core methodologies, biophysical impacts, and socio-economic implications of natural farming, with a specific focus on the Zero Budget Natural Farming (ZBNF) model in India. The paper further evaluates empirical evidence from longitudinal field studies, highlighting NF's role in climate resilience, soil health restoration, and rural livelihood enhancement. Limitations, scalability challenges, and policy considerations are also discussed.

Introduction

The degradation of natural resources under industrial agriculture is well-documented. The overuse of synthetic fertilizers, pesticides, mechanization, and monocultures has led to soil erosion, biodiversity loss, water contamination, and significant GHG emissions (Lal, 2020; FAO, 2021). In contrast, Natural Farming (NF), a term popularized by Masanobu Fukuoka (1978) and later adapted in South Asia by Subhash Palekar, proposes a low-input, biologically regenerative model of agriculture.

Natural farming, while often framed as a “traditional” or “alternative” practice, is increasingly recognized as a scientifically grounded, systems-based agroecological approach. Its core objective is to optimize ecological processes within farming systems, reducing dependence on external inputs while enhancing productivity, resilience, and sustainability.

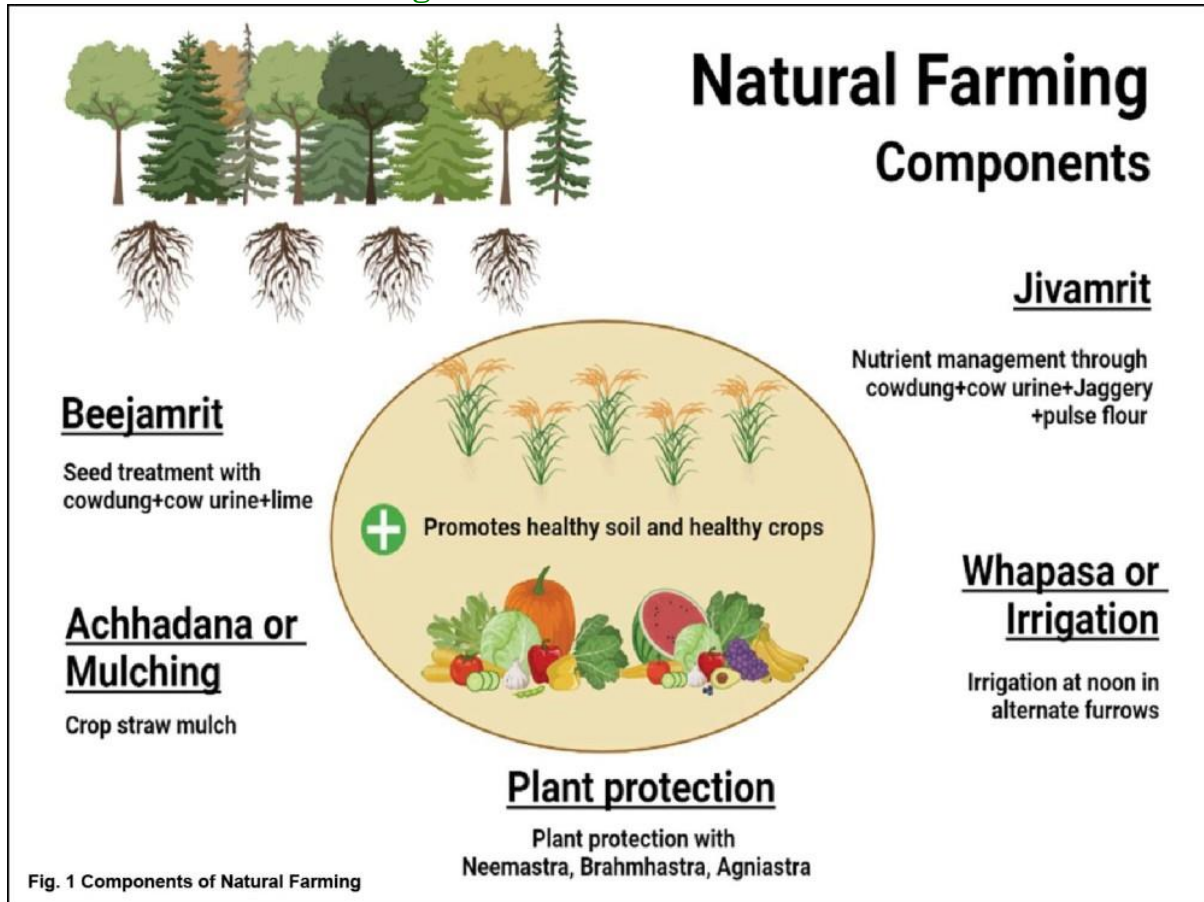
Theoretical Foundations of Natural Farming

Natural Farming is informed by three interrelated conceptual frameworks:

- 1. Agroecology:** Focuses on integrating ecological principles into farm management (Altieri, 1995). NF aligns with agroecology through polyculture, soil food web restoration, and minimal ecological disturbance.
- 2. Systems Theory:** Views the farm as an interconnected system, emphasizing feedback loops, resilience, and emergent properties (Meadows, 2008).
- 3. Traditional Ecological Knowledge (TEK):** Draws from indigenous practices rooted in local bioregional knowledge, emphasizing coexistence and sustainability.

NF thus synthesizes scientific ecology, ethnobotany, and systemic agronomy, offering a comprehensive framework for sustainable land use.

Components of Natural Farming



Biophysical and Agroecological Impacts

- 1. Soil Health:** Studies show a statistically significant increase in soil microbial biomass, enzyme activity, and aggregate stability under NF compared to conventional systems (Rajendran et al., 2022). The application of jeevamrutha restores native microbial communities, enhancing nitrogen fixation and phosphorus solubilization.
- 2. Water Use Efficiency:** Mulching and soil structure improvements lead to increased water retention capacity. Waaphasa reduces irrigation frequency, with field trials in Andhra Pradesh reporting 25–40% reductions in water usage (Andhra Pradesh CF Project, 2020).
- 3. Carbon Sequestration:** Undisturbed soil and increased biomass input enhance soil organic carbon, making NF a potential carbon-negative practice when scaled (Lal, 2020).
- 4. Biodiversity:** NF systems host greater functional and taxonomic biodiversity, including beneficial arthropods, earthworms, and pollinators, contributing to natural pest regulation and ecosystem services.

Socio-Economic Implications

NF reduces dependency on agrochemical corporations, enabling input cost minimization and risk mitigation for smallholders. Reports from Himachal Pradesh and Karnataka show a decline in farmer indebtedness, increased net incomes, and improved food self-sufficiency (CES, 2021).

However, labor intensiveness in early phases and lack of market incentives for naturally grown produce pose adoption barriers. Knowledge transfer and extension services remain crucial for effective dissemination.

Criticisms and Limitations

While promising, NF faces several challenges:

- 1. Yield Variability:** Yields under NF may initially decline, especially in monoculture-transitioning farms. Yield stabilization can take 2–3 seasons (FAO, 2022).

2. Lack of Standardization: Variability in practices and inputs makes scientific assessment and policy integration difficult.

3. Scalability: Natural Farming's success is context-specific, and scaling without ecological contextualization risks reducing it to a formulaic approach, undermining its systems-based ethos.

Policy and Research Recommendations

1. Incorporate NF into National Agroecology Frameworks alongside scientific validation mechanisms.
2. Invest in long-term comparative trials between NF, organic, and conventional systems.
3. Create certification systems for naturally farmed produce to ensure market access and price premiums.
4. Develop community-led extension models leveraging local knowledge and farmer-to-farmer learning.

Conclusion

Natural Farming, as a holistic agroecological system, presents a viable and necessary alternative to input-intensive agriculture. By restoring soil life, enhancing biodiversity, and re-embedding agricultural practice within ecological and cultural contexts, it addresses the triple crisis of environmental degradation, economic distress, and climate change. For academia and policy alike, NF challenges us to move beyond productivity-centric metrics and towards a systems understanding of agricultural sustainability.

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Nutrition-Sensitive Extension: Growing Farms, Feeding Families, Nourishing Future

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Introduction

Agricultural development has long been recognized as the cornerstone of food security and rural livelihoods. However, in many developing regions, the traditional focus of agricultural extension has been limited to enhancing productivity and profitability, often overlooking the critical dimension of nutrition. As a result, increased crop yields have not always translated into improved dietary diversity or better health outcomes for farm families. In recent years, the paradigm of nutrition-sensitive agriculture has gained prominence as an integrative approach that seeks to bridge this gap by aligning agricultural interventions with nutritional objectives. Within this framework, agricultural extension plays a pivotal role in linking farmers not only to technologies and practices that raise yields, but also to knowledge and resources that enhance food quality, household nutrition, and community well-being. Nutrition-sensitive extension emphasizes the dual responsibility of agriculture: to provide economic sustenance for farming households and to ensure access to safe, diverse, and nutrient-rich foods for society at large. This approach encourages farmers to adopt practices such as crop diversification, kitchen gardening, biofortification, and improved food storage and processing techniques. By doing so, extension services move beyond their conventional role of technology dissemination and become active agents in addressing hidden hunger and malnutrition. In contexts where malnutrition persists despite adequate food availability, nutrition-sensitive extension provides a pathway for translating agricultural gains into nutritional outcomes.

The relevance of this paradigm is particularly acute in countries like India, where agriculture sustains nearly half of the population's livelihoods, yet malnutrition remains a persistent public health challenge. Despite impressive progress in crop production, the prevalence of undernutrition, micronutrient deficiencies, and diet-related diseases highlights the urgent need to reorient agricultural strategies. By making nutrition an explicit goal of extension services, it becomes possible to enhance the resilience of farming systems, improve dietary quality, and strengthen the human capital necessary for long-term development.

Thus, the concept of "Growing Farms, Feeding Families, Nourishing Futures" captures the essence of this integrated vision. It reflects the understanding that agricultural productivity alone is insufficient without ensuring that the food produced contributes to healthier lives and sustainable futures. The exploration of nutrition-sensitive extension is, therefore, not only timely but also essential for designing policies and practices that link agricultural success with nutritional well-being, contributing directly to the Sustainable Development Goals (SDGs) of zero hunger, good health and well-being, and reduced inequalities.

Farming Beyond Yields

For decades, agricultural progress has been largely measured in terms of yield – the ability of farmers to produce more grains, pulses, or cash crops per unit of land. While yield improvement has undoubtedly been essential for ensuring food availability, this narrow focus often overlooks the broader dimensions of food and nutrition security. The concept of "Farming Beyond Yield" challenges the traditional productivity-centric view of agriculture and advocates for a more holistic approach where farming is evaluated not only by the quantity of food produced but also by its quality, diversity, and contribution to human health.

In relation to the main theme of Nutrition-Sensitive Extension: Growing Farms, Feeding Families, Nourishing Futures, farming beyond yield implies that agricultural extension services should encourage farmers to adopt practices that address nutritional outcomes alongside productivity goals. For example, extension strategies that promote crop diversification, biofortified varieties, home gardens, and improved

post-harvest practices ensure that farming systems provide both sufficient calories and essential micronutrients. This shift highlights the importance of integrating health, nutrition, and sustainability considerations into agricultural advisory systems.

By going beyond yield, farming becomes a driver of dietary diversity, community health, and intergenerational well-being, rather than just an engine of economic output. This perspective also aligns with the broader development agenda, where agriculture is seen not only as a livelihood activity but also as a means to achieve the Sustainable Development Goals (SDGs). In essence, “Farming Beyond Yield” complements the vision of “Growing Farms, Feeding Families, Nourishing Futures” by reminding us that true agricultural success lies in nourishing people, not merely in producing crops.

What is Nutrition-Sensitive Extension?

Nutrition-sensitive extension is an approach within agricultural extension that deliberately integrates nutritional goals into farming advice, training, and outreach. Unlike traditional extension services, which mainly focus on increasing crop yields, reducing production costs, and boosting farm incomes, nutrition-sensitive extension emphasizes how agricultural practices can also improve the quality, diversity, and nutritional value of food available to households and communities.

At its core, nutrition-sensitive extension:

1. Promotes crop diversification (fruits, vegetables, pulses, millets, biofortified crops) rather than focusing only on staple grains.
2. Encourages nutrition-linked farming practices such as kitchen gardens, livestock rearing for milk and eggs, and improved food storage and processing to reduce nutrient losses.
3. Links farmers especially women with knowledge about balanced diets, safe food preparation, and nutrition-sensitive technologies.
4. Bridges agriculture, health, and nutrition sectors, ensuring that farming outcomes translate into healthier families.
5. Recognizes the role of gender and empowerment, since women’s participation in farming and decision-making has direct links to household nutrition.

Nutrition-Sensitive Extension: Key Dimensions

1. Crop Diversification for Dietary Quality: Conventional extension systems have long prioritized staple crops such as rice, wheat, or maize because of their role in ensuring calorie sufficiency. However, calorie sufficiency alone does not guarantee nutritional adequacy. Nutrition-sensitive extension introduces the idea of crop diversification, where farmers are encouraged to cultivate a mix of cereals, pulses, vegetables, fruits, and millets. This not only reduces risk from monocropping but also enriches the household diet with essential nutrients like iron, zinc, vitamin A, and proteins. Diversified farming systems improve food access at the household level, reduce dependence on markets for nutrient-rich foods, and directly contribute to addressing micronutrient deficiencies, commonly referred to as “hidden hunger.”

2. Nutrition-Linked Farming Practices: Agricultural practices can be deliberately tailored to enhance nutrition outcomes. Nutrition-sensitive extension promotes kitchen gardens, enabling families to grow vegetables and leafy greens close to their homes for daily use. Similarly, rearing poultry, goats, or dairy animals provides households with milk, eggs, and meat vital sources of protein and micronutrients. Extension services may also encourage the use of biofortified crop varieties (e.g., zinc-rich rice, iron-rich pearl millet, or vitamin A-enriched sweet potatoes). These practices ensure that farming not only generates income but also improves the nutritional well-being of farming households.

3. Knowledge on Diet, Food Safety, and Nutrition-Sensitive Technologies: Another crucial aspect of nutrition-sensitive extension is the knowledge transfer that goes beyond farming practices. Extension workers educate farmers about balanced diets, portion sizes, and the importance of dietary diversity. They also promote safe food handling, hygiene, and storage methods to prevent contamination and nutrient losses. For example, improper storage may lead to aflatoxin contamination in groundnut or maize, which has severe health implications. The dissemination of nutrition-sensitive technologies such as solar dryers,

improved storage bins, and food fortification techniques ensures that food is not only available but also safe, diverse, and nutrient-rich when consumed.

4. Linking Agriculture, Health, and Nutrition Sectors: Nutrition-sensitive extension thrives on cross-sectoral collaboration. Agriculture does not exist in isolation; its impacts on health and nutrition are well-documented. By linking agricultural interventions with health and nutrition services, extension programs create a more holistic development pathway. For instance, a farmer learning about diversified cropping could also receive information on child feeding practices, maternal nutrition, or government health and nutrition schemes. Partnerships with health workers, NGOs, and nutrition specialists strengthen the impact, ensuring that increased food production translates into real improvements in community health indicators.

5. Gender Empowerment and Household Nutrition: Nutrition-sensitive extension pays special attention to gender dynamics because women are central to household nutrition decisions. Women often manage food preparation, dietary choices, and childcare, yet they are frequently marginalized in agricultural decision-making. Extension programs that actively involve women through women's self-help groups, farmer field schools, or targeted capacity-building can significantly improve nutrition outcomes. When women have greater control over resources, income, and farming decisions, research shows that households tend to allocate more resources toward nutritious food, healthcare, and child education. Thus, gender empowerment becomes a crucial bridge between agricultural interventions and nutritional improvements.

6. Contribution to Global Development Goals: Nutrition-sensitive extension aligns strongly with international development priorities. It directly supports Sustainable Development Goal (SDG) 2: Zero Hunger, which emphasizes not only ending hunger but also achieving food security, improving nutrition, and promoting sustainable agriculture. It also contributes to SDG 3: Good Health and Well-being and SDG 5: Gender Equality. By focusing on both productivity and nutrition, extension systems foster resilient farming households, healthier communities, and sustainable rural livelihoods. This integrated approach ensures that agriculture remains not only a source of economic growth but also a foundation for human development and intergenerational well-being.

Why does it Matter?

Despite agricultural achievements, malnutrition remains widespread. NFHS-5 data highlights the following challenges among children under 5:

Stunting	35.5%
Wasting	19.3%
Underweight	32.1%

Additionally, 57% of women (ages 15–49) are anemic, and two-thirds of the population face micronutrient deficiencies.

Farmers as Champions of Nutrition

Case studies reveal the impact of nutrition-sensitive practices. In Gujarat, women-led kitchen gardens have improved family diets with spinach, beans, and carrots. These interventions reduced illness and spending on market vegetables. Similarly, in Andhra Pradesh, integrated programs combining homestead gardens, nutrition education, and cooking demonstrations increased dietary diversity scores in intervention villages.

Minimum Dietary Diversity Failure (MDDF)

The Minimum Dietary Diversity Failure (MDDF) refers to the inability of children, particularly those aged 6–23 months, to consume foods from the minimum number of food groups recommended by the World Health Organization (WHO) for healthy growth and development. According to WHO, young children should consume foods from at least five out of eight food groups daily, including breast milk, cereals, legumes, dairy products, flesh foods, eggs, vitamin-A rich fruits and vegetables, and other fruits and vegetables. Meeting this threshold is critical because it ensures adequate intake of essential vitamins, minerals, and proteins required during the most vulnerable period of early childhood.

Recent research highlights a concerning trend: nearly 77–80 percent of children in India fail to meet this standard, making dietary diversity one of the weakest aspects of child feeding practices. This high rate of MDFF contributes significantly to persistent malnutrition, stunting, wasting, and micronutrient deficiencies in the country. The consequences extend beyond physical growth to impair cognitive development, immunity, and long-term productivity of children.

The problem is especially severe in several central and western Indian states, including Uttar Pradesh, Madhya Pradesh, Rajasthan, and Gujarat, where cultural food practices, low household incomes, inadequate knowledge of nutrition, and limited access to diverse foods exacerbate the challenge. In these regions, diets are often cereal-dominated with limited inclusion of pulses, dairy, fruits, vegetables, or animal-sourced foods. The lack of dietary diversity is further linked to gender disparities, limited women's decision-making power, and weak linkages between agriculture and nutrition programs.

Addressing MDFF requires an integrated strategy that combines nutrition-sensitive agricultural practices with effective extension services, behavior change communication, and targeted interventions such as kitchen gardens, women's empowerment initiatives, and improved food distribution systems. Without tackling MDFF, progress in reducing child malnutrition and achieving Sustainable Development Goal 2 (Zero Hunger) will remain limited, particularly in rural India where agriculture and nutrition are deeply interconnected.

The Road Ahead

To mainstream nutrition-sensitive extension, the following steps are essential:

1. Train extension workers in nutrition education.
2. Foster inter-sector collaboration between agriculture, health, and women's development.
3. Provide incentives for nutrient-dense crops.
4. Launch awareness campaigns on dietary diversity.
5. Strengthen data collection and monitoring for targeted interventions.

A Diagnostic Tool for Evaluating and Managing Diseases in Pulses: PulsExpert

Article ID: 72210

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Abstract

A group of field farmers and State Agriculture Officers evaluated PulsExpert to be good and appropriate as an automated diagnostic tool for the control of diseases suffered by pulse crops. PulsExpert has enabled extension workers and farmers find out diseases in important pulse crops such as chickpea, pigeonpea, mungbean, and urdbean which are the most important and popular among the other pulses. PulsExpert's automatic knowledge acquisition technology makes it easy for domain experts to enter, store, and organize domain-specific knowledge. Using an automatic knowledge acquisition system, more than one expert can submit information about a certain crop. The system then automatically combines the information to create a consistent knowledge base. PulsExpert is a knowledge base that is always up to date with information about 19 key diseases that affect pulses from seedling to maturity. The technology is easy for farmers to use as they can ask questions in both words as well as pictures. PulsExpert diagnoses pulse crop illnesses based on the answers and gives a confidence factor. It then proposes the best ways to control the diseases, which can include both cultural practices and chemical controls.

Introduction

India produces 14.52 million tons of pulses annually over an area of around 24.38 million hectares which accounts to an average pulse yield of approximately 600 kg/ha as compared to the global average yield of 857 kg/ha. In India, rainfed pulse crops are typically farmed on marginal lands. India is also the biggest pulse consumer in the world. There are numerous pulse crops cultivated in the nation, and the most important ones are—Chickpea (Chana or Bengalgram), Pigeonpea (Arhar or Tur or Redgram), Mungbean (Moong or Greengram), and Urdbean (Urd or Blackgram). These are grown in a variety of agroclimatic conditions and account for almost 86% of the nation's total pulse production. Pulses have developed diseases since their cultivation had begun in agriculture. Due to the significant losses experienced in different production techniques, they have always been a significant limitation in the production of pulses. Despite all of the advancements in crop protection technology, 8–10% of pulse crops are lost each year as a result of disease ravages, costing the national exchequer close to Rs. 1500 crores. Few diseases cause significant output losses, despite the fact that pulse crops are vulnerable to numerous diseases from seedling to maturation and then storage. The production of pulses as a whole might rise significantly if we could just manage these serious diseases. Crop experts and professionals, as well as experienced farmers, are mostly responsible for diagnosing and controlling diseases based on what they know. Each pulse crop needs its own set of management techniques and planting patterns, and even seasoned farmers may not know everything about them. So, having quick access to all the informations they need may help growers make quick decisions on how to take best care for their crops. An expert system or computer-aided diagnosis system could be a great instrument for speeding up the diagnosis and control of diseases in order to solve these challenges. A lot of expert systems have been made for farming in general and for diagnosing crop diseases. It was thought that farmers would get a better crop yield if they used the system. For the most part, they were made using task-specific information and standard ways of gathering and representing knowledge. PulsExpert does, however, have an important trait that sets it apart: an automatic knowledge acquisition system that lets the system grow and get better over time. With only a few small changes, the general design of the system could be used to find diseases in crops other than pulses.

A prototype expert system for pulses (PulsExpert) was proposed for the design and development in order to provide farmers and extension workers with information for the early diagnosis and control of detrimental diseases that are frequently encountered in pulse crops. The knowledge base for four key pulse

crops has been developed with the assistance of numerous domain experts (plant pathologists from the Indian Institute of Pulses Research, Kanpur) through the use of an automatic knowledge acquisition system. The knowledge base's accuracy is enhanced by the direct involvement of domain experts, who reduce the likelihood of errors that arise from the communication divide between the developer and the experts.

Architecture of PulsExpert

PulsExpert is composed of **four interlinked modules** forming an integrated diagnostic framework:

1. Automatic Knowledge Acquisition System (AKAS)
2. Knowledge Base (KB)
3. Inference Engine
4. System Consultation Interface

The software follows a **client-server architecture**: the client side provides the interactive interface for knowledge acquisition and user consultation, while the server side manages the **inference engine**, **data storage**, and **knowledge base maintenance**. This modular design ensures **flexibility, scalability, and real-time updating**.

Automatic Knowledge Acquisition System (AKAS)

The typical knowledge acquisition model involves the knowledge engineer collecting expert knowledge, encoding it, and validating it with the expert to create the final knowledge base (Rafea et al., 2001; Zetian et al., 2005). When a knowledge base is created, it can be challenging for users or experts to update it without the assistance of a knowledge engineer. PulsExpert features an automated knowledge acquisition system that allows users/experts to directly input knowledge for knowledge base construction. To create this automated system, the knowledge engineer employed a manual way to ascertain the necessary knowledge for PulsExpert. Knowledge-edge engineers analyzed text-based information (e.g., books, journals, bulletins, databases), consulted domain experts and farmers, and identified relevant knowledge (e.g., attributes, relationships, decisions, goals) for pulse crop disease diagnosis. Before creating the automated knowledge acquisition system, the team of domain experts (pathologists) examined the structure of diagnostic rules and limitations, in addition to identifying possible symptoms. To diagnose pulse crops disease, four key parameters were identified: crop parameters, field parameters, symptom parameters, and visible pictorial parameters. A questionnaire was created to assist users/experts in entering data online. PulsExpert, a user-friendly interactive knowledge acquisition system, was developed after analyzing the types of knowledge and their parameters. It allows for adding, viewing, modifying, and deleting both textual and pictorial knowledge. This solution allows experts and knowledge engineers to easily input knowledge and maintain its consistency in the knowledge base. The development process of an automatic knowledge acquisition system involves four main steps: identifying and abstracting necessary knowledge, determining knowledge structure, identifying knowledge acquisition processes, and customizing the interface.

The PulsExpert knowledge acquisition system enables participation from several experts for the same crop. The technology automatically integrates expert input to create a knowledge base for the pulse crop. Each domain expert estimates data reliability. A reliability estimate indicates the importance of a query in diagnosing a specific disease. Expert knowledge for each crop is contained in the database. The system automatically incorporates disease-specific knowledge for a specific pulse crop. The system combines expert questions and responses, removes duplicates, and calculates overall reliability estimates for each question. PulsExpert stores all expert solutions for a certain issue in its knowledge base. Prioritizing knowledge based on reliability estimates creates a complete diagnosis base for pulse crop disease.

Knowledge Base

PulsExpert's knowledge base includes current descriptions and images of 19 important diseases, including wet root rot, stem rot, wilt, dry root rot, collar root rot, Ascochyta blight, Botrytis grey mold, Phytophthora blight, Alternaria blight, and sterility. In pulse crops, diseases include mosaic, yellow mosaic virus, cercospora leaf spot, powdery mildew, and anthracnose occur. The PulsExpert 'Disease Diagnosis and

therapeutic' knowledge base consists of three parts: textual, visual, and therapeutic. The textual knowledge base includes disease-specific symptoms, reliability estimates, and probable replies in question form. The system stores disease-related images in its knowledge base, which are displayed with queries. Preliminary diagnosis relies on textual symptoms, whereas final diagnosis considers pictorial signs. PulsExpert's knowledge base includes a third portion with illness treatment data and control measures for each ailment. Learn about cultural norms and chemical controls for control measures. Tables and production rules are utilized in PulsExpert to express knowledge. The questionnaire data for symptom identification is stored in eight database tables (pulsemaster, disease_Master, pulse_questions_Master, pulse_questions_Child, pulse_option, Disease_Knowledge_Base, \ng, and control_measures) for diagnosis and treatment of pulse crops. Tables were designed in MS-ACCESS 2000 and recommended treatments.

Inference Engine and Decision-Making Process

PulsExpert's Inference Engine is the "brain" or analytical center. It uses probabilistic logic and rule-based reasoning to look at the inputs that users give it. The engine uses rules from production to figure out what the farmer's text or picture input means (like "yellow leaves with black specks").

IF (symptom = X and field condition = Y)

THEN (probable disease = Z)

WITH (confidence factor = n %).

Each disease diagnosis is derived from multiple symptom rules processed in parallel, producing a **ranked list of probable diseases** with confidence values. The system then outputs:

1. Probable disease name
2. Confidence percentage (accuracy index)
3. Recommended cultural, biological, and chemical measures

Through iterative user feedback, PulsExpert **learns and refines** its reasoning patterns, continuously improving diagnostic precision. The mechanism reflects **adaptive machine-learning principles** and contributes to building a **self-improving agricultural AI ecosystem**.

System Consultation Interface

PulsExpert's **consultation interface** is tailored for practical use by **farmers, field officers, and extension agents**. Key features include:

1. **Bilingual operation (English / Hindi)** for broader accessibility.
2. **Interactive diagnostic questionnaires** with guided symptom selection.
3. **Image-based query submission** for visual matching.
4. **Instant IDM recommendations** integrating preventive and curative approaches.
5. **Offline functionality**, ensuring usability in low-connectivity rural areas.

Additionally, embedded **disease galleries, pictorial symptom libraries, and training modules** enhance user comprehension and enable participatory learning. The overall design prioritizes **clarity, inclusivity, and user empowerment**.

Field Evaluation and User Feedback

To mainstream nutrition-sensitive extension, the following steps are essential:

1. Train extension workers in nutrition education.
2. Foster inter-sector collaboration between agriculture, health, and women's development.
3. Provide incentives for nutrient-dense crops.
4. Launch awareness campaigns on dietary diversity.
5. Strengthen data collection and monitoring for targeted interventions.

The Road Ahead

State agricultural agencies, farmers, and extension agents all took part in extensive field tests that showed PulsExpert was accurate, useful, and could be used in a variety of situations. People who used it liked its real-time advice, easy-to-use interface, and quick diagnostics. Early tests show that PulsExpert's detection

accuracy for major diseases like Yellow Mosaic Virus and Fusarium wilt was over 85%, which is very close to what professional humans said. People really liked that it could automatically update information because it made it easy to adapt to new infections and the fact that illnesses can affect people in different parts of the world.

Future Enhancements

Ongoing and proposed improvements to PulsExpert include:

1. Automatically finding diseases in pictures with deep learning algorithms (CNNs). • An Android app for spatial disease mapping that uses GPS-enabled geotagging.
2. Syncing in the cloud lets many people share data in real time.
3. Adding regional languages like Bengali, Tamil, Telugu, and Marathi to the interface that can be used in more than one language.
4. Putting weather-based predictive analytics and pest-disease complex modules into early warning systems.

Conclusion

PulsExpert is a big step forward in the computerized control of diseases that affect pulse crops. By combining AI technology with domain knowledge, it gives farmers and extension specialists quick, reliable, and scientifically proven diagnostic advice. The system's adaptive learning architecture and ability to learn on its own make sure that the accuracy of diagnoses and the amount of knowledge it has will always get better. PulsExpert could become a national-level disease-forecasting and decision-support system that can change how pulse crop health is managed and increase productivity in sustainable farming by connecting with IoT, satellite-based surveillance, and mobile platforms in the future.

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Genome Wide Association Studies on Identification of QTLs and Candidate Genes

Article ID: 72211

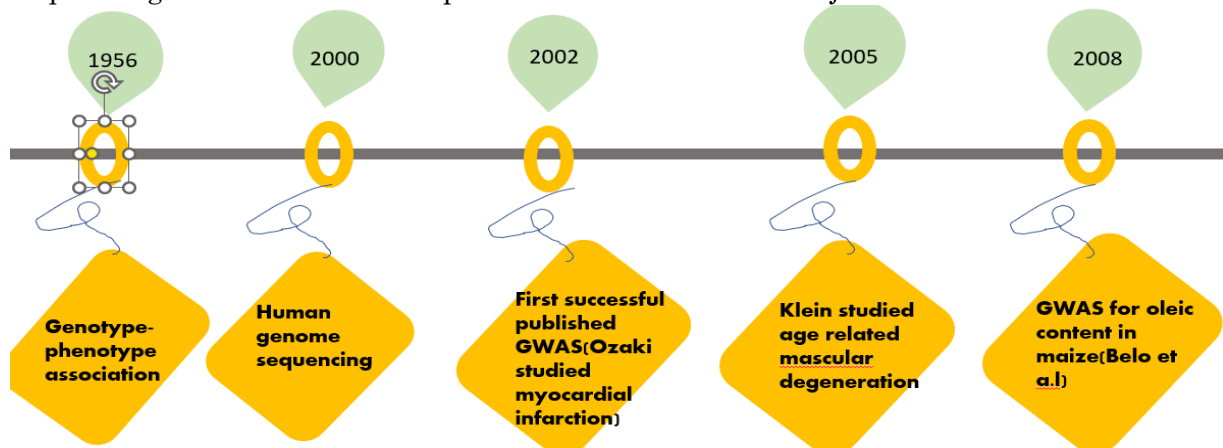
A. Gouthami¹, D. Ram Babu²

Genome Wide Association Studies

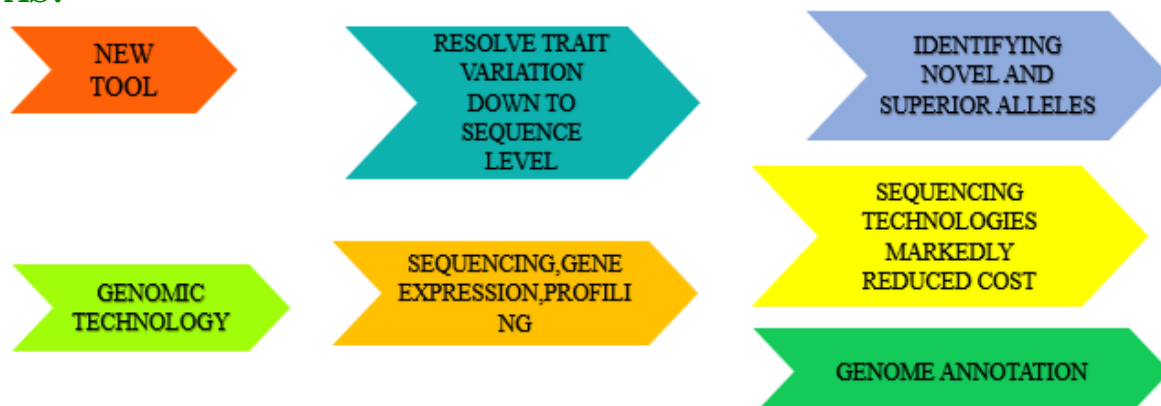
GWAS The discovery of associations between certain inherited variations in our genetic code and a certain physical trait. (National Cancer Research Institute, 2013). This method studies the entire set of DNA (the genome) of a large group of people, searching for small variations, called single nucleotide polymorphism 'SNPs. SNPs are DNA sequence variations that occur when a single nucleotide (A, T, G,C) in the genome sequence is altered. For a variation to be considered a SNP it must occur in at least 1% of the population. On average occur 1 out of 300-1000 nucleotides.

History of GWAS

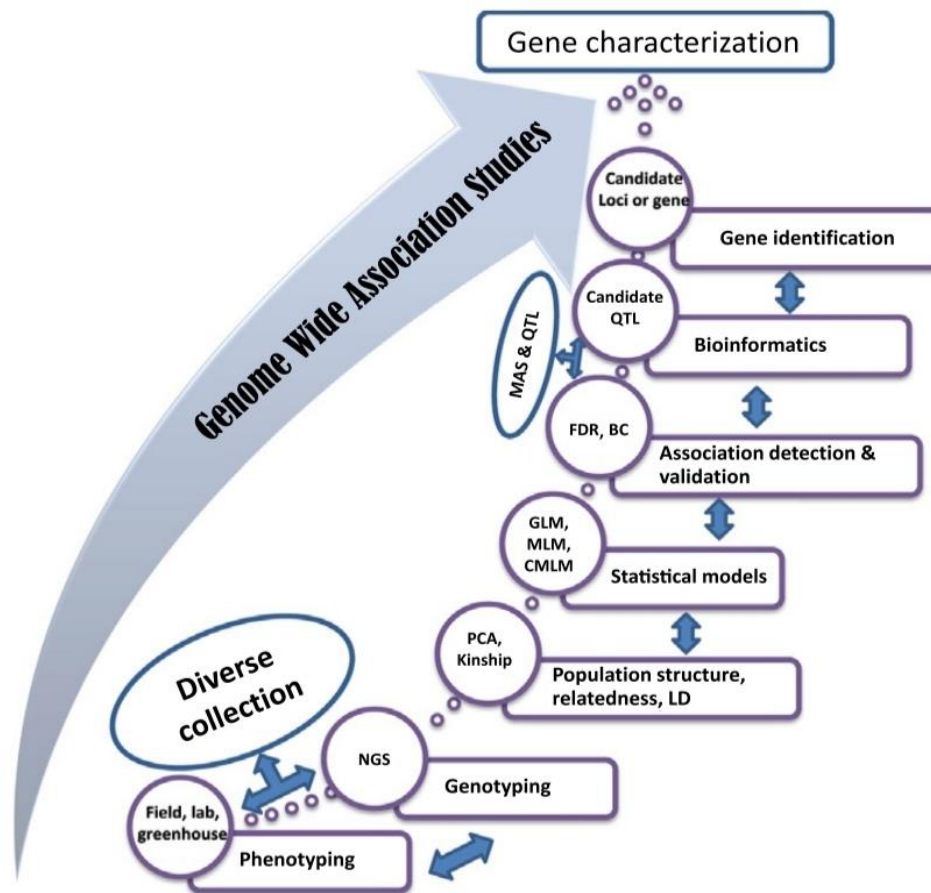
Successful study published in 2005, with investigating patients age related muscular degeneration. And two SNP with significantly altered allele frequency compared to healthy controls. Completion of human genome sequencing was announced on April 2003. The HAPMAP Project is a natural extension of the HGP.



Why GWAS?

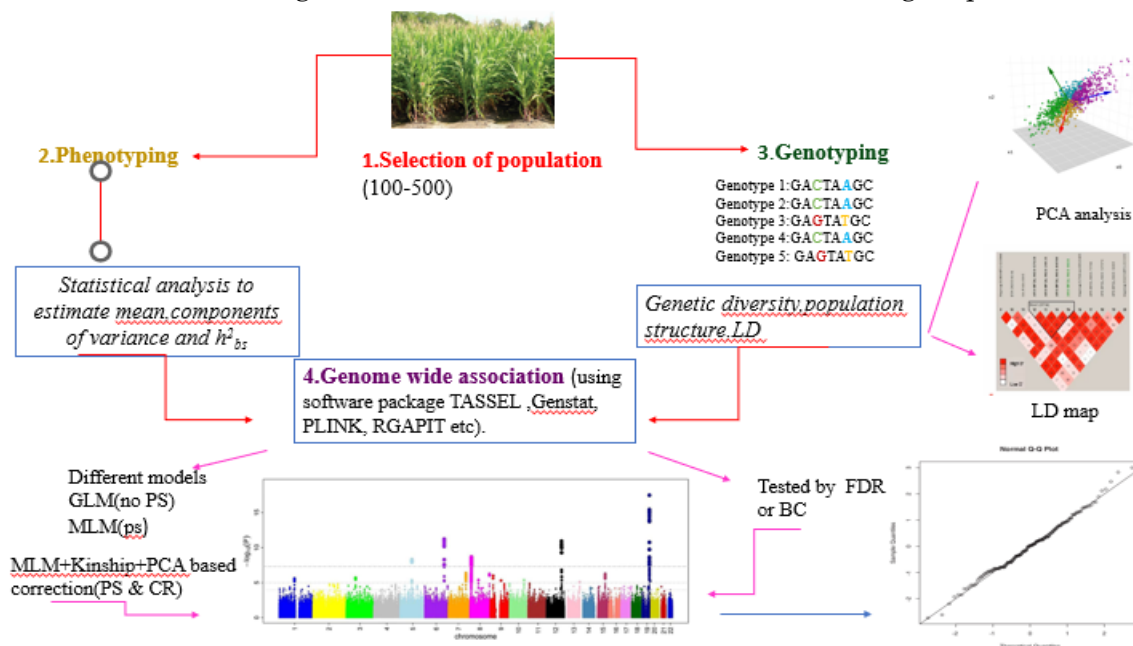


Outline of GWAS



1. Application of GWAS in core set for identification of favourable alleles.

2. GWAS study provides future directions for genomics assisted gene bank management and utilization of germplasm collections for linking natural variation to human selection during crop evolution.



Linkage Disequilibrium

An indicator for GWAS

LINKAGE DISEQUILIBRIUM is non-random association of alleles at separate loci within a population. It is denoted by higher the likelihood of two SNPs staying together said to have higher **LINKAGE DISEQUILIBRIUM**.

Gwas only works if a LD surrogate of the causal variant exists on the chip.

Gwas works close enough SNPs that is having LD with causal variant is typed then it will show a indirect association with phenotype.

Genome Wide Association Programme

P-Value: A measure of the likelihood that the association found in the distribution of data points was due to random chance given that there is no association between the SNP and trait. The stronger the data points are close around the slope of the regression line (**EFFECT**), less likely it is due to the random chance, producing the smaller **P VALUE**.

Bonferroni Correction

$P=0.05$ Can still have 5% probability of false positives. For quantative genomics field $5E-8$ as a default threshold for significance. This will sharply reduce how many SNPs having significance association with phenotype.

Relatedness Among Individuals

Population structure: Systemic difference in allele frequencies between subpopulations (caused by geographical and climate distance, familiar relationship)

Can lead to spurious association (false positive/Type I error)

Kinship: Unequal familiar relationship.

Caused by recent ancestry among individuals usually exists in a collection of diversity panel, which can lead to spurious association.

Mixed Linear Model Framework

UNIFIED MIXED MODEL: Population structure as fixed fact, kinship as random fact. By fitting this factor in the mixed model framework one can control relatedness that could lead false positives. Mixed Linear model framework was published in 2006.

By controlling population structure and kinship at the same time, mixed linear model is able to reduce Type I and Type II errors in GWAS.

MANHATTAN PLOT -a visual interpretation

Dots above the line represents SNPs associated with the trait. Often significant SNPs will be closer together due to linkage disequilibrium.

GWAS for Identification of QTL and Candidate Genes

GWAS a better approach due to: - Much larger and more representative gene pool can be surveyed. Bypasses the expense and time of mapping studies. Finer mapping resolution can be achieved, resulting in small confidence intervals of the detected loci compared to classical mapping, where the identified loci need to be fine mapped. It has potential not only to identify and map QTLs but also to identify the causal polymorphism within gene that is responsible for the difference in two alternatives.

Candidate Gene

The term candidate gene refers to a gene that is believed to be related to a particular trait, such as a disease or a physical attribute. Because of its genomic location or its known function, the gene is suspected to play a role in that trait, thus making it a candidate for additional study.

GWAS Overcome Limitations of QTL Mapping

To remove the false positives error, validations of the results are necessary. Validations are done using FDR false discovery rates & Bonferroni correction (BC).

Pros

1. Biochemical pathway of the trait does not have to be known.
2. Discovering novel candidate gene
3. Rules out specific genetic association
4. Provides more robust data
5. Identifies the mutations explaining few percent of phenotypic variant.

Cons

1. Results need replication in independent samples in different population.
2. Large study of population is required, detects association not causation.
3. Identifies specific location not complete gene.
4. Detect any variant >5% in a population.
5. Cost of each DNA sample and pooling them.

Conclusion

GWAS proved to be a innovative approach to identify statistical association of the specific trait with certain variations in genome. The applicability of GWAS could be widen by improvement in reduction of false positives, to it's integration to genomics and finally making it as an interdisciplinary tool which could be preferably accessible among all.

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Red Palm Weevil (*Rhynchophorus ferrugineus* Olivier): A Major Threat to Date Palm Cultivation in Bundelkhand Region and its Integrated Management

Article ID: 72212

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Introduction

The date palm (*Phoenix dactylifera* L.) family (Arecaceae) is one of the earliest perennial plants to undergo domestication. The Red Palm Weevil (*Rhynchophorus ferrugineus* Olivier) is the most devastating insect-pest of date palm (*Phoenix dactylifera* L.) in the world. The genus *Rhynchophorus* contains many weevil species, but the most important globally is *R. ferrugineus*, commonly known as the red palm weevil (RPW) or Asiatic palm weevil, coconut weevil, palm weevil, and red stripe weevil. The weevil was first discovered in India in 1891 and was later described as a serious pest on coconut in 1906 and on date palm in 1917. Worldwide, the pest has infested more than 40 palm species and is now found in over 60 nations. The yield losses from infestations can be as high as 10-25% per year, and heavily infested plantations can have up to 100% mortality of palms if not controlled. Since symptoms are late to manifest, detection is challenging, rendering the Red Palm Weevil a "hidden enemy" of date palm farming.

Classification of Red Palm Weevil

Phylum: Arthropoda

Class: Insecta

Order: Coleoptera

Family: Curculionidae

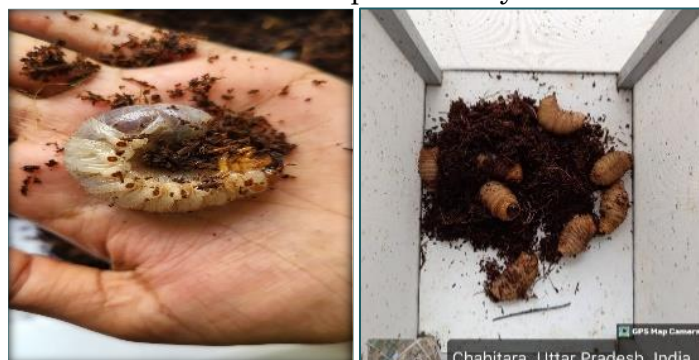
Scientific name: *Rhynchophorus ferrugineus* (Olivier).

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

Egg- Females lay the eggs in cracks and crevices of soft or wounded tissues. A single female lays 300 eggs over a period of 47 days at 28 °C. The whitish-yellow eggs (approximately 2.8 mm long and 1 mm wide) are smooth, cylindrical, and have rounded ends. Eggs hatch after two to five days.



Larvae (Grub) - After hatching from the eggs, the whitish-yellow, legless, newly emerged larvae feed on the surrounding soft tissues. The larvae keep boring their way towards the centre of the palm trunk, creating feeding galleries as they go. These galleries are filled with frass (chewed-up palm tissue) that has a distinctive odour. The larvae grow up to 5 cm in length and have up to 16 instars in summer. The larval period lasts for 35 days in summer and can extend up to 129 days in winter.

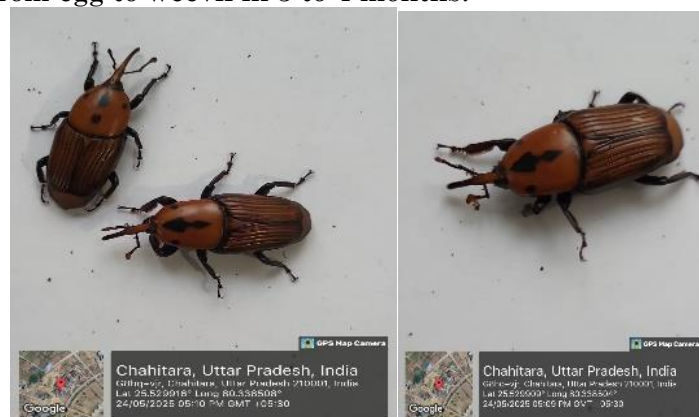


Pupae- The full-grown larva pupates inside the stem, and makes a fibrous cocoon 38 mm in length and 13 mm wide of fibrous strands. The pupal stage requires an average of three weeks.



Pupa

Adult - The newly emerged, reddish-brown, cylindrical weevil has a long, prominent, curved snout. Male and female adults are distinguished based on soft hairs on the dorsal side of the snout. The female weevils lack these hairs on the snout. The adult weevils leave the palm seeking new food sources and suitable mates, and can live for up to four months. An infested palm tree may contain several overlapping generations of weevils. Oviposition is strongly affected by temperature. Under laboratory conditions (25–27°C), the RPW develops from egg to weevil in 3 to 4 months.



Symptoms of Damage: The grubs cause damage inside the stem or crown by feeding on soft tissues and often cause severe damage, especially when a large number of them bore into the soft, growing parts. The earliest damage symptom is the oozing of a brown, viscous liquid from the site of infestation. In some cases, this ooze also forms a mild froth that drips down the trunk. After a few days, the ooze dries up into a flaky substance. The fibres, when fresh, are wet and form small lumps called “frass” that have a typical

fermented and foul odour. In case of severe infestation, the inside portion of the trunk is completely eaten and becomes full of rotting fibres. In case of young palms, the top withers, while in older palms, the top portion of the trunk bends and ultimately breaks at the bend (wilting). Sometimes the gnawing sound produced by the feeding grubs inside will also be audible.



Integrated management: Red palm weevil is managed by employing an integrated pest management (IPM) strategy, the main components of which are:-

- Regular inspection of palms to detect infestations, capture of adult weevils using food-baited pheromone traps.
- Removal/eradication of severely infested palms.
- Preventive and curative chemical treatments
- Install pheromone trap @ 1 trap per ha.

Step 1: Specialized buckets with 3 of 4 holes are made, the bucket is wound with coconut fibre/ jute sack, so that the pests can enter.

Step 2: The lure (Ferrolure +) is suspended inside the bucket, and one liter of water is added along with 100g of pineapple/ sugarcane, 2g of yeast, and 2g of Carbaryl in the bucket.

Step 3: The bait buckets are placed at sites in the farm, where infestation is seen most.

Step 4: After a week, the water is checked for the catch & refilled to prevent mosquitoes from breeding.



- Use of beneficial agents like entomopathogenic nematodes (e.g., *Steinernema carpocapsae*) and fungi (e.g., *Beauveria bassiana* and *Metarhizium anisopliae*) can be effective.
- Application of Emamectin benzoate via micro-injection directly into the trunk to reach the larvae as an endotherapy, @ 100 ml of the insecticide per tree injected.
- Use of Chlorantraniliprole via trunk injection.

Conclusion

Red palm weevil is an emerging but serious threat to palm and ornamental plantations in the Bundelkhand area. Though it is not yet reported to cause extensive outbreaks, its hidden lifecycle and quick destructive capacity require prompt attention. Its effective management is through the implementation of an

integrated approach by adopting a combination of surveillance on a routine basis, pheromone trapping, and removal of infested palms, coupled with biological and eco-friendly management. The encouragement of the use of entomopathogenic fungi, nematodes, and preventative trunk sprays should go hand in hand with the selective and judicious use of insecticides. Phytosanitary regimes and rigorous monitoring of planting material must be employed to limit the spread. Encouragement of farmer education, village participation, and the introduction of up-to-date detection methods will ensure sustainable control, averting future ecological and economic losses in Bundelkhand's palm ecosystem.

Agro-Technological Insights into Rice Cultivation under DSR Systems

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Direct Seeded Rice (DSR) is an innovative agricultural practice that involves sowing of rice seeds directly into the field rather than transplanting seedlings from a nursery. It is an alternative method from the traditional method of puddled transplanting, where rice seedlings are being raised in a separate nursery bed and later transplanted into flooded puddled fields. Puddling creates hard-pans to reduce water loss through percolation during rice cultivation, but it has negative impact on the non-rice crops followed by harvesting of rice. The puddled transplanted rice is a major source of greenhouse gases (GHGs) mainly methane (CH₄), which contributes significantly to global warming and climate change. DSR has gained attention for its potential to save water, labour and reduce greenhouse gas emissions.

Importance of DSR

The DSR approach has usually been used in rainfed upland and rainfed shallow lowland regions, and now it is gaining popularity in irrigated areas also which are facing water limitation. DSR is gaining importance in the context of climate change due to its potential to kye environmental challenges like water conservation, reduction in GHGs emission, resilience towards vagaries of climate, improved soil health and quality etc.

1. Traditional rice cultivation methods involve puddling and flooding, which are highly water-intensive. DSR eliminates the need for continuous flooding, reducing water consumption by 20-50%, making it a critical method in water-scarce regions increasingly affected by climate change.
2. Flooded rice fields are a significant source of methane emissions, a potent greenhouse gas. DSR minimizes methane production as it reduces the anaerobic conditions prevalent in flooded fields.
3. DSR allows for quicker planting and adaptation to changing rainfall patterns, reducing dependency on the monsoon. It helps mitigate risks associated with delayed or erratic rainfall, which are becoming more common due to climate change.
4. The traditional puddling method degrades soil structure and reduces organic matter. DSR improves soil health over time by maintaining better soil aeration and structure.
5. Climate change exacerbates labour shortages and increases energy costs. DSR is less labor- and energy-intensive compared to transplanting methods, offering a sustainable and cost-effective solution.
6. In areas with declining groundwater levels, DSR reduces dependency on groundwater resources, which is critical for long-term agricultural sustainability.

Types of DSR

Based on the conditions of seed as well as main field situations DSR can be broadly classified into three types

Dry DSR: Seeds are sown directly into dry soil through broadcasting, dibbling, and line sowing, followed by irrigation. This is suitable for areas with good irrigation facilities. Conventionally practiced in rainfed upland and rainfed shallow lowland. The seedbed condition is dry (un -puddled), and the seed environment is mostly aerobic.

Wet DSR: Pre-germinated seeds are sown into puddled soil or saturated or wet soil without flooding through broadcasting or line sowing using Drumseeder. Generally practiced in favourable rainfed lowlands and irrigated areas with good drainage facility.

Water-Seeded DSR: Pre-germinated seeds are sown into flooded fields in standing water. Generally practiced in areas with weedy rice problem and in irrigated lowland areas with good land levelling.

Field and Crop Management Under DSR

Agronomical practices for cultivation of direct seeded rice involves specific agricultural operations to ensure optimal crop growth, yield, and sustainability under this cultivation method. Proper agronomic practices are crucial to address challenges such as weed management, nutrient requirements, and irrigation while maximizing the advantages of DSR.

Field Preparation: Precise field levelling is critical for uniform water distribution and effective irrigation. Fine tilth soil ensures good seed-to-soil contact and proper germination. Prepare the land well by using tractor drawn plough in dry condition; it can be done during pre-monsoon rain or immediately after the harvest of the second crop. This will reduce pest and weed incidence. Before final ploughing, add 5-7 t ha⁻¹ of well decomposed FYM or compost into the soil uniformly.

Seed Selection and Treatment: Take high-quality, genetically pure and healthy seed or certified seeds of short-duration and high-yielding rice varieties suited to local conditions. Treat seeds with fungicides or bioagents to prevent seed-borne diseases. Prepare a salt solution of 1.06 specific gravity (60 g common salt in 1 liter of water). Place the seed in a container of the salt solution. Remove the floating seeds. Wash the selected seeds in fresh water and dry under shade for two days. This procedure will help in a good healthy crop stand in the field, and uniform growth and flowering of the plants leading to high yield. Prepare 10 liters of salt solution for 5 kg of seeds and the same solution can be used 3-4 times. For Dry sowing (unbunded upland), treat the seed with beam 75WP @2.0 g kg⁻¹ of seed. For Wet sowing (bunded upland), soak the seed for 8-10 hours in a solution prepared by dissolving 1.5 g Streptocycline and 20 g Captan in 20 litres of water, which is sufficient for 10 kg of seed, and then drain the water. Dry the seeds in shade before sowing.

Sowing Technique: For dry direct-seeding, optimal time is during the second fortnight of June and wet seeding first fortnight of July. Use a seed rate of 60-80 kg ha⁻¹ for dry direct seeding, keeping the row to row distance 20 cm. Seeding can be done either by seed drill or behind the plough. In case of wet seeding, dibble sprouted seeds using drum seeder or manually with a seed rate of 50-60 kg ha⁻¹ keeping row to row distance 20 cm.

Irrigation Management: Ensure adequate moisture during germination, tillering, and panicle initiation stages. Alternate Wetting and Drying (AWD) technique is preferred to save water and improve root development. Avoid waterlogging as it can reduce seedling emergence and increase weed problems.

Nutrient Management: Conduct soil tests to determine the actual nutrient requirements. Apply Nitrogen (N), Phosphorus (P), and Potassium (K) based on soil fertility levels. Three weeks before seed sowing, incorporate the well decomposed FYM / compost into soil to improve the soil organic matter or carbon. On an average, apply NPK @ 60:30:30 kg ha⁻¹. Apply the 50% N at sowing, with entire amount of P and K as basal. The remaining N to be applied in two equal splits, 25% at tillering, and 25% at panicle initiation. Incorporate micronutrients (zinc and iron) if deficiencies are detected or there is history of micronutrient deficiency in the soil.

Weed Management: Weeds are significant challenge in DSR due to the absence of continuous flooding. Suitable variety with early vigour should be selected for cultivation, which can grow better in initial stage and competes with weeds. Apply Pre-emergence herbicides immediately after sowing: Spray Butachlor @1.5 kg a.i. ha⁻¹ or Pendimethalin @ 1.0 kg a.i. ha⁻¹ with 500 liters of water at 3-5 days after sowing (if the soil is moist) followed by one hand weeding at 25-30 days after sowing. Apply Post-emergence herbicides: Bispyribac Sodium @ 250 ml ha⁻¹ can be used as post-emergence herbicide to control the weeds at the later stage e.g. at the 2-3 leaf stage of weeds. Integrate mechanical weeding using tools like a rotary weeder or hand weeding in 30-40 days after seeding. Integrated approaches may lead to reduce the weed pressure and provide the good environment for crop growth.

Pest and Disease Management: For termite, treat the seed with chloropyriphos @ 7 g a.i. kg⁻¹ of seed. Apply Carbofuran granules @ 30 kg ha⁻¹ at panicle initiation stage for control against stem borer and leaf folder. Foliar spray of Imidacloprid @ 1 ml/L or Chloropyriphos @ 5 ml/L can be applied for brown plant hopper, leaf folder and caseworm. Use 500 liters of water per ha for spraying pesticide and keep the field

bunds clean to minimize disease and pest attack. Install pheromone traps for pest monitoring. Introduce biological agents like Trichogramma for natural pest control.

Harvesting and Post-Harvest Management: Harvest the crop at physiological maturity (25-30 days after flowering). Thresh immediately after harvesting and dry gradually under shade up to 12% moisture content for seed purpose and 14% for milling for safe storage.

Proper agronomic management is essential for the success of Direct Seeded Rice, as it addresses the unique challenges of this method while capitalizing on its benefits. Adoption of DSR with appropriate practices can lead to sustainable rice production, reduced resource use and cost of production, and enhanced resource use efficiency as well as profitability for farmers.

Suitable Rice Varieties for DSR

Many rice varieties grown in DSR system were bred for transplanted puddle rice. However, most of these varieties were selected based on yield performance under favorable environments and most often they failed to perform well under DSR. High yielding DSR varieties should have traits like early vigour, weed competitiveness, lodging resistance, long and dense panicles, and high harvest index. Most of the current high-yielding varieties experience a 20–50% yield reduction when grown under DSR. The yield under DSR is often reduced due to problems like poor seedling establishment owing to waterlogging immediately after sowing, heavy weed infestation, low nutrient- and water-use efficiency, poor plant architecture, and susceptibility to lodging. High-yielding new plant types for DSR can be achieved by combining the characteristics like tolerance of drought and anaerobic germination, early vegetative vigour and weed competitiveness of rainfed upland varieties, and the characteristics such as high yield potential, high nutrient use efficiency, and desirable grain quality of the lowland varieties. To cultivate under DSR, various upland aerobic rice varieties have been developed (Table.1).

Table.1: List of varieties of rice suitable for DSR condition:

Name of variety	Year of Release	Recommended Area	Recommended ecology
CR Dhan 808	2023	Bihar, Jharkhand	Rainfed
CR Dhan 807	2023	Odisha, Jharkhand, Chhattisgarh, Andhra Pradesh, Tamil Nadu, Gujarat	Rainfed
CR Dhan 211	2023	Odisha, Bihar, Jharkhand, Maharashtra, Gujarat, Chhattisgarh	Aerobic
CR Dhan 212	2023	Odisha, Bihar, Jharkhand	Aerobic
CR Dhan 214	2023	Odisha, Bihar, Haryana, Gujarat	Aerobic
CR Dhan 103	2021	Jharkhand	Rainfed Upland
CR Dhan 107	2021	Jharkhand	Rainfed Upland
CR Dhan 102	2020	Odisha	Upland
CR Dhan 210	2020	Odisha	Aerobic
CR Dhan 207	2016	Odisha	Aerobic
CR Dhan 209	2016	Odisha	Aerobic
CR Dhan 201	2014	Chhattisgarh, Bihar	Aerobic
CR Dhan 202	2014	Jharkhand, Odisha	Aerobic
CR Dhan 203		Odisha	Aerobic
CR Dhan 204	2014	Jharkhand, Tamil Nadu	Aerobic
CR Dhan 205	2014	Tamil Nadu, Odisha, Gujarat, Madhya Pradesh, Punjab	Aerobic
CR Dhan 206	2014	Odisha	Aerobic
CR Dhan 101	2014	Odisha	Upland
CR Dhan 100	2012	Odisha	Bunded Upland
CR Dhan 200	2012	Odisha	Aerobic

Sahbhagi Dhan	2009	Odisha, Jharkhand	Rainfed Upland
CR Dhan 40	2008	Jharkhand, Maharashtra	Bunded Upland
Virendra	2006	Odisha, Gujarat	
Sadabhar	2004	Jharkhand	Upland
Anjali	2002	Uttar Pradesh, Bihar, Jharkhand, Assam, Tripura	Upland
Birsa Vikas Dhan 111	2015	Jharkhand	Upland
Birsa Vikas Dhan 110	2005	Jharkhand	Upland
Birsa Vikas Dhan 107	1996	Jharkhand	Rainfed Upland
Birsa Vikas Dhan 104	1993	Jharkhand	Rainfed Upland
Vandana	1992, 2000	Odisha, Bihar	Upland
Sneha	1992	Odisha	Upland
Heera	1991	Odisha	Upland
Kalinga III	1983	Odisha	Upland

			
CR Dhan 103	CR Dhan 107	CR Dhan 214	CR Dhan 808

Challenges & Future Scope of DSR

- Weed Management:** The absence of standing water makes DSR fields more prone to weed infestations, requiring cost effective weed control measures.
- Soil Health:** Continuous use of DSR may lead to soil compaction and nutrient imbalances if not managed properly. Hence proper soil and nutrient management is needed for better soil environment.
- Seed Quality and Uniformity:** Uneven seed distribution can result in irregular plant growth and yield. Proper calibration of sowing machinery is essential. Good seed quality must be ensured for proper plant growth and to achieve the maximum yield.
- Water Management:** While DSR is less water-intensive, it requires precise irrigation management to prevent water stress during critical growth stages.
- Limited Adoption:** Farmers accustomed to traditional practices may hesitate to switch due to lack of awareness or access to necessary equipment or facilities.

While DSR has advantages over transplanted rice, its adoption is low till date. Challenges like availability of high yielding suitable varieties as well as production practices need to be addressed through concerted efforts from scientists, farmers and policy makers. As water scarcity and labour shortages increase, DSR offers a promising alternative for sustainable rice cultivation. Governments and agricultural organizations are promoting DSR by providing subsidies on machinery, providing training programs, and awareness campaigns. With advancements in precision agriculture, the adoption of DSR is expected to rise, contributing to enhanced resource efficiency and environmental sustainability. Direct Seeded Rice is not only a cost-effective and eco-friendly alternative to traditional methods but also a significant step toward addressing the challenges of modern rice farming. DSR aligns well with sustainable agricultural practices and offers an adaptive strategy for mitigating the adverse impacts of climate change.

Corn Leaf Aphid, *Rhopalosiphum maidis* (FITCH) in Maize

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Summary

The maize aphid, *Rhopalosiphum maidis* (Fitch) is the most dreaded insect, infesting the maize crop right from tasseling stage to maturity. It is a significant agricultural polyphagous, multivoltine pest and one of the most severe pests of maize. Although it has Asian origins, it may found in all tropics and temperate regions of the planet. It is found in maize, barley, oats and occasionally in wheat. In maize aphid a sexual viviparous parthenogenic reproduction has been commonly noted. By parthenogenesis, adult females give birth to live infants. Each instar of its four nymphal stages, which last two to three days depending on the temperature, around seven to ten days pass from birth to maturity.

Introduction

Maize, *Zea mays* L. originated in Mexico, is a member of the Poaceae family. It is a crop with a wide range of adaptability and a high potential output (Tali *et al.*, 2018). It is the most significant cereal crop, grown all over the world and has the biggest production of any grain. Due to its numerous uses, maize is frequently referred to as the "Queen of Cereals" (Tali *et al.*, 2018). Maize grain contains protein (10 %), oil (4 %), carbohydrates (70 %), fat (5 to 7 %), fibers (5 to 7 %) and minerals (2%) (Tali *et al.*, 2018). Because the maize crop has lush growth, soft, succulent foliage, an endless supply of food, space, and shelters, it attracts a large number of insect pests. Among them, *R. maidis* is a significant pest of maize that can cause substantial damage to crop through sap feeding and the transmission of plant viruses. So, it is needed to be understanding the character and behavior of maize aphids for effective management.

Origin

It has Asian origins, it may found in all tropics and temperate regions of the planet (Hill, 1987; Blackman and Eastop, 2000 and Kuo *et al.*, 2006). Infestation of the aphids on maize crop was observed from month of December to March.

Host Plants

It is found in barley, oats, maize and occasionally in wheat. It's most common wild host is Johnson grass. Both are connected to orchards and fields of cereal. Two weeds, *Chromolaena odorata* and *Cynodon dactylon*, served as alternate food sources.

Life Cycle

By parthenogenesis, the pest gave birth directly to the young nymphs (viviparous). There were four nymphal instars and the adults were produced from the final nymphal instar. The instars were determined from the exuviae casted off at each moulting. Each instar lasts for two to three days depending on the temperature and require seven to ten days to attained maturity (Kuo *et al.*, 2006). The nymphs are smaller and without wings than the wingless adult but otherwise similar (Carena and Glogoza, 2004). The oval, slow moving, 2.5 mm long, often pale bluish-green adult has black antennae, legs, and tube like structure (cornicles) in addition to its soft body.

Nature of Damage

Aphid caused mechanical as well as chemical damage to the maize plant. By feeding, spreading viral disease and producing honeydew, this pest damages in different stages of crop growth. It infests seedlings,

leaves in whorls, and inflorescences of plants. The nymphs and adults consumed the sap of leaves, which caused them to turn yellow and eventually dry.

			
First instar	Second instar	Third instar	Fourth instar
			
Apterate adult		Alate adult	

Plate 4.1: Different Life Stages of Corn Leaf Aphid, *R. maidis*



1: Infestation of corn leaf aphid, *R. maidis* on maize tassel



2: Infestation of corn leaf aphid, *R. maidis* on maize tassel”



b: Honeydew secreted by corn leaf aphid, *R. maidis* on maize

Plate 1: Damage caused by corn leaf aphid, *R. maidis* on maize

Honeydew Production

The sucking cell sap by sharp needle like stylet into cell that result into stunted growth of plant and secreting honeydew like sweet sugary substance by nymphs and adults which gives the plant sticky appearance, while also luring black ants. Honeydew serve as a medium for black sooty mould and disturbs normal photosynthesis of plants through causes inflorescences to be sterilised and leaves to become malformed, while also luring black ants (Tali *et al.*, 2018).

Virus Transmission

Maize aphids are known vectors for several plant viruses, which can exacerbate crop losses. It spreads 10 viral diseases including the barley yellow dwarf virus, sweet potato feathery mottle virus, millet red leaf

virus, sugarcane mosaic virus or sugarcane yellow leaf virus, potato virus, onion yellow dwarf virus and maize chlorotic dwarf virus (MCDV) and is a significant vector for many harmful pathogenic plant viruses (Kuo et al., 2006). It is widely acknowledged that the maize dwarf mosaic virus is mostly spread by corn leaf aphids under field conditions (Carena and Glogoza, 2004).

The infested plants develop slowly. If there was a serious injury, the main shoot died and produced late tillers with earheads devoid of grains. Aphid saliva affected water uptake, transmission, gas exchange and produced intercellular changes. As aphid population increased, the older leaves became wilted and brownish colour found on younger leaves. The pest also significantly reduced the production of fodder as well as grains.

Management Practices

Cultural Practices: Crop rotation, maintaining healthy plant vigor and monitoring for aphid populations can help manage infestations. Encouraging natural predators can also be beneficial.

Biopesticidal Control: Spraying of *Lecanicillium lecanii* 1.15% WP 40 ml/10 litre, *Metarhizium anisopliae* 1.15% WP 40 ml/10 litre and *Beauveria bassiana* 5% WP 40 ml/10 litre have been shown to effectively reduce maize aphid populations.

Chemical Control: Various insecticides, such as I tolfe npyrad 0.03 % 20 ml/10 litre of water and flonicamid 0.015 % 3 ml/10 litre of water were found most effective in reducing incidence of aphid and increase crop yields.

Conclusion

The maize aphid is a critical pest that can significantly impact maize production. Understanding the biology and behaviour of maize aphids can use in plan effective management strategies to minimize damage and ensure healthy crop yields.

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Underutilized Fruits: Boosting Nutrition & Income with Neglected Local Crops

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Executive Summary

Underutilized fruits—sometimes referred to as *neglected, minor, or orphan crops*—represent a treasure trove of nutrition, biodiversity, and rural livelihood potential. Although these species thrive naturally in diverse agro-climatic conditions, they remain undervalued in mainstream agricultural systems. Many underutilized fruits are nutrient-dense, climate-resilient, and culturally significant, providing immense potential to combat malnutrition, diversify farmer income, and restore ecological balance.

In India and other tropical countries, these fruits have been part of traditional diets and folk medicine for centuries. However, industrial agriculture and globalized food systems have marginalized them. By promoting their cultivation, processing, and marketing, we can turn these neglected crops into engines of sustainable development. This article explores the nutritional, economic, environmental, and social value of underutilized fruits, highlighting strategies to unlock their true potential.

Introduction: Understanding Underutilized Fruits

Underutilized fruits are species that are regionally important but receive little attention from researchers, policymakers, and markets. They are typically cultivated in small quantities by tribal and rural communities for household consumption and local trade. These crops are adapted to local environments, require minimal inputs, and play a crucial role in sustainable land-use systems.

Defining Characteristics

1. Limited presence in formal seed systems and markets.
2. Poorly represented in agricultural research and breeding programs.
3. Excellent adaptability to local stress conditions.
4. Strong cultural and traditional significance.
5. Enormous potential for nutrition and value addition.

Common Underutilized Fruits in India

Aonla, Bael, Karonda, Ber, Jamun, Phalsa, Mahua, Wood Apple, Tamarind, Kachnar, and Jackfruit.

Nutritional and Medicinal Value: Powerhouses of Health

Underutilized fruits are nutrient-dense and rich in bioactive compounds that can prevent chronic diseases. They provide essential micronutrients often missing in staple-based diets.

Major Nutritional Attributes:

Nutrient Component	Function in Human Health	Rich Sources among Underutilized Fruits
Vitamin C	Boosts immunity, antioxidant	Aonla, Karonda, Ber
Iron	Prevents anemia	Jamun, Bael, Wood apple
Calcium	Strengthens bones	Bael, Tamarind, Phalsa
Antioxidants	Fights oxidative stress	Aonla, Jamun, Phalsa

Dietary Fibre	Supports digestion	Bael, Karonda, Ber

Traditional Health Uses

- Aonla:** Used in Ayurveda as a rejuvenator and immune booster.
- Bael:** Known for digestive benefits and cooling effects.
- Jamun:** Helps regulate blood sugar levels.
- Karonda:** Used in home remedies for anemia.
- Phalsa:** Acts as a natural coolant and anti-inflammatory.

Role in Sustainable Agriculture

Underutilized fruits contribute significantly to sustainable farming systems. They require low inputs, support biodiversity, and are well suited for degraded lands.

Environmental Benefits

- Tolerant to drought, salinity, and poor soils.
- Support soil fertility through leaf litter and root biomass.
- Provide habitats for pollinators and birds.
- Reduce dependency on chemical fertilizers and pesticides.

Integration in Farming Systems

Underutilized fruits can be successfully integrated into:

- Agroforestry systems:** Combining fruit trees with annual crops.
- Bund planting:** Using boundary areas for species like ber and karonda.
- Home gardens:** Mixed cultivation for household nutrition.

Agro Model	forestry	Fruit Component	Associated Crops	Major Benefits
Aonla + Pulses System		Aonla (<i>Emblica officinalis</i>)	Green gram, black gram	Enhances soil nitrogen, dual income
Bael + Fodder Crops		Bael (<i>Aegle marmelos</i>)	Napier grass, cowpea	Provides fruits + animal feed
Ber + Cereal System		Ber (<i>Ziziphus mauritiana</i>)	Pearl millet, wheat	Utilizes residual moisture; high profitability
Jamun + Vegetables		Jamun (<i>Syzygium cuminii</i>)	Okra, brinjal	Shade-tolerant intercrops, diversified yield
Phalsa on Bunds		Phalsa (<i>Grewia asiatica</i>)	Sorghum, cowpea	Soil erosion control, quick returns

Nutritional Composition of Selected Fruits

Fruit	Vitamin C (mg/100g)	Fibre (g/100g)	Calcium (mg/100g)	Energy (kcal/100g)	Special Compounds
Aonla	600–700	3.4	25	44	Polyphenols, tannins
Bael	25	2.9	85	137	Carotenoids, coumarins
Jamun	45	0.9	15	60	Anthocyanins, ellagic acid
Karonda	250	3.1	20	62	Iron, flavonoids
Phalsa	45	5.0	60	55	Polyphenols, anthocyanins
Ber	70	2.6	35	79	Flavonoids, Vitamin C

Economic Importance and Market Potential

Underutilized fruits are emerging as profitable niche crops. The market for herbal products, organic foods, and natural health supplements is expanding rapidly.

Value Chain Opportunities:

Level	Key Opportunity	Example Product	Market Benefit
Production	Intercropping with cereals or pulses	Aonla + Wheat	Diversified income
Processing	Development of shelf-stable items	Aonla candy, Bael pulp	Value addition 4–6×
Marketing	Branding as natural, local superfoods	Jamun powder, Karonda pickle	High consumer appeal
Export	Nutrient powders and dried pulp	Bael & Aonla powder	Foreign exchange earnings

Employment Generation:

- Encourages rural entrepreneurship and women's SHGs.
- Provides jobs in fruit collection, grading, and packaging.
- Promotes eco-tourism through fruit-based food trails.

Cultivation and Orchard Management

Site Selection: Select marginal lands with full sunlight. Species like bael and ber perform well even in saline or dry soils.

Propagation:

- Vegetative propagation (budding, grafting) ensures true-to-type plants.
- Seed propagation used for hardy rootstocks.

Orchard Care:

- Organic manure: 10–15 kg per plant annually.
- Pruning: Remove diseased and unproductive branches.
- Irrigation: Needed mainly during fruiting and flowering.

Crop	Recommended Spacing	Planting System	Remarks
Aonla	6 × 6 m	Square or hexagonal	Ideal for high-density planting
Bael	8 × 8 m	Square	Deep planting pits (1×1×1 m) filled with FYM
Ber	5 × 5 m	Hedge or boundary planting	Suited for rainfed orchards
Karonda	2 × 2 m	Hedge or contour planting	Good for fencing and intercropping
Phalsa	3 × 3 m	Contour or block	Suitable for annual pruning cycles

Pest and Disease Management

Common pests include fruit fly (ber, aonla) and leaf spot (bael). Use neem-based sprays or pheromone traps.

Problem	Crop Affected	Symptoms	Eco-friendly Control
Fruit fly	Ber, Aonla	Larvae feed inside fruits, causing premature drop	Pheromone traps (Cue-lure), Neem oil spray (2%)
Leaf spot	Bael, Karonda	Brown circular spots on leaves	Copper oxychloride @ 0.3%, pruning of infected leaves
Powdery mildew	Phalsa, Ber	White powdery coating on leaves	Sulphur dusting (0.25%) or cow dung filtrate spray
Bark borer	Aonla, Jamun	Holes with gum exudation	Remove infested branches, apply neem cake and lime

Fruit cracking	Bael, Karonda	Cracks on ripening fruits	Maintain proper irrigation and boron spray (0.2%)

Post-Harvest Management and Processing

Proper post-harvest handling adds tremendous value. Storage, grading, and packaging extend shelf life and enhance market appeal.

Fruit	Processing Method	Value-Added Product	Shelf Life
Aonla	Dehydration, syrup preparation	Candy, murabba, powder	6–12 months
Bael	Pulp extraction	Bael squash, sherbet	8 months
Jamun	Juice, drying	Syrup, seed flour	6 months
Karonda	Pickling	Pickle, jelly	1 year
Phalsa	Juice extraction	RTS beverage	4 months

Recommended Storage Practices:

- Use ventilated crates to reduce bruising.
- Maintain 10–12°C temperature and 85–90% humidity.
- Use solar dryers for dehydration.

Case Studies and Field Experiences

Case 1: Aonla Cooperative in Uttar Pradesh: Aonla growers in Pratapgarh district formed a cooperative to process fruits into candy and murabba. With support from NABARD, they established a small-scale unit. Income increased by 50%, and employment for rural women doubled.

Case 2: Bael Value Chain in Chhattisgarh: A women's SHG network produces Bael squash and toffees. Their products are sold at melas and through e-commerce, generating an annual turnover exceeding ₹10 lakh.

Case 3: Jamun Seed Flour Startup in Maharashtra: A young entrepreneur transformed jamun seeds—once discarded waste—into diabetic-friendly flour. This innovation earned recognition in startup fairs and secured institutional funding.

Research, Policy, and Extension Interventions

- Research Focus:** Identify high-yielding, nutrient-rich varieties; develop climate-resilient strains.
- Policy Support:** Incentives for establishing fruit nurseries and processing units.
- Market Development:** Branding and GI tagging of local fruits.
- Extension Role:** Organize training on pruning, grafting, and post-harvest technologies.
- Institutional Linkages:** Encourage tie-ups between farmers, universities, and agri-startups.

Future Prospects and Entrepreneurial Pathways

Promising Business Models:

Model	Description	Benefits
Community Processing Unit	Collective pulping, drying, packaging	Low cost, shared profits
Organic Farming Cluster	Group certification and marketing	Premium prices
E-commerce Retailing	Online sale of herbal and fruit-based items	Global reach
Tourism Integration	Farm visits, pick-your-own fruit events	Diversified income

Investment Opportunities: Government schemes such as PM-FME, MIDH, and MSME Startup India offer funding for fruit processing enterprises.

Cultural and Social Importance

These fruits are deeply embedded in folklore, rituals, and cuisine. For instance, Bael is sacred to Lord Shiva; Aonla is used during Kartik Purnima rituals. Promoting these fruits thus revives traditional food culture while ensuring biodiversity conservation.

Global Relevance: Linking Local Crops to Global Goals

Underutilized fruits contribute to multiple Sustainable Development Goals (SDGs):

- 1. SDG 2 (Zero Hunger):** Ensures nutritional security.
- 2. SDG 3 (Good Health):** Promotes dietary diversity.
- 3. SDG 5 (Gender Equality):** Empowers rural women through enterprise.
- 4. SDG 13 (Climate Action):** Supports resilience and carbon sequestration.

Conclusion

Underutilized fruits symbolize the perfect synergy between nutrition, nature, and livelihood. They offer opportunities for inclusive rural development while supporting climate adaptation. By integrating them into agricultural and nutrition strategies, India can achieve sustainable food and income security.

Reviving these forgotten treasures requires coordinated efforts—from farmers and researchers to policymakers and entrepreneurs. The future of resilient agriculture may well lie in rediscovering the potential of these humble, underutilized fruits.

Importance of Polythene Mulching in Horticultural Crops

Article ID: 72216

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Introduction

Technique of covering soil by natural crop leftovers or plastic films for soil and water conservation is called mulching. Plastic mulches act principally by blocking evaporation of water from soil surface. Main factors affected by mulches are soil moisture & temperature and also plastic mulches helps in utilization of irrigation water to its last drop.

Why is Plastic Mulching Needed?

1. Prevents weed growth
2. Conserve soil moisture
3. Saves water
4. Prevents soil compaction
5. Increase root branching, extension and diameter
6. Improve rate of seed germination
7. To improve productivity
8. To improve quality.

Benefits of Plastic Mulching

Earlier harvest: The greatest benefit from plastic mulch is that the soil temperature in the planting bed is raised, promoting faster crop development and earlier harvest.

Evaporation: Soil water loss is reduced under plastic mulch. As a result, more uniform soil moisture is maintained, and irrigation frequency can be reduced more.

Fewer weed problem: Silver/black mulches will reduce light penetration to the soil. Weeds cannot generally survive after applying mulch.

Clean produce: The edible product from a mulched crop is clean and less subject to rot, since no soil is splashed onto the plants or fruit.

How Polythene Mulches Conserve Soil Moisture?

Plastic film with its moisture barrier properties does not allow the soil moisture to escape water that evaporates from the soil surface under mulch film, condenses on the lower surface of the film and falls back as droplets. Thus, moisture is preserved for several days and increases the period between two irrigations (Irrigation frequency). The irrigation water or rainfall either moves into the soil through holes on the mulch around the plant area or through the un-mulched area.

Types of Polythene Mulches

1. Photodegradable – Get destroyed by light in short period
2. Biodegradable – Get destroyed in the soil in organic condition
3. Black mulches – Weed management & soil conservation
4. Reflective silver mulches – Maintains cooler root zone
5. Transparent mulches – Soil solarisation.



Black polythene Mulch



Silver Polythene Mulch

Mulch Colour - The Colour of the Mulch Shows Effects on

1. Soil temperature
2. Temperature of air around the plants
3. Soil salinity:
 - a. Due to lesser quantity of water used
 - b. Due to reduction in evaporation and prevention of upward movement of water.
4. Weed flora
5. Insect control.

Types of Coloured Mulches

Colour	Properties
Black	Most popular colour used in commercial horticulture crop production, especially for weed control
White	White plastic mulches can be used to establish crops in the summer, where a reduced soil temperature might be beneficial.
Silver	They tend to repel aphids and other sucking pests which could serve as vectors for various viral diseases
Red	Red plastic mulch has been reported to increase tomato yield and quality, reduced severity of early blight in tomatoes

Criteria for Selection of Mulch

The selection of mulches depends upon the ecological situations and primary and secondary aspects of mulching.

1. Orchard and plantation	: Thicker mulch
2. Soil solarisation	: Thin transparent film

3. Weed control through solarisation	: Transparent film
4. Weed control in cropped area	: Black film
5. Sandy soil	: Black film
6. Saline water use	: Black film
7. Summer cropped land	: White film
8. Insect repellent	: Silver coloured film
9. Early germination	: Thinner film

Thickness of Film

In plastic mulching the thickness of film should be according to the types and age of horticultural crops.

Recommended Thickness of Mulch Film for Different Crops

Crop duration	Name of crop	Thickness of mulch film	
		Micron	Guage
Annual crop	Vegetables crops and strawberry	25	100
Biennial crop Vegetables crops	Papaya, Banana	50	200
Perennial crop	Fruit crops, Plantation crops and roses	100	400



White Polythene Mulch



Red Polythene Mulch

Precautions During Laying of Mulches

1. Do not stretch the film very tightly. It should be loose enough to overcome the expansion and shrinkage
2. The slackness for black film should be more as the expansion; shrinkage phenomenon is maximum in this colour
3. The film should not be laid on the hottest time of the day, where the film will be in expanded condition.

Limitations

1. Costly to use in commercial production when compared to organic mulches
2. Probability of burning or scorching of young plants due to high temperature of black film
3. Difficulty in application of top-dressed fertilizer
4. Environmental pollution
5. Difficulty in machinery movement.

Ragi Malt: A Sustainable Approach to Health and Rural Entrepreneurship

Article ID: 72217

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Abstract

Ragi malt, derived from finger millet (ragi), is a highly nutritious and health-enhancing beverage that holds immense potential for rural markets. Kisan mela, an agricultural fair and self-help groups provides an excellent opportunity for raising public awareness and promote ragi malt among farmers, health-conscious consumers, and agri-entrepreneurs, which ultimately contribute to the nation's progress towards sustainable development. The targeted promotional efforts, farmer participation, and value chain development can enhance the acceptance and commercialization of ragi malt, benefiting both consumers and millet producers. This article addresses the significance of ragi malt, its health benefits, marketing strategies, economic viability of ragi malt as a value-added agricultural product and the role of Kisan mela and self-help groups in enhancing awareness and demand of ragi malt to ensure market expansion and rural economic growth.

Introduction

Finger millet (*Eleusine coracana*), commonly known as ragi is one of the ancient millets in India (Shobana et al., 2013). It is widely grown in Karnataka, Andhra Pradesh, Tamil Nadu, Maharashtra, Gujarat and Bihar. Ragi is highly nutritious millet known for its high iron, calcium and fiber content, contributing considerably to the food and nutritional security of the country. With an increasing awareness about health and wellness, consumers are preferring ragi malt as an alternative to other energy drinks. Although, despite its health benefits, the consumption of ragi-based products remains low due to the lack of information about the advantages that it offers and lack of availability of ragi-based products. The processing of finger millet for making value added and convenience products would increase its consumption in the food industry. The preparation of items that are either ready-to-use or ready-to-cook would increase the consumption pattern of finger millet among the customers. Ragi malt is one such product prepared by malting process. Malting involves soaking, sprouting, drying, toasting, grinding, and sifting. It is done to increase the nutritional quality, improve taste, digestibility, and reduce the antinutrients (Pawar and Dhanvijay, 2007; Rathour, 2015). Malting increases the availability of vitamin B, vitamin C, phosphorous and fiber levels in grains, and also helps to synthesize lysine and tryptophan, simultaneously reducing the antinutritional compounds (tannins and phytic acid) (Bhatt et al., 2003). Finger millet (ragi) is the best millet for malting due to its good quality and enzyme release during the process (Thomas and Karuna, 2019). Kisan mela and self-help groups provides an excellent opportunity for raising public awareness and promote ragi malt among farmers, health-conscious consumers, and agri-entrepreneurs, which ultimately contribute to the nation's progress towards sustainable development.

Nutritional and Health Benefits of Ragi Malt

Ragi malt is a powerhouse of essential nutrients, making it an ideal drink for all age groups. The key benefits are as follows.

1. High calcium content: Strengthens bones, prevents osteoporosis and rickets in young children (Thacher et al., 2000; Vanderjagt et al., 2001).
2. Rich in iron: Helps combat anaemia, especially among women and children (Babu et al., 1987; Vanderjagt et al., 2007).
3. Dietary fiber: Supports digestion and aids in weight management.
4. Gluten free: Suitable for individuals with gluten intolerance.
5. Diabetes friendly: Low glycemic index helps regulate blood sugar levels.

6. Rich in essential amino acids (methionine and tryptophan) (Malleshi and Klopfenstein, 1998; Fernandez et al., 2003).

Promoting these health benefits at Kisan Mela can increase consumer trust and drive sales.

Preparation of Ragi Malt Flour

For malting of ragi, cleaned ragi grains should be washed under water for about 5-7 times and are soaked for about 5 hours in fresh water and then excess water should be drained. Then, the grains are tied in muslin cloth and incubated for about 24 hours at $27\pm 30^{\circ}\text{C}$ for sprouting. The sprouted grains are then dried under shade for two days followed by grinding to make flour (Desai et al., 2010).

Market Potential of Ragi Malt

The demand for healthy and organic foods is rising globally. Ragi malt, being a traditional and natural beverage, aligns well with this trend. The market potential of ragi malt assesses the following aspects:

- 1. Consumer awareness:** Understanding knowledge gaps and designing targeted campaigns.
- 2. Pricing strategy:** Ensuring affordability while maintaining profitability.
- 3. Market competition:** Analysing alternative health drinks and positioning ragi malt effectively.
- 4. Value addition:** Introducing flavoured ragi malt variants to achieve diverse consumer preferences.

Role of Kisan Mela in Ragi Malt Promotion

Kisan Mela acts as a convergence point for farmers, researchers, and consumers, offering the following advantages:

- 1. Awareness Campaigns:** Live demonstrations on Ragi malt preparation and benefits.
- 2. Farmer Engagement:** Encouraging millet cultivation and processing.
- 3. Tasting Sessions:** Allowing consumers to experience the taste and texture.
- 4. Collaborations:** Partnering with government agencies and NGOs (non-governmental organisations) to support millet-based businesses.

Strategies for Effective Promotion of Ragi Malt

To maximize outreach and sales at Kisan Mela, the following strategies can be adopted.

- 1. Informative workshops:** Educating visitors on the health benefits and economic advantages of ragi malt.
- 2. Packaging and branding:** Attractive, eco-friendly packaging to appeal modern consumers.
- 3. Subsidized sales:** Offering introductory discounts to increase product trials.
- 4. Social media and digital promotion:** Extending awareness beyond the event to reach a larger audience.

Economic Viability and Farmer Benefits

The commercialization of ragi malt provides a sustainable income source for small-scale farmers. By integrating ragi cultivation with processing and marketing, farmers can gain higher returns through value addition, diversify their agricultural practices, reduce dependency on single-crop farming, and access government incentives for millet cultivation.

Conclusion

The preparation of either ready-to-use or ready-to-cook items would increase the consumption pattern of finger millet among the customers. Ragi malt is one such product prepared by malting process. Nutritious ragi grains are germinated at home scale to prepare malted weaning food ideal for all age groups. The promotion of ragi malt at Kisan mela by encouraging rural entrepreneurs, rural women, and farmers enhances public health while supporting rural entrepreneurship. To achieve long-term success, it is important to invest in awareness campaigns, product diversification, training and capacity development of the farmers, women, and youths, and robust supply chains. Collaboration among farmers, entrepreneurs, and policymakers can further strengthen the millet value chain, ensuring sustainable agricultural and economic development. Recently, rural women have gained more independence through the self-help

groups and non-governmental organisations (NGOs). By implementing strategic promotional activities at Kisan Mela and with the involvement of self-help groups, ragi malt can be established as a mainstream health drink, benefiting both consumers and millet farmers alike.

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Empowering Farmers through Mechanized Harvesting

Article ID: 72218

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Introduction

Harvesters are specialized machines/tools designed to efficiently and effectively gather crops, reducing manual labor and increasing productivity. By automating the harvesting process, these tools enable farmers to: increase crop yields; reduce labor costs; minimize crop damage; Improve quality and consistency and enhance profitability. From sapota to mango, okra to drumstick, harvesters are transforming the agricultural landscape, empowering farmers to cultivate more, harvest more, and prosper. The All India Coordinated Research Project on Farm Implements and Machinery (AICRP-FIM) at MPKV, Rahuri has developed innovative harvesters for various horticultural crops, including sapota, drumstick, mango, and okra, which were tested and demonstrated by AICRP(FIM), Zonal Agricultural Research Station, V.C. Farm, Mandya, UAS, Bangalore centre. These harvesters aim to reduce manual labor, increase efficiency, and enhance productivity.

Objectives

To conduct demonstrations of the farm implements and machinery in the farmers fields for assessing the workability of the machine; To encourage the farmers to adopt the farm implements and machinery through demonstrations and trainings; To workout the cost economics of operation of the machine towards ascertaining their practical utility.

Justification

The farm implements and machinery developed by various Research and Development institutions available are not reaching the farmers in an effective way. The awareness about improved farm implements and machinery has to be created among the farmers through transfer of technology. Demonstrations are effective method for popularization of improved farm implements and machinery. Selected farm implements and machinery were demonstrated for better utilization by the farmers based on the cropping system. The selected farm implements and machinery will be demonstrated to the farmers and stakeholders for the adoptability and for better understanding the benefits of farm implements and machinery in reducing drudgery and cost of operation.

Materials and Methods

The study utilized harvesters designed and developed by MPKV, Rahuri, including sapota, mango, drumstick, and okra harvesters. These machines were demonstrated in farmers' fields of Mandya region, and feedback was collected on their performance, acceptability, and suitability.

Results and Discussion

Frontline demonstrations of selected harvesters were conducted in farmers' fields, and their performance was evaluated based on feedback collected from the farmers.

1. Drumstick Harvester: A specialized drumstick harvester, designed to efficiently and gently harvest drumsticks, was demonstrated at a research station and in 22 farmers' fields across Mandya district. This innovative machine reduces labor costs, increases productivity (harvesting 5-8 kg/h), and minimizes damage to the pods. Farmers praised the harvester's performance, citing significant reductions in labor costs and operating expenses. In the demonstrations, the harvester successfully harvested 211 kg from 44 trees, earning high satisfaction ratings from farmers. This technology has the potential to enhance profitability and competitiveness for drumstick farmers and processors.



Plate 1: Drum stick harvester demonstrated at farmer's field

2. Sapota Harvester: Sapota, a tropical fruit, is widely cultivated in many parts of the world, but its harvesting process can be labor-intensive and time-consuming. Manual sapota harvesting is labor-intensive, yielding only 2-4 kg/h. Sapota harvester boosts productivity, harvesting 6-8 kg/h while minimizing damage. This device enables efficient, gentle harvesting, reducing labor costs and enhancing profitability for farmers. The sapota harvester addresses these challenges by enabling farmers to quickly and easily pick sapota fruits at the optimal stage of ripeness. The device uses include increasing harvesting efficiency, improving productivity, and enhancing profitability, allowing farmers to focus on other critical tasks and enjoy higher yields and better fruit quality. The harvester was successfully demonstrated in 24 farmers' fields, Mandya district, harvesting 2141kg from 83 trees.



Plate 2: Sapota harvester demonstrated at farmer's field

3. Mango Harvester: The mango harvester is designed to efficiently and gently harvest mangoes from trees, reducing labor costs and minimizing fruit damage. Equipped with features that enable it to navigate through dense mango orchards, identify and pick mature fruits, and collect them in a container for further processing, this device offers numerous benefits. With a capacity of 8-10 kg/h, it streamlines the harvesting process, boosting productivity and profitability for farmers. The mango harvester enhances profitability for mango farmers and orchard owners, and streamlines the harvesting process, allowing farmers to focus on other critical tasks. The harvester was successfully demonstrated in 4 farmers' fields, harvesting 4165kg from 230 trees.



Plate 3: Mango harvester demonstrated at farmer's field

4. Okra harvester: The Okra harvester, with a capacity of 2-13 kg/h, was successfully demonstrated in 14 farmers' fields across Mandya district. Farmers showed keen interest in the machine, which proved efficient in harvesting okra crops, reducing manual labor, and increasing productivity. The demonstration

showcased the potential of the Okra harvester to increase efficiency, reduce labor costs, and improve crop yields, highlighting the need for further training and support for widespread adoption.



Plate 5: Okhra harvester demonstrated at farmer's field

Conclusion

The harvesters were showcased in the Mandya region, creating awareness among the farming community about the benefits of mechanized harvesting. The successful demonstration of these innovative harvesters has paved the way for increased adoption of mechanized harvesting, reducing manual labor and enhancing productivity for horticultural crops. Farmers are now adopting and utilizing the harvesters in their fields after witnessing successful demonstrations. They're also renting them out to others, generating additional income through harvesting services. Farmers are transforming into entrepreneurs by leveraging improved harvesters, unlocking new income streams and boosting their agricultural businesses.

Melatonin – A Plant Growth Regulator with Antioxidant and Stress-Mitigating Properties

Article ID: 72219

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Abstract

Melatonin is an important signaling molecule that helps regulate plant growth, development, and stress tolerance. It acts as an antioxidant and adjusts physiological and molecular responses to drought, salinity, extreme temperatures, and heavy metal toxicity. By improving antioxidant enzyme activity, maintaining redox balance, and controlling stress-related gene expression, melatonin helps plants grow under stress conditions. It also participates in signaling pathways involving calcium ions, hydrogen peroxide, and phytohormones like abscisic acid and gibberellic acid. Understanding how melatonin is made and how it works can help plants to withstand stress.

Keywords: Melatonin, abiotic stress, antioxidant defense, stress tolerance, signal transduction, plant growth.

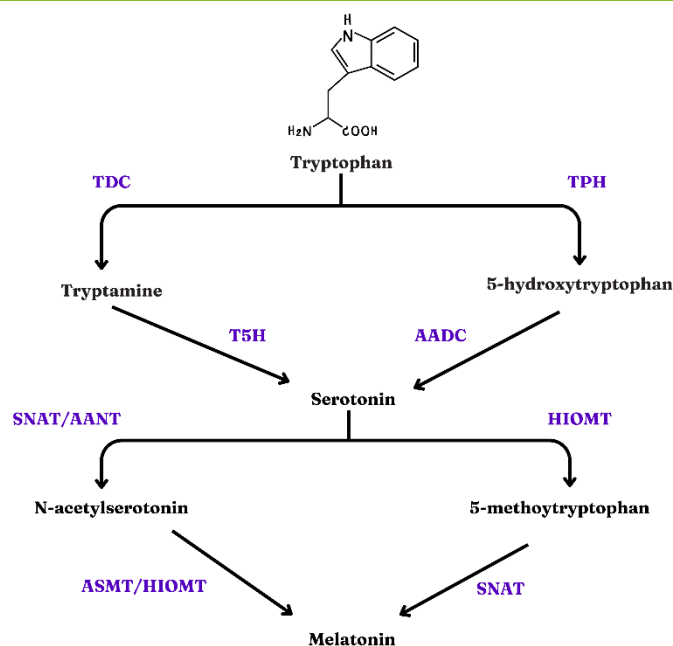
Introduction

In plants, both biotic and abiotic environmental stresses affect their growth and development. These stresses lower yields, slow growth, disrupt cellular metabolism, and may even cause plant death. To deal with these challenges, plants have developed strategies to reduce stress-induced damage. Phytohormones such as auxins, cytokinins, gibberellins, abscisic acid, ethylene, brassinosteroids, jasmonates, and salicylic acid, along with signaling molecules like nitric oxide and calcium ions, are key players in stress responses. Recently, researchers have shown a growing interest in melatonin, a remarkable signaling molecule. Many studies suggest that melatonin is vital for plant growth and stress tolerance.

Biosynthesis

Melatonin biosynthesis in plants begins with tryptophan, which is converted to tryptamine by tryptophan decarboxylase (TDC) and then to serotonin by tryptamine 5-hydroxylase (T5H). In some species, such as *Hypericum perforatum*, tryptophan is first hydroxylated by tryptophan 5-hydroxylase (TPH) to form 5-hydroxytryptophan, then decarboxylated by TDC/AADC to produce serotonin, similar to the animal pathway. Subsequently, serotonin is acetylated by serotonin N-acetyltransferase (SNAT/AANAT) to form N-acetylserotonin and methylated by N-acetylserotonin methyltransferase (ASMT/HIOMT) to yield melatonin.

Alternative routes include the conversion of tryptamine to N-acetyltryptamine or serotonin to 5-methoxytryptamine, both of which can lead to melatonin formation. A reverse pathway has also been reported, where N-acetylserotonin is converted back to serotonin. Since tryptophan also serves as a precursor for indole-3-acetic acid (IAA), this highlights the multifunctional role of melatonin in plants.



Biosynthesis of Melatonin

Tryptophan undergoes decarboxylation via the action of tryptophan decarboxylase (TDC) enzyme and converts into tryptamine, which latter converts into 5-hydroxy tryptamine (serotonin) via the action of tryptamine 5-hydroxylase (T5H). Serotonin then undergoes N-acetylation via the action of serotonin N-acetyl transferase (SNAT) and produces N-acetylserotonin, which later undergoes methylation via the action of acetylserotonin methyl transferase (ASMT) and yields melatonin via the action of hydroxyindole-O-methyltransferase (HOMT). The methylation of N-acetylserotonin can also be performed by caffeic acid O-methyltransferase (COMT) in plants.

Effect of Melatonin on Drought Stress

Drought is one of the most severe stresses affecting plant growth and productivity. Melatonin improves drought tolerance by reducing oxidative damage, boosting photosynthesis, and keeping water balance. It enhances the antioxidant enzyme activity and encourages root growth, helping plants survive better in low water situations. Additionally, melatonin controls stress-related genes by lowering the expression of the abscisic acid synthesis gene *MdNCED3* and increasing the levels of catabolic genes like *MdCYP707A1* and *MdCYP707A2*, which helps plant controlling water loss and enhances drought tolerance.

Effect of Melatonin on Cold and Heat Stress

Temperature extremes, both low and high, can severely affect plant growth and development. Melatonin helps plants withstand cold and heat stress by maintaining redox balance, boosting antioxidant enzyme activity, and protecting cells from oxidative damage. Under cold stress, melatonin encourages the buildup of protective compounds like putrescine and spermidine. It also improves photosystem II efficiency and increases the survival and regrowth of plant tissues exposed to low temperatures. When heat stress occurs, melatonin levels naturally rise. This enhances tolerance by improving germination, stabilizing cellular membranes, and strengthening antioxidant defenses. Overall, melatonin is crucial for protecting plants from damage caused by temperature fluctuations.

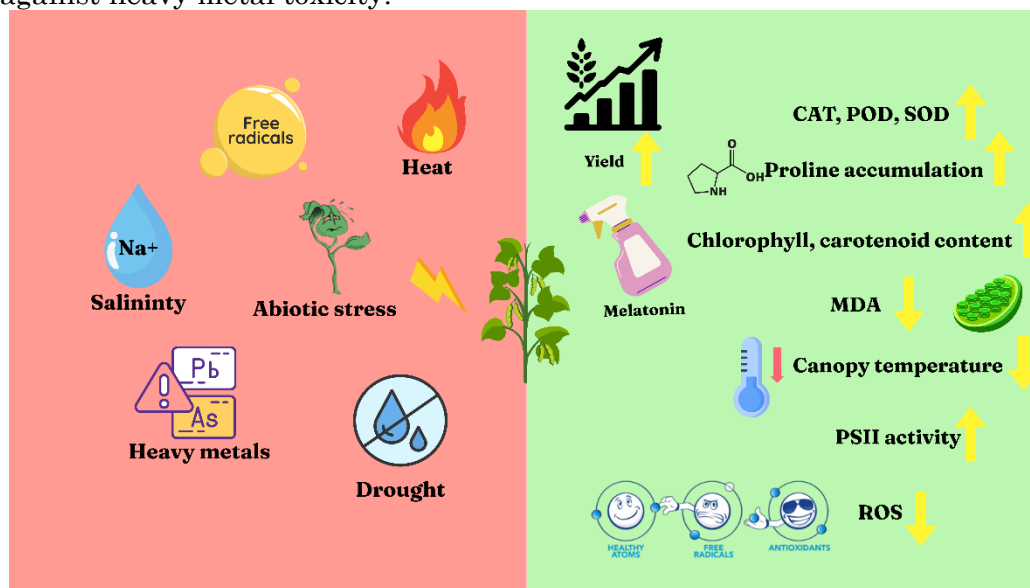
Effect of Melatonin on Salt Stress

Salt stress is a major factor limiting plant growth and productivity worldwide. It causes water deficit, oxidative stress, and metabolic imbalance. Melatonin enhances salinity tolerance by reducing hydrogen peroxide (H₂O₂) accumulation and increasing the activity of antioxidant enzymes such as ascorbate peroxidase (APX), catalase (CAT), and peroxidase (POD). It also promotes root development particularly lateral root formation thereby improving water and nutrient uptake under saline conditions. Additionally,

melatonin regulates genes involved in the biosynthesis and catabolism of abscisic acid (ABA) and gibberellic acid (GA), contributing to improved salt tolerance and overall plant resilience.

Effect of Melatonin on Heavy Metal Stress

Heavy metal contamination poses a serious threat to plant growth and survival. It results in metabolic imbalance, oxidative stress, and water deficit. Melatonin enhances tolerance to salinity by reducing the accumulation of hydrogen peroxide (H_2O_2) and increasing the activity of antioxidant enzymes such as ascorbate peroxidase (APX), catalase (CAT), and peroxidase (POD). Furthermore, it promotes the development of roots, particularly lateral roots, which improves the uptake of water and nutrients in salinized environments. Overall, melatonin acts as an efficient and eco-friendly molecule that strengthens plant defense against heavy metal toxicity.



Effect of melatonin under stress conditions

Stress Signalling

In *Arabidopsis thaliana*, CAND2/PMTR1 functions as a phytomelatonin receptor located in the plasma membrane. Upon melatonin binding, it interacts with the G-protein α subunit (GPA1), leading to the dissociation of the $G\alpha$ and $G\beta\gamma$ subunits. This activation triggers NADPH oxidase (RBOH), resulting in the production of hydrogen peroxide (H_2O_2). The generated H_2O_2 enhances calcium (Ca^{2+}) influx and promotes potassium (K^+) efflux, together causing stomatal closure. Although abscisic acid (ABA) also induces stomatal closure, studies in *cand2* mutants which are insensitive to melatonin show that melatonin acts through a receptor distinct from ABA but shares some downstream signaling components such as $G\alpha$, H_2O_2 , and Ca^{2+} . This signaling mechanism, along with melatonin's roles in growth promotion, rooting, and anti-senescence, supports its recognition as a multifunctional signaling molecule and potential phytohormone.

Conclusion

In recent years, significant progress has been made in understanding melatonin's presence, biosynthesis, and functions in plants. Melatonin acts as a multifunctional molecule involved in growth regulation, stress tolerance, and antioxidant defense. It has a dynamic regulatory role, as evidenced by the fact that its levels vary among plant organs and alter with developmental stages and environmental factors. The precise processes controlling the distribution, metabolism, and signaling of melatonin are still unknown. Future research should focus on identifying the receptors, enzymes, and signaling pathways that mediate melatonin's diverse functions in plants.

Vegetables as a Source of Nutraceuticals

Article ID: 72220

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Summary

The term Nutraceutical was coined in 1989 by Dr. Stephen L. DeFelice, founder and chairman of the Foundation of Innovation Medicine (FIM) (Crawford, New Jersey). It is a food or food product that provides health and medical benefits, including the prevention and treatment of disease. They are the product isolated or purified from foods, and generally sold in medicinal forms not usually associated with food and demonstrated to have a physiological benefit or provide protection against chronic disease. Vegetables are considered to be potential source of nutraceuticals.

Introduction

Nutraceuticals have been claimed to have a physiological benefit and provide protection against various diseases such as Cardiovascular, diabetes, cancer, chronic inflammatory disorders, degenerative disorders etc. Vegetables are good source of nutraceutical compounds.

Vegetable Crops as a Potential Source of Nutraceuticals

Vegetables provide health protection on account of the presence of secondary metabolites of therapeutic importance. The most important phytonutraceuticals in vegetables that have biological activity against chronic diseases are vitamins, minerals, dietary fiber, organosulfur compounds (glucosinolates and thiosulfides) and flavonoids (Table 1, 2 & 3).

Table 1: Nutraceuticals compounds in vegetables:

Nutraceuticals	Vegetables
Glucosinolates, Sulforaphane	Cole crops
Lycopene	Tomato and other Solanaceous vegetables, Watermelon
Silymarin	Artichoke
Vit C	Cabbage, Croccoli, Green leafy vegetables (GLV)
Vit E	GLV
Allyl Sulphides	Onion and Garlic
Vit A	Carrot, Pumpkin, Cantaloupe
Vit C	Bitter gourd, Capsicum
Folates	GLV
Alliin, Methiin	Alliums
Quercetin	Onion and Garlic
Kaempferol, Myricetin, Fisetin	Onion, Lettuce, Endive, Horse Radish
Luteolin	Celery, Broccoli
Apigenin	Celery
Isoflavonoids	Legume vegetables, Broccoli and Okra
Genistein and Daidzein	Soybean
Glucoraphanin	Red cabbage and Broccoli
Glucobrassicin, Progoitrin, Gluconasturtiin	Broccoli
Glucoerucin, Glucoraphanin	Turnip and Rutabaga
Lysine, Chlorogenic Acid	Potato
Caffeic acid, Chlorogenic Acid	Eggplant
Nasunin	Eggplant
Angelicin, Xanthotoxin	Parsnip
Ferulic Acid, Betanin	Beet root

Anthocyanin and Chlorogenic Acid	Sweet Potato
Rutin	Asparagus, Green Chilli
Patuletin, Spinacetin	Spinach

Table 2: Edible pigments in Vegetables:

Vegetables	Colour	Pigments
Broccoli	Purple	Anthocyanin
Cauliflower	Yellow	Beta-carotene
Brinjal	Purple	Anthocyanin
Black carrot	Black	Anthocyanin
Carrot	Orange	Beta-carotene
Pumpkin	Orange	Beta-carotene
Lettuce	Yellow	Lutein
Broccoli, Kale, Cabbage and GLV	Green	Chlorophyll
Tomato	Red	Lycopene
Tomato	Black	Anthocyanin
Watermelon	Red	Lycopene
Capsicum	Red	Capsanthin
Purple potato, Red flesh potato	Purple, Red	Anthocyanin
Red onion	Red	Anthocyanin
Sweet potato	Purple Flesh	Anthocyanin
Cauliflower	Purple	Anthocyanin
Red cabbage	Red	Anthocyanin
Broccoli	Yellow	Beta-carotene
Cucumber	Orange flesh	Carotenoids

Table 3: Vegetable varieties rich in natural pigments/colours:

Pigments	Crop	Varieties
Anthocyanin	Carrot	Pusa Asita, Punjab Black Beauty
Anthocyanin	Radish	Pusa Jamuni, Pusa Sagarika Pusa Gulabi
Betalin	Beet root	Detroit Dark Red
Quercetin	Onion	Pusa Ridhi, Brown Spanish, Pusa Red, Pusa Madhvi
Anthocyanin	Amaranth	Pusa Lal Chaulai, Arka Arunima
Anthocyanin	Red cabbage	Red Acre
Lycopene	Carrot	Pusa Rudhira, Pusa Vrishti
Beta-carotene	Carrot	Pusa Nayanjyoti
Lycopene	Tomato	Pusa Rohini, Pusa Hybrid-8
Anthocyanin	Broccoli	Palam Vichitra
Beta-carotene	Broccoli	Palam Kanchan
Carotenoids	Carrot	Pusa Vssuda
Anthocyanin	Brinjal	Pusa Shyamla Pusa Uttam
Beta-carotene	Sweet Potato	Sree Kanaka, Gouri, Kiran, Sree Vardhini
Anthocyanin	Greater Yam	Da-331

Conclusion

Vegetables are considered as protective food due to the multiple health benefit they provide to human body. Variety of vegetables should be included in our daily diet to ensure the body's requirement of dietary fibre, vitamins, minerals, phytochemicals and nutraceuticals. Regular consumption of a vegetable rich diet has undeniable positive effects on health since bioactive compounds of vegetables can protect the human body from several types of chronic diseases.

Protected Cultivation, Hydroponics, and Vertical Farming of Vegetables

Article ID: 72221

Aitha Soujanya¹, Teluganam Srikanth²

Introduction

Vegetable farming has always been an essential part of food production, providing fresh and nutritious food for people all around the world. But with increasing population, shrinking land availability, and unpredictable weather due to climate change, traditional open-field farming is facing serious challenges.

To meet the growing demand for vegetables, modern farmers are turning toward protected cultivation, hydroponics, and vertical farming advanced systems that allow them to produce more vegetables using less land, less water, and fewer pesticides, while ensuring high quality and year-round availability.

These systems are not just futuristic ideas; they are already being used successfully in India and other parts of the world. Let's explore how they work, their advantages, challenges, and what the future looks like for smart vegetable farming.

Protected Cultivation – A Shield for Plants

Protected cultivation means growing vegetables inside a structure that provides protection from harsh weather, pests, and diseases. These structures can range from simple low-cost tunnels to advanced climate-controlled greenhouses or polyhouses.

1. Types of Protected Structures:

- a. **Polyhouses** – Covered with UV-stabilized polyethylene sheets, they help control temperature and humidity.
- b. **Shade Nets** – Used mainly for leafy vegetables to protect against excessive sunlight and wind.
- c. **Insect-Proof Net Houses** – Prevent insect entry and reduce virus-borne diseases.
- d. **Greenhouses** – High-tech versions with automated systems for temperature, light, irrigation, and CO₂ control.

2 Benefits:

- a. **Higher Yields:** Plants grow faster and healthier due to favorable microclimate.
- b. **Off-Season Production:** Farmers can produce vegetables even during non-traditional seasons.
- c. **Reduced Pest Attacks:** Controlled environment limits insects and diseases.
- d. **Better Quality:** Uniform shape, color, and taste attract premium market prices.
- e. **Efficient Resource Use:** Less water and fertilizer are wasted.

3. Common Vegetables Grown: Tomato, capsicum (bell pepper), cucumber, lettuce, spinach, chili, and exotic vegetables like broccoli and zucchini are most common under protected cultivation.

Protected cultivation has already shown success in states like Telangana, Maharashtra, Karnataka, and Himachal Pradesh, where farmers have adopted polyhouses with government support schemes like MIDH (Mission for Integrated Development of Horticulture).

Hydroponics – Growing Without Soil

The word hydroponics comes from two Greek words: “hydro” (water) and “ponos” (work). Simply put, hydroponics means growing plants without soil, by providing all essential nutrients through water-based nutrient solutions.

In this system, the roots of plants are either submerged in water or supported by inert media like **cocopeat**, **perlite**, or **rock wool**.

1. Major Hydroponic Systems:

- a. **Nutrient Film Technique (NFT):** A thin film of nutrient-rich water flows over plant roots in narrow channels.

- b. Deep Water Culture (DWC):** Plant roots float directly in aerated nutrient solution.
- c. Drip System:** Nutrient solution is dripped near the root zone, ensuring minimal wastage.
- d. Ebb and Flow (Flood and Drain):** Water periodically floods and drains from the growing bed.

2. Advantages:

- a. No Soil-Borne Diseases:** Eliminates problems like nematodes or fungal root rot.
- b. Water Efficiency:** Uses 80–90% less water compared to open-field farming.
- c. Space Efficiency:** Ideal for urban areas with limited land.
- d. Faster Growth:** Plants get nutrients directly, reducing growth time
- e. Cleaner Produce:** No soil contamination or pesticide residues.

3. Challenges: Initial setup cost is high, and farmers need technical know-how to monitor pH, electrical conductivity (EC), and nutrient balance. Power supply and water quality are critical factors.

Despite these challenges, hydroponics is rapidly expanding in India especially around cities like Hyderabad, Bengaluru, Pune, and Delhi, where companies such as UrbanKisaan, Hydrogreens, and Letcetra Agritech supply fresh vegetables directly to consumers through hydroponic farms.

Vertical Farming – Farming Upward, Not Outward

Vertical farming takes hydroponics and protected cultivation to the next level. Instead of spreading crops horizontally over large land areas, vertical farms grow them in stacked layers or multi-level shelves, often inside buildings, warehouses, or containers.

This approach makes it possible to grow vegetables in urban spaces even in city centers, rooftops, or basements using artificial lighting and fully controlled conditions.

1. Key Components:

- a. Multi-Layer Racks:** Crops are grown in vertical shelves.
- b. LED Lights:** Provide the required light spectrum for photosynthesis.
- c. Climate Control Systems:** Maintain ideal temperature, humidity, and CO₂ levels.
- d. Hydroponic or Aeroponic Systems:** Supply nutrients and water.
- e. Sensors and Automation:** Manage irrigation, nutrient dosing, and lighting schedules.

2. Advantages:

- a. Maximum Productivity per Area:** Grows up to 10–20 times more crops per square meter.
- b. Urban Freshness:** Vegetables can be harvested minutes before delivery.
- c. Minimal Water Use:** Uses up to 95% less water compared to traditional farming.
- d. No Pesticides Needed:** Controlled environment eliminates pest entry.
- e. Climate Resilience:** Works year-round, unaffected by weather or drought.

3. Examples:

- a. AeroFarms (USA)** operates one of the world’s largest vertical farms using aeroponics.
- b. UrbanKisaan (India)** runs vertical farms in Hyderabad that produce lettuce, basil, kale, and cherry tomatoes.
- c. Infarm (Germany)** grows greens inside supermarkets to ensure zero transport time.

4. Limitations: High electricity use for lighting and cooling, and high setup costs, remain major challenges. However, solar power and automation are helping to reduce operational expenses gradually.

Comparison of the Three Systems

Feature	Protected Cultivation	Hydroponics	Vertical Farming
Medium	Soil	Nutrient solution	Nutrient solution
Land Use	Moderate	Low	Very Low
Water Use	50% less than open field	80–90% less	90–95% less
Pest Control	Moderate	High (no soil pests)	Very High
Cost	Medium	High	Very High
Climate Control	Partial	Controlled	Fully Controlled

Suitable Crops	Tomato, cucumber, chili	Leafy greens, herbs	Lettuce, microgreens	herbs,

Future Outlook and Opportunities

With rapid urbanization and climate challenges, these modern systems are not just alternatives they are the **future of vegetable farming**. Here's what lies ahead:

- 1. Integration of Technologies:** Combining hydroponics, sensors, AI, and IoT to monitor plant health automatically.
- 2. Renewable Energy Use:** Solar-powered pumps and LED systems to reduce carbon footprint.
- 3. Decentralized Urban Farms:** Small vertical farms in cities reducing transport costs and food miles.
- 4. Skill Development:** Training programs for youth and farmers in controlled-environment agriculture.
- 5. Government Support:** Subsidies, low-interest loans, and technology incubation programs will help make adoption easier.

These systems promise sustainable, clean, and efficient vegetable production, ensuring year-round supply and less dependency on weather conditions.

Conclusion

Protected cultivation, hydroponics, and vertical farming are transforming the way we grow vegetables. By creating controlled environments, these methods produce high-quality crops with less water, land, and pesticides.

While initial investments can be high, the long-term benefits including consistent yield, urban food security, and resource efficiency make them worthwhile. The combination of technology, sustainability, and innovation will shape the next generation of vegetable farming, ensuring fresh produce for growing populations and greener cities.

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Super Veggies: How Biofortified Varieties are Revolutionizing Your Plate and Your Health

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Introduction

Biofortified vegetables are revolutionizing nutrition by delivering higher levels of essential micronutrients like vitamin A, iron, and zinc directly through the foods we love. These supercharged crops, developed through selective breeding or agronomic enhancements, tackle global “hidden hunger,” affecting over two billion people with micronutrient deficiencies. From orange-fleshed sweet potatoes to iron-rich spinach, they offer a sustainable, affordable way to boost health without changing diets.

The Hidden Hunger Crisis and the Rise of Supercharged Produce

Imagine biting into a carrot that's not just crunchy and sweet, but packed with enough vitamin A to keep your eyes sharp and your immune system firing on all cylinders. Or picture a handful of spinach leaves that deliver a hefty dose of iron, helping you power through your day without that mid afternoon slump. This isn't science fiction it's the reality of biofortified vegetables, the nutrient dense heroes quietly transforming global agriculture and everyday diets.

In a world where billions battle “hidden hunger” a sneaky form of malnutrition where people get enough calories but lack essential vitamins and minerals biofortified crops are stepping up as a game changer. According to the World Health Organization, over two billion people suffer from micronutrient deficiencies, leading to issues like weakened immunity, stunted growth in kids, and even higher risks of chronic diseases like anemia and blindness. These deficiencies hit hardest in developing countries, where diets heavy on staples like rice or maize leave little room for diverse fruits and veggies. But even in wealthier nations, busy lifestyles and processed foods mean many of us aren't getting the nutrients we need.

Biofortification: a smart, sustainable way to crank up the nutritional punch in our favorite veggies right from the farm. Unlike industrial fortification, where vitamins are sprinkled into processed foods like cereals, biofortification builds nutrients into the plant's DNA through selective breeding, agronomic tweaks (like better fertilizers), or even gentle genetic tweaks.

Think of it as upgrading your grocery cart from economy to first class. Traditional veggies are nutritious, sure—spinach for folate, broccoli for vitamin C but biofortified versions supercharge those benefits. For instance, a single serving of biofortified sweet potato can provide up to 400% of your daily vitamin A needs, helping combat night blindness and boosting child development in places like Mozambique, where trials showed a 24% drop in vitamin A deficiency among kids. And the best part? These veggies don't require fancy processing or expensive supplements; they're ready to eat, affordable, and farmer approved because they yield just as well (or better) than standard varieties.

Biofortification isn't new it's been in the works for decades, thanks to organizations like HarvestPlus and CGIAR research centers. They've released hundreds of varieties across 128 countries, focusing on staples that feed the masses. But with climate change threatening food security and diets growing more monotonous, these nutrient dense veggies are more relevant than ever. They're not just about survival they're about thriving in a healthier, greener world. As we dive deeper, we'll explore how scientists make this magic happen and spotlight some star players you can add to your plate today.

Top Biofortified Veggies and their Superpowers

If veggies were superheroes, biofortified varieties would wear capes embroidered with vitamins and minerals. These aren't gimmicks they're bred (pun intended) to tackle specific nutrient gaps while keeping the flavor and crunch intact.

The orange fleshed sweet potato (OFSP), a vitamin A powerhouse. Regular sweet potatoes offer some beta carotene (the plant form of vitamin A), but OFSP varieties like those developed in Africa crank it up to eye

popping levels sometimes 10 times more. In Uganda and Mozambique, farmers have embraced these golden spuds, which not only fight vitamin A deficiency (affecting 250 million preschool kids globally) but also resist drought and pests better than old school types. Roast them for fries, mash them into a side, or blend into smoothies their sweet, earthy taste shines, and one medium potato can cover your daily vitamin A quota, supporting everything from vision to skin health.

Biofortified spinach and other leafy greens pumped with iron and zinc. Iron deficiency causes anemia in nearly 2 billion people, sapping energy and focus, especially in women and children. Enter varieties like "Pusa Bhindi" spinach from India or iron rich kale hybrids, bred by crossing nutrient packed wild relatives with everyday greens. These leaves pack 20-50% more iron, which your body absorbs better thanks to natural enhancers like vitamin C already in the plant. Zinc, crucial for immune function and growth, tags along too. Toss them in salads, wilt into soups, or sauté as a side your body will thank you with steadier energy and fewer sick days.

Don't sleep on carrots and tomatoes, biofortified for pro vitamin A and antioxidants. "Baby carrots" aren't the only mini marvels; new carrot breeds like those from the International Center for Tropical Agriculture boast double the beta carotene, turning a snack into a sight saving treat. Tomatoes get a lycopene boost in varieties like "High Lyc" from research programs, fighting inflammation and heart disease while adding that juicy pop to sauces and salads. And for a tropical twist, biofortified cassava roots in Nigeria deliver iron and zinc, staples that once drained soils now nourish communities.

These veggies aren't lab experiments gone wild they're the result of clever breeding that preserves taste and yield. Conventional methods cross high nutrient plants with hardy ones, while agronomic boosts like zinc enriched fertilizers amp up density without GM drama. Studies show bioavailability the amount your body actually uses is high, with biofortified beans improving iron status in Indian schoolkids and zinc rich rice doubling absorption in U.S. trials. Whether you're battling urban stress or rural hardships, these nutrient dense picks make healthy eating effortless and effective.

From Farm to Fork: Real Impact, Challenges, and Your Next Meal

The proof is in the pudding or in this case, the stir fry. Biofortified veggies aren't just theoretical wins; they're delivering tangible health upgrades. In India, iron packed pearl millet cut anemia in young kids, while zinc boosted wheat improved growth in rural Pakistan. A systematic review of over 50 studies found that consistent consumption of these crops boosts micronutrient levels by 10-30%, reducing "hidden hunger" without overhauling diets. For farmers, the perks are practical: higher yields and resilience mean more income, fueling adoption in places like Bangladesh where biofortified rice now covers millions of acres.

But no revolution is without hurdles. Breeding takes time up to 10 years per variety—and scaling up seeds for smallholders requires investment. Consumer acceptance can lag if veggies look "different" (though most don't), and in high income countries, awareness is low despite rising interest in functional foods. Climate variability and policy gaps slow progress, but collaborations between governments, NGOs like Harvest Plus, and private seed companies are accelerating releases over 100 varieties in the last decade alone.

Vegetable	Nutrient Enhanced	Notable Varieties	Details
Orange Fleshed Sweet Potato	Beta Carotene (Pro Vitamin A)	<i>Vita</i> , <i>Ejumula</i> , <i>Beauregard Improved</i>	Up to 400% daily vitamin A per serving. Combats deficiency in kids, improves vision, immunity. Drought/pest resistant.
Spinach	Iron, Zinc	<i>Pusa Biofortified Hybrids</i> <i>Bhindi</i> , <i>Kale</i>	20-50% more iron to fight anemia, plus zinc for immunity. High bioavailability with natural vitamin C.
Carrot	Beta Carotene (Pro Vitamin A)	<i>Nutri Orange</i> , <i>CIAT Hybrids</i>	Double the vitamin A precursor of regular

			carrots. Supports vision, skin health.
Tomato	Lycopene (Antioxidant)	<i>High Lyc, AVRDC Hybrids</i>	Boosts heart health, reduces inflammation. Juicy flavor for sauces, salads.
Cassava	Iron, Zinc	<i>TMS 30572, NR 8082</i>	10-20% more bioavailable iron/zinc. Staple crop addressing anemia, growth issues.
Cauliflower	Beta Carotene, Iron	<i>Pusa Beta Kesari 1</i>	Enhanced vitamin A and iron. Creamy texture, versatile for cooking.
Beans (Common)	Iron, Zinc	<i>NUA45, ICTA Superchiva</i>	15-30% more iron and zinc. Improves energy, cognitive development in kids.
Amaranth (Leafy Green)	Iron, Vitamin A	<i>Madiira 1, Madiira 2</i>	High iron for anemia prevention, plus vitamin A for immunity. Popular in African home gardens.

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Smart Farming with AI: Transforming Agriculture for the Next Decade

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Abstract

Artificial intelligence (AI) is opening up a new frontier for agriculture with data-driven solutions, including machine learning and computer vision and robotics that can improve production practices. With the global population expected to exceed 8.5 billion people as we approach 2030, AI is poised to help increase crop yields, better allocate resources and support a more sustainable and climate-resilient agriculture worldwide. The paper discusses the transformative role of AI, examples of its usage, statistical findings and case studies on the ground, challenges and a forward-looking roadmap for 2030 with practical recommendations for inclusive use.

Introduction

Agriculture, which is at the base of the food system that supports humanity and life on earth, suffers from a critical threat climate change as well as challenges with land degradation, labor shortages and an increasing demand for food. Global food production will need to increase by more than 50% from 2012 levels by the year 2030, in order to feed an increasing world population (FAO, 2017). AI is stepping in as a powerful partner to help drive smarter decisions, automate hard work and foster sustainability on these demands.

How AI is Transforming Agriculture?

AI is transforming the agriculture sector by bringing new applications that improve efficiency, productivity and sustainability. With precision agriculture, AI uses data from drones, satellites and sensors to monitor soil health, forecast crop yields and spot issues like diseases or nutrient deficiencies early on so farmers can see the data and make decisions. Such innovations have cut down chemical use of pesticides and fertilizers by 30–50% in addition to raising crop outputs up to 20% (World Bank, 2020), providing the farmers with the ability to produce more with less. For example, within the domain of smart irrigation, AI-enabled systems such as CropX and Netafim leverage real-time soil moisture data for optimal water delivery that saves 20–40% of water over conventional methods (ICRISAT, 2021), which is a significant move towards sustainable resource management in geographically diverse cultures. Furthermore, AI-based computer vision solutions including Plant Village Nuru offers quick and precise diagnosis of pests and diseases in cassava and maize crops at greater than 90% accuracy (Penn State University, 2020) which gives farmers the chance to respond promptly in shielding their harvest. And in this revolution of the countryside, autonomous tools like John Deere's self-driving tractors have again dramatically changed farming as well, taking over tasks such as planting and weeding with far more precision than humans can offer cutting back on reliance upon manual laborers and operating costs. Furthermore, AI platforms such as IBM's Watson Decision Platform deliver indispensable market insights and supply chain optimisation, forecasting trends and maximising planting schedules to minimise post-harvest losses by 30%, which in turn boosts profitability for farmers (IBM, 2021). Combined, these breakthroughs illustrate how AI stands to fundamentally revolutionize the future of faster and smarter Agriculture.

Data and Projections for 2030

The adoption of AI in agriculture is growing rapidly, with significant impacts projected by 2030:

Metric	2020	2030 (Projected)	Source
Global Agricultural AI Market	USD 1.1 Billion	USD 11.2 Billion	Markets & Markets, 2023
Yield Increase via AI	10–15%	Up to 30%	FAO & AI4Ag Reports, 2022
Water Usage Reduction	10–20%	30–40%	ICRISAT, 2021
AI Adoption (Farmers)	8%	35–45% (developed); 20% (developing)	McKinsey, 2023
Labor Reduction via AI	5–10%	Up to 25%	World Economic Forum, 2022

Real-World Success Stories

Artificial intelligence (AI) is leading to transformative achievements in agriculture with exciting case studies from multiple locations. In India, Microsoft’s AI Sowing App (developed with ICRISAT) has already transformed rice farming for smallholder farmers in Andhra Pradesh by applying AI to recommend the best time to sow based on data on weather, soil and previously harvested crops – generating a significant 30% increase in rice yield (Microsoft & ICRISAT, 2020), allowing farmers to optimize efficiency and lift their own livelihoods. On a different continent, the US-based Blue River Technology has developed “See&Spray”, which uses AI-enhanced computer vision to automatically differentiate between crops and weeds by sight in collaboration with advanced farming systems manufacturer John Deere, boasting a 90% reduction in herbicide use (John Deere, 2023). Efficient operations utilise less chemical substances thereby promoting environmentally friendly agriculture. Elsewhere, Dutch farmers are leading the world in efficiency by using AI-supported climate control systems in greenhouses – which fine-tune temperature, humidity and light levels to create the best possible conditions for growing produce (20–25% more productive than with human input), a harbinger of AI’s capacity to improve operations and increase yields within controlled environments. They serve as ‘proofs of concept’ for AI generated tailored, replicable and scalable impacts in diverse agricultural environments.



Fig1: Illustration of AI based future agricultural systems

Challenges to Overcome

1. **Data Privacy:** Farmers are cautious about sharing the sensitive data with tech providers, leading to questions of ownership and security.
2. **Cost:** High prices for AI tools may become a roadblock in smallholder dissemination of uptake.
3. **Infrastructure** Despite rural areas are seeing advancements in high-speed internet connections, the lack of access to them remains a major challenge for many rural communities.
4. **Model bias:** The models generated by AI could fail to perform well in different regions or on other crops, where the local robust training data were not available.

A Vision for 2030

Moving on to the future, Agriculture 4.0 is likely to transform farming in a big way by driving precision agriculture and full automation supported through everything from the IoT and robotics to satellite imagery and blockchain, AI is set to disrupt nearly all farm processes. By 2030, Agriculture-4.0 will create an ecosystem which connects farmers and agribusinesses with innovative technologies ensuring productive use of land resource across crops and livestock growth from sowing till harvesting /off taking matured farm output. Sensors in the internet of things (IoT) will provide constant monitoring of soil health, crop conditions and other environmental factors, supplying real-time data to AI systems that can fine-tune irrigation, fertilization, and pest control like never before. Robotics, assisted by AI, will automate labour-intensive activities such as planting, harvesting and weeding, cutting costs to depend on manpower while at the same time enhancing operational efficiency and speed. Satellite data will help feed AI algorithms that can predict yields, provide early alerts for crop stress, and even monitor land use around the world and allow growers to make informed decisions customized to their regions. By integrating blockchain tech, transparency can be provided all the way from farm to market so consumers can be assured about where their produce was made and how sustainably it was grown, enabling them to enjoy trust in the product and practice fair trade. To reach widespread adoption levels, however, larger investments in digital infrastructure such as high-speed internet to rural regions will close connectivity gaps, and prices of AI tools and platforms will need to become palatable by smallholder farmers. Farmer literacy programs will educate agricultural communities about how to effectively use these tools, promoting equitable access across different regions. Key among this will be AI diagnostics to drive climate-smart agriculture, by sifting through oceans of data to help farmers respond to unpredictable weather and erratic rainfall or extreme temperatures with precise crop advice and management plans. The data-driven optimization of water use and reduction of chemical input, as well as the development of resilient varieties, will be essential to saving species and limiting environment destruction driven by agriculture. This 2030 vision places AI as a fundamental in an agriculturally sustainable, productive and resilient future, which accelerates the way food is grown globally to feed our population while preserving the planet.

Recommendations for Inclusive AI Adoption

1. Create Digital Infrastructure: Governments must invest in rural connectivity and digital literacy training, administered for freePG.
2. Lower cost barriers: Financial subsidies and open-source AI solutions can bring technology within reach of every farmer
3. Encouraging Ethical AI: Clear data policies and algorithms created for different regions will build trust and efficacy.
4. Deepen Partnerships: Governments, tech companies and farmers working together can speed up innovation and adoption.

Conclusion

Artificial intelligence (A.I) will revolutionize farming, turning it into a high performance, sustainable and resilient activity able to meet the needs of a fast-growing human population under challenging climate conditions. By 2030, AI and related innovations will have enormous impacts on farming energy use, crop yields, fertilizer usage, water conservation and much more thanks to precision agriculture, smart irrigation systems for farms and deep learning analytics. Such developments will support farmers to increase food production using less inputs in order to cater for the estimated 50% increase in global food demand with respect to year 2012 (FAO, 2017), while attempting not to increase ecological footprints. Yet challenges including expensive deployment, scant digital infrastructure outside of cities, and worries about data privacy and algorithmic bias continue to be formidable obstacles, especially for smallholder farmers in developing nations. In his editorial, Qiao also said that strategic measures need to be taken to address these obstacles, including the development of affordable AI tools; ensuring widespread access in rural areas and digital literacy programmes for global farming communities. Cooperation among the government, technology companies and communities of farmers will be critical for equitable access to AI tools to promote inclusive innovation. By confronting these challenges, by 2030 AI can be at the heart of global agriculture's effort feeding and creating for food for a growing population expected to top 8.5 billion people while also

meeting environmental goals through climate-smart approaches that conserve biodiversity and reduce waste of resources. This transformational power makes it a critical ally in creating a sustainable and food-secure future where agriculture prospers through the challenges of the 21st century.

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Geographical Indication (Gi) Tags of Tropical Fruit Crops in India

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Introduction

A Geographical Indication (GI) tag is a sign used on products that have a specific geographical origin and possess qualities or a reputation that are due to that origin. GI tags are used to identify products that are unique to a particular region or area, and are often associated with traditional production methods or unique characteristics.

Purpose of GI Tags

The main purpose of GI tags is to:

1. Protect traditional knowledge and intellectual property: GI tags help to safeguard the traditional knowledge and intellectual property associated with products that are unique to a particular region or area.
2. Promote local economies: GI tags can help to promote local economies by recognizing and protecting the unique products of a region, which can attract tourists and investors.
3. Ensure quality and authenticity: GI tags ensure that products bearing the tag meet certain standards of quality and authenticity, which can help to build consumer trust.

Fruit Crops with Geographical Indication Tags in India

India has a diverse range of fruit crops that have been awarded Geographical Indication (GI) tags, recognizing their unique characteristics and geographical origins. Here are some of the notable fruit crops with GI tags

GI Tags in Mango:

State	GI Tag Variety Name
Andhra Pradesh	Banganapalle Mango
Bihar	Jardalu Mango
Goa	Mankurad Mango
Gujarat	Gir Kesar Mango
Karnataka	Appemidi Mango
Kerala	Kuttiattoor Mango
Maharashtra	Alphanso Mango (Hapus), Marathwada Kesar Mango
Uttar Pradesh	Malihabadi Dashehari Mango, Banaras Langda Aam, Rataul Mango
West Bengal	Himsagar Mango, Fazli Mango, Laxman Bhog Mango, Malda Fazli Mango

GI Tags in Banana:

State	GI Tag Variety Name
Karnataka	Nanjanagud Rasabalehannu (Banana), Kesarimangalam Banana
Tamil Nadu	Virupakshi Hill Banana, Sirumalai Hill Banana
Maharashtra	Red Banana (Jainarayanpur)
Karnataka	Kamalapura Red Banana (Kamalapur Red Banana)

GI Tags in Citrus:

State	GI Tag Variety Name
Assam	Karbi Anglong Orange, Assam
Nagaland	Naga King Chilli and Orange
Maharashtra	Nagpur Orange, Jalna Sweet

Punjab	Kinnow Mandarin
Meghalaya	Khasi Mandarin, Memong Narang
Karnataka	Devanahalli pomello
Arunachal pradesh	Arunachal
Manipur	Kachai lemon

GI Tags in other fruit crops:

Crop	GI tags
Guava	Allahabad Safeda Guava from Allahabad
Grapes	- Thompson Seedless Grapes from Maharashtra - Maharashtra Grapes (specifically from Nashik region)
Pomegranate	Solapur Pomegranate from Maharashtra
Pineapple	Vazhakulam Pineapple from Kerala
Sapota	- Dahanu Gholvad Sapota from Maharashtra - Amalsad Chikoo from Gujarat
Custard apple	- Balanagar Custard Apple from Telangana - Beed custard apple from Maharashtra - Seoni Sitaphal from Madhya Pradesh
Jackfruit	Panruti Jackfruit from Tamila Nadu
Litchi	- Shahi Litchi from Bihar. - Tezpur Litchi from Assam
Aonla	Pratapgarh Aonla from Uttar Pradesh
Fig	Purandar Fig from Maharashtra

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Seed Quality & Hybrid Seed Sector and its Impact on Crop Yield for Sustainable Agriculture

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Abstract

In the rapidly changing world of agriculture, where farmers are expected to produce more with fewer resources, one element is the key to a successful harvest ~ Quality Seed. The genetic purity, physical purity, physiological purity, and seed health together determine the Quality of a seed. It acts as a foundation for crop productivity and for sustainable farming. The quality seed ensures uniform crop stand, resistance to abiotic and biotic stress, and optimal use of inputs or resources and thus producing higher yields. Whereas the factors like improper field conditions, mechanical mixtures, poor post harvest handling, and poor storage results in low quality seeds which further results in poor germination, uneven crop growth, incidence of diseases and thus results in low productivity and production. The hybrid seed sector in India is experiencing significant growth, driven by technological advances and increasing demand for high-yield crops. As per **The National Seed Association of India (NSAI)** there are over 700 companies involved in the seed business, many of which produce hybrid seeds. Ultimately enhancing seed quality is identified as a foundational strategy for achieving food security and promoting a sustainable agricultural system.

Introduction

Seed is the backbone or basic input for agriculture. Several factors such as physical purity, genetic purity, viability, and vigour define the seed quality. High quality seeds ensure better germination rate, uniform crop growth and comparatively better resistance to disease and pest attack whereas low quality seed results in low germination and thus lower yields. In case of sustainable agriculture, the ultimate goal is to produce higher yields while using resources wisely and protecting the environment. The good quality seed not only increases the productivity and resistance, but in-turn also helps in minimising the usage of chemical fertilisers. In India institutions like **National Seed Corporation (NSC)** and **Indian Council of Agricultural Research (ICAR)** regulate and promote quality seed production and certification.

Characteristics of Good Quality Seed

1. Physical purity: absence of other crop seeds, weed seeds and inert matter.
2. Genetic purity: True to type - ensuring the plant is identical to its parent material.
3. Physiological purity: It comprises of seed viability and seed vigour.
 - a. Seed Viability - ability of seeds to germinate and grow into a healthy plant under suitable or favourable conditions.
 - b. Seed Vigour - ability of seeds to germinate and grow under unfavourable or different environmental conditions.
 - c. Dormancy - inability of a seed to germinate even in suitable environmental conditions.
4. Seed Health: must be free from seed borne pathogens and insect infestation and damage.
5. Moisture content: 6% to 8% is to be maintained for maximum longevity whereas in general a minimum of 10-14% is to be maintained. It impacts the storage life, viability, and germination.

Factors Affecting Seed Quality

1. Environmental and field conditions:

- a. Soil conditions such as soil fertility, texture, pH,

- i. Water availability- sufficient water supply during growth period,
- ii. Climatic conditions such as temperature, rainfall, humidity, length of daylight (photoperiod) affect seed development and viability.
- b. Biotic factors including insect pests, fungal diseases, and nematodes impact seed health.
- c. Crop management practices such as proper cultivation techniques, weed control or weeding, timely planting.

2. Seed handling and Post-harvest / Processing factors:

- a. Method and time of harvesting effect seed quality.
- b. Mechanical damage during threshing and handling can cause seed injury, further effects germination.
- c. Contamination with inert matter, weed seeds and other crop seeds lower physical purity.
- d. Improper grading results in non uniform seeds.
- e. Seeds to be stored at low temperature (10-14 degrees min) and relative humidity of less than 60% to preserve viability.

Challenges Faced Due to Low Quality Seeds

1. Reduced germination and poor crop stand
2. Increased susceptibility to pests and diseases
3. Significant yield loss
4. Higher production costs due to increased input use
5. Market rejection
6. Environmental stress (example - drought)
7. Spread of invasive species (example - *Parthenium hysterophorus*, *Phalaris minor*)

Current Status of Hybrid Seed Sector in India

There are no exact current figures, but India has over 700 seed companies in both the private and public sectors, and a recent report mentioned 277 hybrid seed startups in addition to established hybrid seed producers. **The National Seed Association of India (NSAI)** states there are over 700 companies involved in the seed business, many of which produce hybrid seed.

While precise overall figures are unavailable, Telangana produces approximately 40% of India's hybrid seed, proving it as the “**Seed Bowl**” of the country. The state is home to about 400 seed companies and functions as a major production hub for various hybrid seeds, including paddy and cotton. In 2016-17, Telangana produced around 1,69,073.2 tons of certified seeds in total, with paddy accounting for a significant portion.

Indian Hybrid Seed Market: Size and Trends

1. The hybrid seed sector in India is experiencing significant growth, driven by technological advances and increasing demand for high-yield crops.
2. **Overall market size:** As of January 2025, the total Indian seed market is valued at approximately \$3.82 billion (₹31,800 crore approximately). It is projected to grow to \$5.01 billion by 2030.
3. **Hybrid market share:** Hybrid seeds, both in field crops and vegetables, are a major driver of this growth. One report shows that hybrid seeds dominated 80.6% of the total cultivation area in 2022.
4. **Hybrid market value:**
 - a. **2020 estimate:** NSAI reported that the hybrid seed market accounted for 45% of the total estimated \$3.1 billion seed business in India in 2020, putting the value at \$1.39 billion (₹11,600 crore).
 - b. **2025 estimate:** Based on the January 2025 market valuation, the hybrid seed market could be valued at approximately ₹10,000 crore.

Telangana Hybrid Seed Market: Trends and Production

Telangana is a crucial state for India's seed industry, with a strong base in seed production and a significant presence of seed companies.

1. Major seed producer: In 2021–2022, the **Telangana State Seed Development Corporation** (TSSDC) reported producing 160,441 quintals (16,044.1 metric tons) of seed, including hybrid varieties. Officials valued this production at ₹6,487 crore.

2. Key crops: The TSSDC produced seeds for 18 different crops, including paddy, maize, and hybrid cotton. This was supplied to other states and exported to other countries.

3. Market share changes: The state's market share in the Indian seed business declined from 30% in 2014 to 18% in 2020. This shift was reportedly due to some hybrid rice and Bt cotton seed production moving to neighbouring states.

India (National Level)

1. The Indian seed industry (organised + certified) is estimated at about ₹10,000 crore (for hybrid seeds) within a total seed industry of ₹22,500 crore. (Scribd)

2. The India seed market is also valued at about ₹30,000 - ₹32,000 crore, depending on exchange rate in 2025. (Mordor Intelligence+1)

3. In the seed industry, hybrid seeds dominate (70 % of market value) in many projections. (Mordor Intelligence+1)

4. About 40 % of the hybrid seed marketed in India is produced in Telangana. (ResearchGate).

Telangana (State Level)

1. Telangana's seed production (all types, not just hybrid) is reported at 98 lakh quintals annually over more than 7.0 lakh acres. (Scribd)

2. Within that, hybrid paddy seed production is done on 1.00 lakh acres producing 7.00 lakh quintals. (Scribd)

3. The TSSDC produced 1,60,441 quintals of seed (for 18 crops) in 2021–22, of value 6,500 crore. (The Hindu)

4. In an older report, Telangana was said to produce about 65,000 tonnes (6.5 lakh quintals) of seed of various crops (not necessarily only hybrids). (The Hindu)

5. Telangana also reportedly “generates one crore quintals annually” of seed (across rice, maize, millets etc.) and exports seeds worth ₹2,000 crore per year. (The Times of India+1)

Estimating Total Hybrid Seed Quantity & Market Value

From the above:

a. If Telangana produces 98 lakh quintals total seed, and if a substantial proportion of that is hybrid (especially in commercial crops), then hybrid seed production in Telangana might be in the tens of lakh quintals.

b. The claim that 40% of hybrid seed marketed in India originates from Telangana suggests that India's marketed hybrid seed (certified / organized) might be 2.5× Telangana's, assuming Telangana's production and marketing are well integrated. But that's a rough assumption.

c. If the hybrid seed market in India is ₹10,000 crore (for hybrid seed), then 40% share corresponds to ₹4,000 crore being attributable to Telangana (in value terms).

d. However, Telangana's actual realised value (export + domestic) is reportedly ₹2,000 crore exports alone (not covering domestic sales) from seed. (The Times of India+1)

So, putting it together:

a. Estimated hybrid seed marketed quantity (India) - If one assumes that the organised hybrid seed market is, say, 20–30 lakh quintals (just as a speculative figure), then Telangana (40 %) might account for 8–12 lakh quintals.

b. Estimated hybrid seed marketed quantity (Telangana) - likely in that order (8–12 lakh quintals) but could be higher or lower depending on which crops, scale, and season.

c. Market size in INR (India, hybrid seed) -10,000 crore. (Scribd+3Scribd+3goldsteinresearch.com+3)

d. Market size in INR (Telangana's hybrid seed share) — If Telangana accounts for 40% of hybrid seed production/marketing, then its share would be ₹4,000 crore (assuming the ₹10,000 crore estimate is accurate) though that would include export + domestic sales.

Conclusion

The quality of seed plays a crucial role in determining agricultural productivity, sustainability, and food security. High-quality seeds are essential for ensuring uniform germination, optimal crop growth, and resilience against biotic and abiotic stresses, ultimately leading to higher yields and efficient resource use. The factors influencing seed quality, such as environmental conditions, proper handling, and post-harvest processing, must be carefully managed to maintain seed viability and vigour. Low-quality seeds, on the other hand, lead to poor crop performance, increased susceptibility to diseases and pests, and reduced yields, making it difficult for farmers and agricultural systems to prioritise seed quality. Improving seed quality is not only important for economic productivity but also for promoting sustainable agricultural practices such as, minimising input use, and harmful chemicals which in-turn pollute environment. Thus, a concerted efforts to enhance hybrid seed quality, through improved production practices, research, and policy regulation, will be a key strategy for achieving long-term agricultural sustainability and food security in the face of a changing climate and growing global population.

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From Traditional Practices to Smart Farming: The Data-Driven Evolution of Farming

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Introduction

The practice of smart farming functions through the development of advanced technological systems coupled with data-driven management approaches that enhance farming operations' precision. Farmers employ GPS systems together with sensors, drones and data analytics tools to track and react to specific crop and soil requirements immediately. This innovative approach enables farmers to use resources such as water, fertilizer and pesticides in precise amounts to transform modern farming practices. The method helps farmers choose the right decisions to boost yield while minimizing waste and environmental damage. Smart farming represents a transformative force that can reshape farming operations through increased efficiency, sustainability and productivity, leading to enhanced food security and resilience.

The Rise of Technology in Smart Farming

The agricultural industry represents one of the oldest economic sectors that has evolved from conventional methods towards modern data-based systems. Traditional farming practices depended primarily on manual work and instinctive methods for both crop and livestock management. These methods proved functional across centuries yet they resulted in inefficient resource utilization and environmental degradation.

The swift development of technology has been a major factor in agriculture entering a new era where the use of data, sensors, and intelligent systems is predominant along with intuition. The transformation led to the birth of Smart farming; the method that relies on geospatial data, remote sensing, and advanced analytics to monitor and control field variability. Where traditional practices had treated whole fields as one, precision farming now allows specific management for each site, therefore, it is possible to use water, fertilizers, and pesticides optimally while also reducing their effect on the environment. As a result, the profession has turned from one based on experience to one based on evidence, thereby promoting sustainability and productivity in times of limited resources and climate change uncertainty.

Component of Smart Farming

1. Artificial Intelligence (AI) and Machine Learning: Artificial Intelligence, or AI, means using computers to think and learn like humans. In farming, AI helps farmers do their work faster, better, and with less waste. It makes farming smarter by using machines and data to make better decisions.

How AI is Used in Farming:

a. Predictive Analytics (Smart Predictions): AI looks at a lot of data like: Soil health (from soil sensors), Weather forecasts, Plant conditions. Then, it uses this information to predict what will happen. This helps farmers: Decide the best time to plant or harvest, Save water by planning better irrigation and Protect crops from pests before they spread.

b. Automation and Robots: AI also controls robots and machines that help in farming. These machines can: Pull out weeds, Plant seeds, Harvest crops. These robots do the work quickly and correctly, which means: Farmers don't need as much help from workers, Less waste is produced, The work gets done on time.

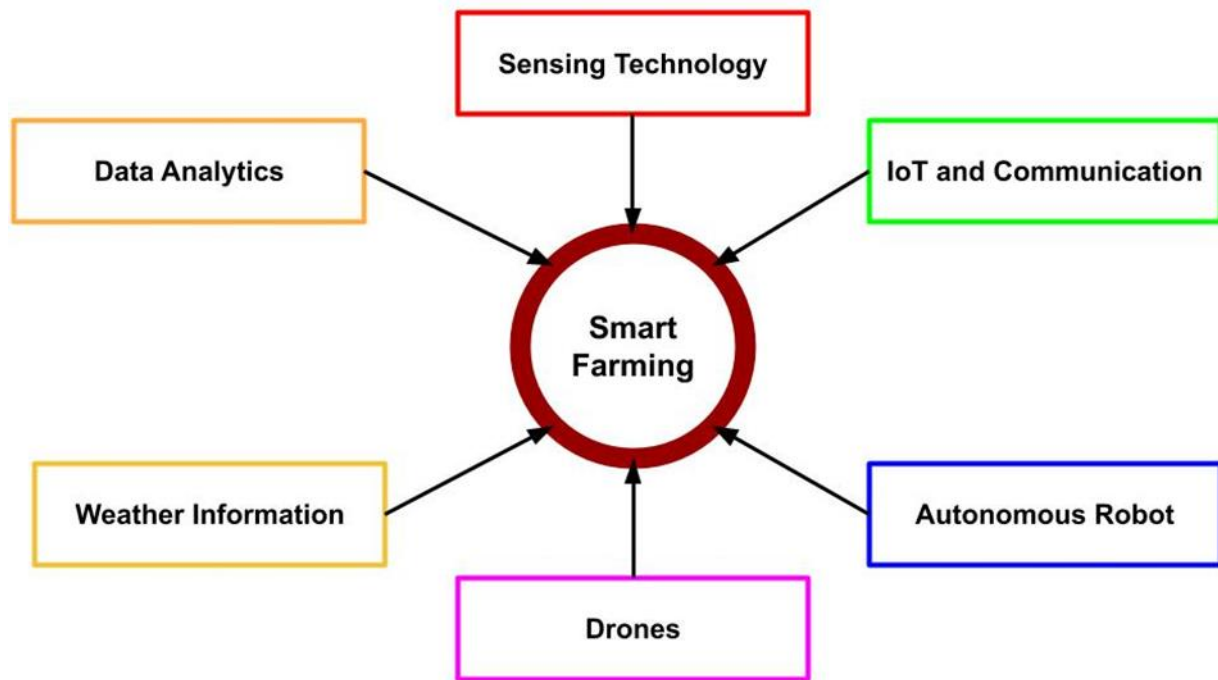


Fig 1: Components of Smart Farming

2. Internet of Things (IoT) Sensors: The Internet of Things is made up of networked sensors that gather and send data in real time about environmental variables including crop health, temperature, and soil moisture. IoT sensors help in resource management, crop status monitoring, and irrigation optimization in smart farming. Their application results in increased productivity, less waste, and more precise farming which are as follows:

- a. Soil and Crop Monitoring:** Real-time measurements of soil temperature, nutrient levels, and moisture using IoT sensors can yield information that improves the application of pesticides, fertilizer, and irrigation. This ensures that crops get the nutrients they need while using less water.
- b. Livestock Monitoring:** Wearable IoT devices for livestock track the location, behavior, and health of the animals, supporting farmers in better managing the productivity and well-being of their livestock.

3. Drones and Satellite Imagery: It is a process of using satellites and aircraft to capture high-resolution, real-time photographs of farms. They help in crop health monitoring, pest identification, soil evaluation, and the development of detailed field maps for targeted treatments in smart farming. This technology enhances decision-making, minimizes labor, and increases efficiency to provide higher yields. Drones using cameras and multispectral sensors can fly over fields to create detailed maps, detect stressors like pests or diseases, and monitor crop health. A larger-scale perspective is provided by satellite images, which can be used to track soil conditions and crop growth over large areas. Drones are also utilized for precision spraying, which ensures consistent application throughout the field while reducing waste along with negative environmental effects.

4. Self-Driving Tractors and Equipment: In simple terms, it refers to farm equipment that uses sensors, GPS, and artificial intelligence (AI) to operate autonomously without human assistance, including harvesters and tractors. These tools help in accurate soil management, planting, and harvesting, which lowers labor costs and boosts productivity in smart farming. Using them increases productivity and ensures more accurate and reliable farming operations.

Robotic Harvesters like devices increase productivity and decrease agricultural damage by using sophisticated machinery with machine vision systems to harvest fruits, vegetables, or other crops at the ideal moment.

5. Block chain Technology: Blockchain is a digital system that makes it nearly impossible to alter or tamper with data by storing it in blocks and sharing it across multiple computers. As every user on the network has an identical copy of the record, this promotes transparency, security, and trust. From farmer

to consumer, agricultural products can be tracked safely and transparently owing to blockchain technology. This might boost consumer confidence, ensure food safety, and improve traceability by giving information about the origin and journey of food products. Farmers can utilize blockchain technology to automate transactions (such as selling crops), reduce paperwork, and ensure fair pricing by utilizing smart contracts that execute automatically when specific conditions are met together.

6. Farming in Layers: The Smart Approach of Vertical Agriculture: Vertical farming is the practice of growing plants in stacked layers as opposed to fields. This approach makes use of specialized techniques that use less water and no soil, such as hydroponics (growing plants in water) and aeroponics (growing plants in air). Because it saves land and resources, it's a great way to grow more food in smaller spaces, especially in cities. It is also good for the environment.

It entails using available resources and available space as efficiently as possible while cultivating crops in controlled conditions in stacked layers. By efficiently using water and nutrients using methods like hydroponics and aeroponics, it allows plants to survive without soil. By using less land and wasting fewer resources, this method increases food production in urban areas while reducing its negative environmental effects.

7. Smart Farming at Your Fingertips: Leveraging Mobile Apps & Platforms: It describes farmers who utilize mobile applications to better control their agricultural business operations. The applications allow users to monitor agricultural productivity while controlling capital and observing weather conditions through their smartphones and tablets. Through these platforms farmers gain real-time data access and tools which lead to increased productivity and time savings and enhanced decision-making abilities. The following mobile applications and platforms enjoy widespread popularity among farmers in Odisha and across India for smart farming: Cropin, Agri Bazaar, Kishan Suvidha, mKisan, Kheti Gaadi, Farmer's Friend, and others.

8. Soil Health Monitoring: The practice utilizes sensors together with data analytics to perform live assessments of soil fertility and health conditions. Sensors that evaluate multiple factors including moisture levels alongside pH and nutrient amounts and organic matter content deliver essential soil condition data to farmers. Knowledge of these variables enables farmers to optimize crop development and implement nutrient management strategies and sustainable methods that boost soil wellness and improve yields while decreasing environmental damage.

How Smart Farming Works

Smart farming represents an agricultural method which utilizes contemporary technology for enhancing crop yields and minimizing waste production. The methodology requires precise and informed field-specific decisions that foster plant development while protecting essential resources such as fertilizer and water. Let's examine its operation in more detail:

1. Using Sensors to Collect Data

2. Data Analysis

3. Automating Farm Tasks.

Systems together with their equipment function independently by processing information through automation. The technology known as Variable Rate Technology (VRT) enables precision agricultural machines to deliver specific quantities of fertilizer along with water and seeds to designated locations. Through its ability to provide customized field treatment each area of the field receives suitable input which results in cost savings for funds and water along with fertilizer usage reduction.

Sustainability and Environmental Benefits of Smart Farming

By supporting farmers in producing food in environmentally friendly and resource-efficient ways, smart farming promotes sustainable farming methods. It encourages sustainability in the following ways:

1. Minimizing Water, Fertilizer, and Pesticide Use: The practice of smart farming enables precise application of water along with fertilizer and pesticides based on specific needs. Sensors detect dry sections of a field so that water application occurs strictly in those areas. The intentional application of water and

controlled chemical use in this system preserves soil and water quality through minimized waste and prevention of excessive accumulation.

2. Better Pest and Disease Management: The application of smart farming methods allows farmers to achieve superior disease and pest control results. Sensors together with mobile applications operate to identify early signs of pest or disease problems across specific portions of agricultural fields. The technology helps farmers cut back on pesticide usage through precise targeting of affected areas thus protecting the environment from unnecessary contamination.

3. Safeguarding the Environment: High levels of pesticide and fertilizer applications create water pollution which damages aquatic life through runoff that enters rivers. Through proper application management smart farming reduces pollution risks thus maintaining ecosystem health which benefits local plant and animal populations.

4. Conserving Natural Resources: The practice of smart farming promotes water and soil conservation. Through Variable Rate Technology (VRT) tools farmers can plant cover crops which helps them reduce water consumption and defend their soil from erosion. The method works best in regions where water availability is limited.

Challenges of Smart Farming Adoption in India

Indian farmers lack technological advancement in their agricultural practices due to widespread illiteracy within this population. The efforts from both public and private sectors to promote information and communications technology (ICT) adoption in agriculture have failed to achieve their intended objectives because farmers remain unaware of the benefits despite the proven advantages of higher productivity and cost reduction and increased returns.

Future of Smart Farming

The upcoming generation of AI models will deliver unmatched predictive analytics capabilities which will enable precise crop management alongside disease prediction and yield optimization. Advanced AI might automate decision-making processes and analyzing data from multiple sources to give farmers real-time, useful information. The application of gene editing technologies including CRISPR/Cas9 to enhance plant resistance against pests and diseases while developing tolerance to environmental stresses and increasing yield production stands to transform the future of crop breeding. Food security stands to benefit from this advancement which will simultaneously decrease chemical input requirements. At the worldwide level nations can collaborate to tackle major problems including climate change together with food shortages. Farmers throughout the entire world have access to optimal smart farming equipment usage through collective knowledge exchange. The sharing of important agricultural data through GODAN enables nations to enhance worldwide food security. Farmers living in remote locations can benefit from mobile apps and online courses which enable them to learn from any place and develop their abilities to gain maximum advantage from smart farming practices.

Conclusion

Smart farming represents an approaching era where agricultural production will fulfill planetary requirements without depleting available resources. The combination of technology with traditional agricultural knowledge enables farmers to create sustainable food production which protects soil health and water quality and mitigates environmental impact. The transformation addresses climate change through its dual purpose of securing universal food access alongside enhancing agricultural operations. Smart farming introduces a new era to agriculture which creates sustainable pathways for future generations' food production.

Approach and Strategies of Genetic Resources Conservation

Article ID: 72227

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Abstract

The biological foundation of global food and nutrition security is provided by genetic resources for agriculture and food, which also directly sustain human livelihoods. Genetic erosion, or the fast loss of genetic variety, is a global issue that is especially bad for crop landraces. The most prized genetic resources are farmer's varieties or landraces, which offer alternatives for a variety of climatic and edaphic stressors. Thus, the public value of agricultural biodiversity is crucial for ensuring global food security.

Keywords: Genetic Resources, Genetic Erosion, Genetic Diversity.

Introduction

“Genetic resources” means genetic material of actual or potential value. “Genetic material” means any material of plant, animal, microbial or other origin containing functional units of heredity (CBD/WIPO). Germplasm of plants, animals, or other organisms, containing useful characters of actual or potential value. In a domesticated species, it is the sum of all the genetic combinations produced in the process of evolution (IPGRI). *Plant genetic resources* refer to “the economic, scientific or societal value of the heritable materials contained *within and among species*” (FAO). The total genetic information is encoded in the sum of the genes in all the populations of a species. Thus, it is the sum of the genetic information in the gene pools of the species (USDA).

Need for Genetic Resources

1. Domestication of new crops
2. Environmental adaptations
3. Pest and Disease resistance.
4. Cytoplasmic male sterility
5. High yield and vigour
6. Petaloid male sterility
7. High food value (vitamins, proteins).
8. Harvest and transport.

Components of Genetic Resources

1. Land races: Land races were not deliberately bred like modern cultivars. They evolved under subsistence agriculture and have high level of genetic diversity which provides them high degree of resistance to biotic and abiotic stresses. Land races have broad genetic base which again provides them wider adoptability. The main drawbacks of land races are that they are less uniform and low yielders.

2. Obsolete Cultivars: These are the varieties developed by systematic breeding effort which were popular earlier and now have been replaced by new varieties. Improved varieties of recent past are known as obsolete cultivars. They have several desirable characters they constitute an important part of gene pool.

3. Modern cultivars: The currently cultivated high yielding varieties are referred to as modern cultivars. They are also known as improved cultivars or advanced cultivars. These varieties have high yield potential and uniformity as compared to obsolete varieties and land races. They constitute a major part of working collections and are extensively used as parents in the breeding programmes. As these are good sources of genes for yield and quality, can be introduced in a new area and directly released. However, these have narrow genetic base and low adoptability as compared to land races.

4. Advanced breeding lines: These are pre-released plants which have been developed by plant breeders in modern scientific breeding programmes. These are known as advanced lines, cultures and stocks. This group includes, nearly homozygous lines, lines derived from biotechnology programmes i.e. transgenic plants and mutant lines etc. which are not yet ready for release to farmers. They often contain valuable gene combinations.

5. Genetic Stocks: They include those carrying gene mutation, chromosomal aberrations and marker genes etc. These stocks are useful in genetic analysis and may find use in breeding programme as well.

6. Wild forms of cultivated species: Wild forms of cultivated species are available in many crop plants. Such plants have generally high degree of resistance to biotic and abiotic stresses and are utilized in breeding programmes. They can easily cross with cultivated species. Wild forms of many crop species are extinct.

7. Wild Relatives: Those naturally occurring plant species which have common ancestry with crops and can cross with crop species are referred to as wild relatives or wild species. Wild relatives include all other species, which are related to the crop species by descent during their evolution. Both these groups are sources of valuable genes for biotic and abiotic stress and for quality traits and yield.

8. Mutants: Mutation breeding is used when the desired character is not found in the genetic stocks of cultivated species and their wild relatives. Mutations do occur in nature as well as can be induced through the use of physical and chemical mutagens. The extra variability which is created through induced mutations constitutes important components of genepool. Mutant for various characters sometimes may not be released as a variety, but they are added in the genepool. The germplasm includes those carrying gene mutations, chromosomal aberrations and markers genes etc. are considered special genetic stocks. They are useful in breeding programmes.

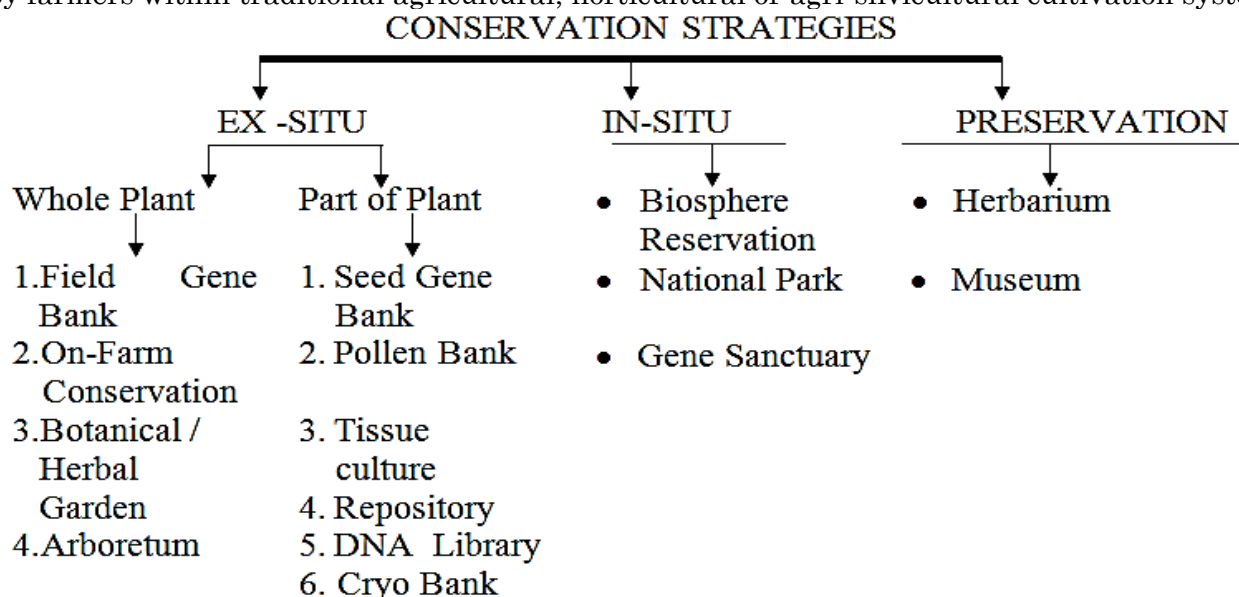
Germplasm Conservation

The Germplasm has to be maintained in such a state that there is minimum risk for its loss and that either it can be planted directly in the field, or it can be prepared for planting with relative ease.

1. Ex-situ Conservation: Germplasm conservation is attempted outside or away from its natural habitat.

2. In-situ Conservation: Conservation of germplasm in its natural habitat or in area where it grows naturally.

3. On-farm Conservation: One of new approaches to in situ conservation of genetic resources, focusing on conserving cultivated plant species in farmers' fields. It's nothing but "The sustainable management of genetic diversity of locally developed traditional crop varieties, with associated wild and weedy species or forms, by farmers within traditional agricultural, horticultural or agri-silvicultural cultivation systems".



Conclusion

Increase in human population has threatened habitats of wild species of both plants and animals. These habitats need to conserve *in situ* if the genes which gave rise to modern crops are to be preserved and allowed to evolve in tune with the changing environment for possible future use. Recent archaeobotanical evidence has shown that wild progenitors of crop plants could have been cultivated as a source of food even before being morphologically domesticated for agriculture. In India, important and unique nut trees over a wide range of genera have been studied, and utilized. Despite this, genetic erosion and loss of important genetic resources have been reported. It is very important to enhance the gene bank systems including exploration, inspection, preservation, evaluation, registration on database, and utilization for the improvement of nut trees. The collection and conservation of wild species related to major nut trees and local nut trees remains an urgent priority.

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Agrotourism: Emerging Concept of Farm Learning and Business Opportunity

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Abstract

Agrotourism has become a crucial element of numerous economies around the world. It has the potential to generate job opportunities for both unskilled and skilled workers. Agrotourism is an economic approach designed to help rural communities create alternative income sources while also preserving their cultural heritage. This form of tourism combines agricultural practices with recreational activities. The advantages of agrotourism are recognized by both urban and rural populations. Nonetheless, there are challenges in the development of these centres.

Keywords: Agrotourism, Agricultural Activities, Rural Populations.

Introduction

Agro-tourism is an emerging trend in travel where guests participate in farming activities to connect with rural lifestyles and gain insights into agricultural methods. This type of sustainable tourism supports farmers and rural areas while providing education about food production, caring for the environment, and local traditions. In India, which has a large farming community, it is essential for us to be educated about the agro-tourism industry. Natural schools act as open-door institutions that lack traditional brick walls, prompting us to pay close attention to them, uncover valuable insights, and learn something new every day. The absence of open schools and classes, as well as the prevalence of cartoons on television, sugary treats, beverages, tasty fast food, and computers, is leading urban children to disconnect from Mother Earth. Today's urban kids rarely even glimpse Mother Earth on their television screens. Furthermore, one-third of the urban population has no family ties to rural areas, and half of them have never visited or experienced life in villages.

Agro-Tourism Provides a Wide Variety of Activities That Cater to Individuals of All Ages and Interests

1. Farm stays: Guests can sleep overnight on an active farm, frequently engaging in daily activities such as milking cows or gathering eggs.
2. Pick-your-own (U-pick): Guests can pick their own fresh fruits and vegetables, including strawberries, apples, or various berries.
3. Farm-to-table dining: These culinary experiences include everything from cooking classes that utilize fresh ingredients to exquisite dinners served right on the farm.
4. Educational tours: Guided excursions educate visitors about farming methods, crop rotation, and eco-friendly practices.
5. For adult guests, numerous wineries and breweries provide tours along with tasting experiences.
6. Seasonal events and agricultural festivals frequently feature hayrides, corn mazes, petting zoos, and stalls showcasing local crafts.
7. Farms can provide opportunities for outdoor activities such as nature walks, fishing, horseback riding, or birdwatching.

Advantages of Agro-Tourism

For farmers and rural communities:

- 1. Income diversification:** Agro-tourism offers farmers an additional revenue source, decreasing their reliance on crop yields and fluctuations in the market.
- 2. Economic development:** By drawing visitors to rural regions, it generates jobs in areas such as hospitality, local food production, and handicrafts, thereby enhancing the local economy.
- 3. Cultural preservation:** It aids in maintaining traditional farming practices and indigenous knowledge by presenting local crafts, cuisine, and customs to tourists.
- 4. Empowerment:** It strengthens rural communities by providing job opportunities, particularly for women, and revitalizing community pride.

Challenges Encountered by the Industry

Despite experiencing growth, the agro-tourism sector confronts various challenges, especially in developing areas.

- 1. Inadequate infrastructure:** Numerous rural locations are missing essential roads, accommodations, and sanitation facilities crucial for a successful tourism sector.
- 2. Lack of awareness and marketing:** Many farmers and potential tourists are unfamiliar with the concept and its advantages. Additionally, farmers may struggle with the marketing expertise needed to draw in visitors.
- 3. Financial limitations:** The significant expense of initial investments, development, and upkeep, along with restricted access to credit and insurance, can dissuade farmers.
- 4. Shortage of labor:** Finding seasonal workers with skills in hospitality and food service can present a challenge for farmers.

Conclusion

The outlook for agro-tourism appears bright, fueled by a growing consumer interest in authentic, sustainable, and educational travel experiences. Digital involvement: Technology such as online reservation systems and social media will continue to be crucial for marketing and appealing to a broader audience. Advanced agriculture: AI and other agri-tech innovations could be incorporated into educational excursions, providing tourists with a deeper understanding of contemporary farming practices. Eco-friendly methods: A focus on sustainable and organic practices will draw in travelers who prioritize environmental consciousness, encouraging responsible consumption and production. Variety: Agro-tourism ventures are anticipated to present a wider range of unique experiences, including upscale farm lodgings and corporate retreats.

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Digital Fields: Genomic Selection and Artificial Intelligence in Plant Breeding

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The digital age has drastically changed plant breeding. The mounting challenges of climate change, population growth, and food security are forcing us to rethink how we develop the next generation of superior crop varieties using genomic selection (GS) in conjunction with artificial intelligence (AI) (Gaynor et al., 2017; and Fritsche-Neto et al., 2024). These data highlight a place in historical time that several researchers as represent the "Breeding 4.0" (Khan et al., 2022) stage, where computational energy and organic perception converge in a new, percent-driven, rapid, attentive way (Scholzel et al., 2023).

The Genomic Selection Revolution

In comparison to the traditional selection approach, which is based on phenotypic traits, GS utilizes densely spaced molecular markers spanning the entire genome to estimate breeding values which potentially improves the rate of genetic gain for variety development (Meuwissen et al., 2001; Bhat et al., 2016). Recent improvements in next-generation sequencing technology that allow rapid and cost-effective genotyping low-pass whole genomes in thousands of individuals simultaneously have fueled success of this approach (e.g., Spindel et al. 2015).

GS is powerful because it can catch the missing heritability that traditional marker-assisted selection typically fails to do (Bhat et al., 2016). Instead of limiting the analysis to a small number of "large-effect" genes, GS includes all markers across the genome to capture both major and minor genetic effects contributing to complex traits (Cuevas et al., 2025). So far, this integrative approach is especially beneficial for traits that are genetically complex and have economic importance, such as yield, quality, and stress tolerance (Ali et al., 2020; Peixoto et al. 2021)

Recent research shows striking success with a range of crop types. To illustrate, simulation studies have repeatedly demonstrated that genomic selection is more effective than phenotypic selection for traits such as yield, which have both low heritability and polygenic architecture, regardless the population size or number of cycles of selection (Gaynor et al., 2017; Muleta et al., 2019; Ali et al., 2020). These accuracies result in high genetic gains per unit time, in which genetic gains of breeding programs using GEBV are 0.5 to 6 times higher than those of phenotypic selection, mainly due the shortening of the breeding cycle length and the improvement of the selection accuracy (Fan et al., 2024; Fritsche-Neto et al., 2024).

AI-Powered Phenotyping: Beyond Human Perception

Another transformative development is the integration of AI in plant phenotyping. Abstract: High-throughput phenotyping (HTP) systems incorporating deep learning algorithms, computer vision, and automated imaging technologies are unlocking the phenotyping bottleneck that has constrained breeding progress for decades (Khan et al., 2022; Selvaraj et al., 2020). Such technologies allow for acquiring plant phenotypes at an unprecedented time and space resolution with quantitative traits that were difficult before to obtain, if at all (Khan et al., 2022).

Recent digital phenotyping platforms are now equipped with high-end sensors such as RGB cameras, hyperspectral imagers, thermal and LiDAR sensors (Araus et al., 2018). Such technologies measure plant features over the development stages of each plant, allowing researchers to quantify dynamic traits in a much more precise way with relatively less human intervention (Araus et al., 2018). The large volume of image datasets and deep learning models, rationally derive important biological information from such printed seeds with accuracies that are often higher than conventional methods based on manual expert assessments (Khan et al., 2022).



Figure: High-Throughput Phenotyping Using Aerial Platforms for Digital Crop Assessment

Recent applications show the power of current AI-based plant phenotyping. In cassava breeding programs, machine learning algorithms including k-Nearest Neighbors, Random Forest, and Support Vector Machines have reported root yield prediction accuracies of $R^2 = 0.67$, 0.66 , and 0.64 respectively (Selvaraj et al., 2020). Likewise, AI-assisted systems have been used for plant growth stages in wheat and maize (Liu et al., 2023), semantic segmentation of oilseed system crops and weeds (Zhang et al., 2022), and high-accuracy disease detection (Khan et al., 2022).

The Convergence: AI Meets Genomics

The real magic happens when AI collides with genomic selection. This integration tackles crucial problems of connecting genotype to phenotype, which empowers breeders to decipher the complex genetic-phenotypic relationships under various environments (Khan et al., 2022; Wang et al., 2023).

Advanced Prediction Models

Genomic prediction is being transformed by deep learning architectures. For instance, advanced neural network models outperform ridge regression only for certain aspects, although having improved capabilities of identifying individuals with high breeding value (Wang et al., 2023). Recent approaches are more sophisticated, using multi-omics data integrated so that they far outperform classical linear models, even in the presence of SNP data download, (Wang et al., 2023). Neural network architecture has also made significant strides over the years. Quickly advancing research has produced attention mechanisms pinpointing key genomic regions, ensemble methods paralleling assembly of multiple weak learners for better predictions, and transfer learning pathways employing learning from model organisms to assist with predictions for crop species that are less well-studied (Cheng & Wang 2024). Such advances allow prediction accuracies to approach theoretical maxima, with some studies reporting correlations greater than 0.90 for specific traits when conditions are optimal (Wang et al., 2023).

Automated Feature Engineering

Automated Feature Engineering — where machine learning is employed to identify and extract informative genetic markers from genomic datasets — is thus becoming one of the most important contributions of AI to genomics research (Cheng & Wang, 2024). Previous methods are based on human expertise that was slow and could be biased to relevant markers. Contemporary machine-learning methods have the capability to autonomously pinpoint SNPs that contribute maximum information for trait prediction, and the selected markers may overlap with the top-significant peaks detected through genome-wide association studies (Cheng & Wang, 2024).

Multi-Omics Integration

Integration of multi-omics data—Genomics, Transcriptomics, Proteomics, Metabolomics and Phenomics—might be at the cutting edge of AI-Powered breeding (Khan et al., 2022). Various machine learning algorithms can process such heterogeneous datasets, integrating different datasets and revealing important patterns that are inaccessible by conventional analytical and statistical methods (Cheng & Wang, 2024). In population-scale multi-omics analysis platforms, we combine dimensionality reduction

algorithms to alleviate the curse of dimensionality from the high-dimensionality of biological datasets (Cheng & Wang, 2024).

Environmental Integration and Climate Resilience

Plant breeding is a multifactorial system as climate change increases this complexity, so integration of environment is necessary to develop varieties (Khan et al., 2022). AI systems are robust and can evaluate and collate heterogeneous physical world data — weather data, soil data, imagery data, and climate data to anticipate genotype-by-environment relationships (Niazian et al., 2020).

With the systematic characterization of environmental conditions, envirotyping has become an essential aspect of contemporary breeding programs. AI algorithms dig through huge environmental datasets and pinpoint particular environmental occurrences which activate certain genetic responses, which then allow breeders to develop varieties that are better suited to particular climatic situations (Khan et al., 2022).

Current Applications and Success Stories

AI-powered genomic selection has been used across a number of crop species and breeding objectives. Genomic selection driven by AI has predicted the breeding values for traits such as yield, protein contents and disease resistance with prediction accuracies of 0.20–0.90 in wheat breeding (Bhat et al., 2016). Use of AI-assisted selection strategies in maize breeding programs is being translated to significant genetic gain, with up to 20 per cent greater yield in phenotyping trials in artificial environments (Farmonaut, 2025).

Digital technologies in particular have found good use in rice breeding. Genomic selection approaches via genotyping-by-sequencing data yielded prediction accuracies of 0.31–0.63 for grain yield and flowering time (Spindel et al., 2015). The integration of high-throughput phenotyping along with genomic prediction is allowing breeders to evaluate thousands of lines with great efficacy, currently decreasing the time for variety development to mere months (Khan et al., 2022).

Challenges and Limitations

However, even with impressive advancements, there are still many obstacles that prevent fully harnessing the potential of AI-based breeding. Data quality continues to be the most important— machine learning models are only as good as the data that trained them (Cheng & Wang 2024). Model performance can be greatly affected by inconsistent phenotyping protocols across different laboratories, environmental variability, and missing data (Van Dijk et al., 2021).

Many AI algorithms are a "black box", and this creates interpretability challenges. Although various deep learning models could lead to a high-level prediction accuracy, it is still hard to know why a certain prediction is made (Van Dijk et al., 2021). This restriction is actually troubling in breeding applications where comprehending the biological foundation of predictions can guide to tactical options (Cheng & Wang, 2024).

Along with those complications, population structure and genetic diversity also lie on another layer of issues over you have to keep data up to October 2023. Genomic prediction models show a limited performance which could lead to a worse accuracy when they are applied to a population far from the training samples (Bhat et al., 2016). Consequently, this challenge needs careful consideration of population stratification and the development of models that generalize across different genetic backgrounds (Cuevas et al., 2025).

Future Directions and Opportunities

Several applications are emerging that will drive the future of AI-enabled plant breeding. Federated learning approaches could allow institutions to jointly develop models while keeping data sensitive (Cheng & Wang, 2024). We have causal inference methods which is another exciting frontier for us. Traditional machine-learning research is mostly prediction-oriented but causal inference-based approaches attempt to clarify the biological processes behind the phenotypic variation (Cheng & Wang, 2024). However, combining these benefits with mechanistic insights makes causal inference more appealing for genomic prediction.

This may be a disruptive approach to how breeding operations are managed, but real-time decision support systems that fuse streaming sensor data with genomic information have potential to revolutionize breeding

operations (Khan et al., 2022). Such systems would monitor crop performance, environmental context, and genetic response over time to create real-time tailored recommendations for breeding choices.

One of the ways to further the development of this field is the creation of standardized evaluation frameworks and benchmarking datasets for a more competent and informative comparison across systems (Van Dijk et al., 2021). The lack of a common set of metrics and datasets prevents comparison of methods, and evaluation results depend on the set of text used. Community standards will accelerate methodological development and adoption.

Conclusion

The combination of artificial intelligence and genomic selection is radical change in plant breeding. Such a digital revolution allows for high accuracy in predicting and selection of complex traits, greatly decreasing the time and cost of variety development. These technologies provide us with high-impact interventions against the backdrop of humanity's agricultural challenges as we are some of the most stressful individualized risks that are being faced in the backdrop of increasing population and climate resilient crops.

The fusion of AI and genomics is not just a technological breakthrough, but a paradigmatic shift in our perception of biological systems. We are now ushering in an era of biology-based breeding decisions made possible by machine intelligence that can translate the non-linear interactions of genes, environment and phenotype into predictive models.

Continued teamwork among the computer scientists, geneticists, plant breeders as well as agronomists will be necessary to be successful in this digital age. With improvement in these technologies and shortage of current limitations, AI-enabled plant breeding will become a reality and will promote a new wave of agricultural productivity and sustainability.

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Precision Horticulture: The Future of Sustainable Farming in India's Fruit Crops

Article ID: 72230

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Introduction

Agriculture continues to be a critical pillar of India's economy, contributing close to 20% of the GDP and supporting over 41% of the population with employment. India cultivates nearly 139.4 million hectares of land with a cropping intensity of 141.6%, making it one of the world's largest agricultural producers. The Green Revolution of the 1960s marked a significant leap in food production, achieving self-sufficiency. However, this success brought challenges such as land degradation, inefficient use of resources, and stagnating productivity. Given these constraints and the increasing demand for sustainable food systems, precision horticulture has emerged as a promising solution to optimize productivity while conserving natural resources.

Precision Farming: Concept and Importance in India

Precision farming, also termed precision agriculture, integrates advanced technologies such as Global Positioning Systems (GPS), Geographic Information Systems (GIS), remote sensing, and Internet of Things (IoT) to monitor spatial and temporal variations within agricultural fields. This data-driven approach allows farmers to supply inputs like water, fertilizers, and pesticides in the right amounts, at the right locations, and at the right times. According to Robert (2022), precision farming is more than technology adoption; it represents a management revolution through enhanced information flow and site-specific interventions.

In the Indian context, characterized by small landholdings averaging 1–2 acres and heterogeneous soil and climatic conditions, precision horticulture enables integration of traditional knowledge with modern technologies. This alignment prevents resource wastage and improves the efficiency of input use based on crop-specific needs, soil health, and weather conditions.

Comparison of Precision and Traditional Farming Systems

Traditional Indian farming largely employed uniform input applications across fields, often overlooking field heterogeneity. Such practices have led to over-application of agrochemicals, increased input costs, and environmental pollution. Precision horticulture utilizes spatial databases and management zones customized to farm characteristics, enabling site-specific decision-making.

Aspect	Precision Horticulture	Traditional Farming
Management Scale	Sub-field/plant-level	Whole-field uniform application
Input Use	Data-driven, site-specific	Uniform application
Yield Potential	Maximized through optimization	Average, unpredictable
Sustainability	High – minimizes waste and pollution	Low – risk of degradation
Labor & Technology	Automated and sensor-based	Labor-intensive
Management Scale	Sub-field/plant-level	Whole-field uniform application

Marrying traditional farming wisdom with precision technology can improve input use efficiency and sustainability, addressing the drawbacks of conventional approaches (Jha., 2021).

Technological Pillars of Precision Horticulture

Precision horticulture is underpinned by three interrelated components: information, technology, and management.

Information: Captures spatial and temporal variability in soil fertility, crop health, pest incidence, terrain, and climate.

Technology: GPS and GIS enable geo-referenced mapping; drones and remote sensing provide multispectral imagery for crop monitoring; sensors track soil moisture, temperature, and nutrient levels. Variable Rate Technology (VRT) delivers inputs precisely based on data analytics.

Management: Raw data is translated into actionable decisions involving timely, site-specific irrigation, fertilization, and pest control measures.

These elements embrace the “Five R’s” of nutrient management: the Right source, Right place, Right time, Right amount, and Right manner (Shukla & Singh, 2023).

		
Drone-Based Crop Monitoring Image	Automated Fertigation System Photo	GPS Yield Mapping Visualization

Applications in Fruit Crop Production

Fruit orchards and plantations, due to their high economic value and intensive management requirements; stand to gain substantially from precision technologies:

Precision Irrigation: Soil moisture sensors integrated with drip and fertigation systems optimize water use efficiency. Studies show water savings of up to 40% in mango, banana, and grape crops without compromising yields.

Variable Fertilization: VRT allows for nutrient applications tailored to intra-orchard variability, reducing fertilizer use by 20–30%.

Disease and Pest Monitoring: Drone imaging using Normalized Difference Vegetation Index (NDVI) aids early detection of physiological stress and pest infestations, facilitating prompt management.

Yield Mapping: GPS and RFID technologies reveal yield variability within orchards, sometimes varying more than tenfold, guiding differential management zones to maximize production.

Protected Cultivation: Precision systems combined with greenhouses and tunnels enable controlled-environment farming for consistent quality and extended seasons.

The above methods support higher yield, improved fruit quality, and reduced input costs, ultimately enhancing grower profitability (Plant Science Advances, 2024).

Socio-Economic and Environmental Benefits

By optimizing resource use, precision horticulture drastically reduces input costs and exposure to environmental hazards such as chemical runoff and water wastage. Automation reduces labor dependency by 20–40%, critical given the shrinking rural workforce. Real-time data-driven decisions improve crop resilience to climatic variability. Precision farming not only supports economic sustainability but also safeguards soil and water quality, contributing to long-term agricultural sustainability (Zhang., 2022).

Moreover, the generation of spatial data enhances land value and facilitates on-farm research, including cultivar evaluation and management practice refinement.

Challenges for Adopting Precision Horticulture in India

Challenges hindering wide-scale adoption include:

1. Fragmented landholdings limiting economic feasibility of sophisticated equipment.

2. High initial capital costs for technology purchase and maintenance.
3. Lack of technical expertise and farmer training on precision systems.
4. Diverse cropping systems requiring adaptable solutions.
5. Policy gaps and inadequate institutional support.

Innovative models promoting cooperative equipment sharing, government subsidies, mobile-based advisory services, and farmer education programs are crucial to accelerating adoption (Halder *et al.*, 2024).

Future Directions

Advancements in Artificial Intelligence (AI), Machine Learning (ML), and enhanced IoT sensor networks promise to revolutionize predictive analytics and automated decision-making in horticulture. Autonomous machinery is set to reduce manual interventions further. Integration of multi-source data analytics will enable optimized harvest timing and market connectivity. Protected cultivation under precision frameworks will broaden crop portfolios and stabilize production under climate uncertainty.

Conclusion

Precision horticulture marks a pivotal advancement towards sustainable, profitable fruit crop production in India. By implementing data-driven, site-specific input management employing advanced technologies, it addresses key challenges of resource efficiency, environmental conservation, and yield enhancement. Supported by government incentives and cooperative strategies, precision horticulture promises to deliver the “Evergreen Revolution,” ensuring the resilience and prosperity of smallholder fruit growers. As technology becomes more accessible, its adoption will be integral to the future of Indian horticultural farming.

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Role of Plant Antimicrobial Peptides in Plant Disease Management

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Abstract

Plant microbiota involves interaction between host plants and taxonomically structured microbes. Plants are armed with sophisticated defense mechanisms to suppress the deleterious effect of disease-causing organisms. Naturally occurring antimicrobial peptides (AMPs), are one of the most common biochemical defensive barriers against invading pathogenic elicitors, thus forming a principal component of innate immunity system of plants. As global concerns over pesticide accumulation and environmental deterioration are rising, the exploration of AMPs for agricultural applications has gained momentum. Recombinant DNA techniques have enabled the incorporation of AMPs producing genes in crop modelling.

Keywords: antimicrobial, peptides, innate immunity, disease management.

Introduction

Host-pathogen interaction can manifest as either parasitic or mutualistic relationship. Plants possess advanced defense mechanisms to counteract the harmful effects of disease-causing organisms including fungi, bacteria, nematodes, protozoans, and insects [1]. Plants are known to produce several antimicrobial peptides (AMPs), which are a kind of biochemical defensive barrier against invading pathogenic elicitors, thus forming a principal component of the innate immunity system of plants. The first AMP ‘purothionin’ was discovered in 1942 from wheat endosperm. AMPs are positively charged, cystine-rich (4-12 residues), small polypeptides (12-50 amino acids) with molecular weight ranging from 2-10kDa [2]. The AMPs shows high stability to chemical, thermal and enzymatic degradation which is due to the formation of disulfide bonds. [3]. The presence of AMPs in all kind of life forms such as microbes, insects, animals and plants have been documented by various researchers. In plants, they have been reported from all the part throughout their life cycle [4]. The first AMP of plant origin was isolated from barley (*Hordeum vulgare*) endosperm [5]. The smallest known AMP was isolated from *Jatropha curcas*, comprising seven amino acids (Lys-Val-Phe-Leu-Gly-Leu-Lys) [6]. Plant AMPs are categorized according to their amino acid sequences and structures and divided into several families. The main families include thionins, plant defensins, hevein-like peptides, knottin-type peptides, α -hairpinins, lipid transfer proteins, snakins, and cyclotides [7]. AMPs synthesized by organisms other than the plants also offer a way to enhance plant resistance levels against pathogens. Synthetic AMPs can be designed by combinatorial chemistry. Recombinant DNA techniques have enabled the incorporation of genes producing AMPs in plants for making them tolerant to biotic stresses [8].

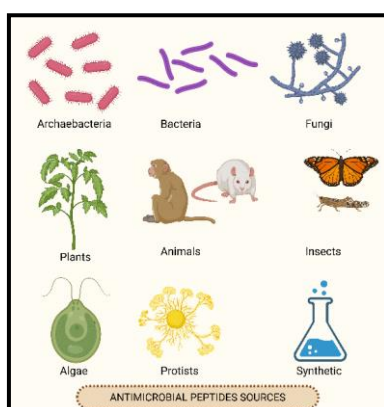


Figure 1: Sources of antimicrobial peptides

Mechanisms of Antimicrobial Activity of Plant AMPs

The diverse structural variability of AMPs and their versatile mechanism of action allows them to be effective against bacteria, fungi as well as viruses. AMPs possess both hydrophilic and hydrophobic domains, allowing them to be soluble in water as well as lipid-rich environments. They have binding affinity to the specific and nonspecific regions of receptors present on the target cell membrane. The interaction between cationic AMPs and lipid-rich anionic membranes of target pathogen results in increased membrane permeability which disturbs the cellular respiration, osmotic regulation, pH gradient and ultimately rapid cell death of the pathogen [9]. Antimicrobial peptides (AMPs) target the cell wall precursors containing lipid II, inducing membrane pore formation and disrupting the cell wall, unlike antibiotics which inhibit peptidoglycan biosynthesis [10]. The antimicrobial activity of AMPs depends on certain internal (net charge, hydrophobicity, amphipathicity, structural features and external factors (pH, temperature, metal ions) [7].

Why are AMPs Considered as Future Wave of Plant Disease Management?

1. Pathogens demonstrate limited capacity to develop resistance against AMPs, rendering them highly suitable for the development of plant disease resistance.
2. AMPs can usually target multiple sites.
3. AMPs show low toxicity to mammals.
4. Even low concentrations of AMPs are highly effective against multidrug resistant pathogens.
5. Apart from plant defence against pathogens AMPs also have housekeeping activities and play a significant role plant growth and development
6. AMPs are fairly safe to the off-targets and environment and can become an efficient alternative to chemical control measures.

Table 1: Some common plant antimicrobial peptides:

S. No.	Host plant	AMP	Class	Biological activity	Reference
1.	Potato (<i>Solanum tuberosum</i>)	Snakin-1	Snakins	Broad-spectrum antifungal and antibacterial	[11]
2.	Pea (<i>Pisum sativum</i>)	Psd2	Defensin	<i>Neurospora crassa</i>	[12]
3.	Maize (<i>Zea mays</i>)	MBP-1	MBP	<i>Fusarium graminearum</i>	[13]
4.	Alfalfa (<i>Medicago sativa</i>)	alfAFP	Defensin	Antifungal effect in transgenic potato	[14]
5.	Radish (<i>Raphanus sativus</i>)	Rs-AFP2	Defensin	Broad spectrum antifungal	[15]
6.	Chinese lima bean (<i>Phaseolus lunatus</i>)	Lunatusin	Defensin	Broad-spectrum antifungal and antibacterial	[16]
7.	Beans (Phaseolus <i>vulgaris</i>)	Vulgarinin	Defensin	Broad spectrum antifungal	[16]
8.	<i>Amaranthus hypochondriacus</i>	Ay-AMP	Hevein-like peptides	Broad spectrum antifungal	[17]
9.	Sorghum (<i>Sorghum bicolor</i>)	Sia2	Thionin	Inhibit gut α -amylase in locust and cockroach	[18]
10.	Rice	OsTHI7	Thionin	<i>Pythium graminicola</i>	[19]
11.	Wheat	β -purothionin	Thionin	<i>Pseudomonas syringae</i>	[20]

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Soil Erosion and Land Degradation India's Silent Environmental Crisis

Article ID: 72232

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Summary

Soil erosion and land degradation are major environmental issues in India, affecting around 30% of the country's land area and threatening agricultural productivity, biodiversity, and rural livelihoods. The main drivers include water and wind erosion, unsustainable agricultural practices, deforestation, and urban expansion. To combat this, India needs integrated monitoring, targeted restoration efforts, and community participation. Effective management strategies include watershed management, agroforestry, and conservation agriculture, requiring coordination across government agencies and financing mechanisms. Addressing land degradation is crucial for ensuring food security, ecosystem services, and sustainable development in India.

Introduction

Soils and landform the foundation of agricultural productivity, food systems, water regulation, and biodiversity conservation, providing vital provisioning, regulating, and cultural ecosystem services (FAO, 2015). In India, where population density, land-use intensity, and climatic variability are extremely high soil erosion and land degradation have emerged as serious environmental and socio-economic challenges (Bhattacharyya et al., 2015). Continuous loss of topsoil through water and wind erosion depletes essential nutrients, organic matter, and soil structure, reducing water-holding capacity and ultimately leading to declines in agricultural yields (Lal, 2019).

As degraded soils produce less for the same input levels, farmers often resort to increased fertilizer use, further disturbing the nutrient balance and accelerating degradation (Bhattacharyya et al., 2015). Beyond biophysical impacts, long-term loss of productive land imposes significant economic and social costs — including declining farm incomes, livelihood insecurity, rural out-migration, and worsening poverty in marginal and rainfed regions. Thus, the degradation of India's soil resources represents not only an ecological threat but also a pressing developmental and human welfare concern.

Definitions and Conceptual Framing

- 1. Soil erosion:** physical detachment and transport of soil particles by water, wind or gravity; leads to loss of fertile topsoil.
- 2. Land degradation:** long-term reduction in the capacity of land to provide ecosystem services, caused by biological, physical and chemical processes (erosion, salinization, acidity, nutrient depletion, loss of vegetation), often accelerated by human activities.
- 3. Desertification:** land degradation in drylands resulting from climatic variations and human activities. Contemporary assessments combine remote sensing, field surveys and socio-economic data to map degradation severity, processes and trends (SDG indicator 15.3.1 uses land cover change, land productivity dynamics and soil organic carbon as key measures).

Magnitude and Spatial Patterns in India

- 1. National extent (recent estimates):** Estimates vary with method and timeframe. Major, widely-used assessments include:
 - a. Desertification & Land Degradation Atlas (SAC-ISRO):** the Atlas (2018–19 timeframe) reports approximately 97.8 million hectares of land under degradation in India (~29.7% of the

country's geographic area). This product provides state-wise maps and 15-year change analysis based on IRS/AWiFS satellite data and expert interpretation.

b. Scientific syntheses and national surveys (e.g., NBSS&LUP, ICAR summaries) have historically produced a range of estimates — earlier studies reported degraded area values ranging from ~90 Mha to >140 Mha depending on definitions and methods; Bhattacharyya et al. (2015) synthesized multiple assessments and reported aggregated estimates (e.g., ~147 Mha under various forms of soil degradation when broader definitions were applied).

c. UNCCD data and dashboards indicate notable recent deterioration: UNCCD reporting and dashboard metrics show that ~30.51 million hectares of land were reported degraded across the 2015–2019 baseline period for India (dashboard reporting year 2019), highlighting rapid loss of healthy productive land in that interval.

2. Regional hotspots:

a. Arid and semiarid zones (Rajasthan, parts of Gujarat, Haryana): high risk of wind erosion, desertification and salinization.

b. Deccan plateau & central India (Maharashtra, Telangana, parts of Karnataka): pronounced water erosion due to intense monsoon runoff on degraded slopes, deforestation and intensive cultivation on marginal lands.

c. Himalayan and north-eastern hill states: landslides, slope erosion and vegetation loss aggravated by deforestation, road cutting and unplanned development.

d. Indo-Gangetic plains: localized salinization in irrigated pockets, loss of organic matter and compaction from intensive cropping and mechanization. State-wise maps in the SAC-ISRO atlas provide the most granular, nationally consistent delineation of these patterns.

Major Processes and Proximate Drivers

1. Water erosion: Water erosion is the predominant process nationally in terms of affected area and soil mass lost — intense monsoon rains, steep slopes, poor residue management, and the absence of contouring or terracing accelerate rill and gully formation and topsoil loss. Annual average soil loss estimates vary regionally; aggregated analyses have estimated average soil-loss rates tens of tonnes per hectare per year in badly degraded watersheds.

2. Wind erosion: Wind erosion is critical in arid and semi-arid tracts (Rajasthan, parts of Gujarat and Haryana). Removal of protective vegetation, over-grazing and exposed fallows increase susceptibility.

3. Chemical degradation: salinity, alkalinity, acidification: Irrigation mismanagement, poor drainage and secondary salinization affect irrigated lands (particularly in canal and groundwater-expanded regions). Acidification and nutrient imbalance (e.g., excessive nitrogen and limited organic inputs) reduce soil fertility in several zones.

4. Vegetation degradation and deforestation: Fuelwood extraction, expansion of agriculture into fragile lands, forest fires and unsustainable harvesting reduce vegetative cover and root structures that bind soil.

5. Mining, urbanization and infrastructure: Surface mining, quarrying, unplanned urban sprawl and road construction destabilize hillsides, cause topsoil stripping, and create large areas of non-productive land.

6. Socio-economic and institutional drivers: Land fragmentation, insecure tenure, short-term economic pressures, subsistence needs, inappropriate subsidies, and under-investment in soil-conserving technologies all push farmers toward practices that can accelerate degradation (excessive tillage, monocropping, over-extraction of groundwater).

Impacts: Ecological, Agronomic and Socio-Economic

1. Yield declines and nutrient loss: loss of topsoil, organic carbon and plant-available nutrients reduce yields and increase dependency on external inputs; several studies quantify large production losses attributable to erosion.

2. Water resource impacts: degraded landscapes show higher runoff, reduced infiltration and recharge, increased flood peaks and sedimentation of reservoirs and irrigation systems.

3. Biodiversity and carbon: land degradation reduces habitat quality, contributes to carbon losses from soils and impedes climate mitigation potential.

4. Rural livelihoods and migration: degraded land reduces on-farm incomes; loss of productive land contributes to distress migration to cities and non-farm jobs.

5. Economic costs: aggregated national estimates (vary by method) point to multi-billion-dollar annual losses when lost production, rehabilitation and ecosystem service losses are considered.

Measurement, Monitoring and Knowledge Gaps

1. Remote sensing & national atlases: Modern monitoring combines satellite imagery (IRS, Landsat, Sentinel), time-series analysis of vegetation productivity, and soil organic carbon proxies to produce SDG-relevant indicators. SAC-ISRO's Desertification & Land Degradation Atlas is a leading national product that provides spatially detailed maps and change analyses for policy makers.

2. Field data and harmonization: Field measurements of soil loss (plot and watershed scale), soil organic carbon, salinity, and agricultural productivity are essential to validate remote sensing. A persistent challenge is harmonizing definitions and methods across agencies so trend estimates are comparable (different national reports and academic studies use varied definitions of "degraded" land).

3. Socio-ecological data gaps: Fine-scale socio-economic data linking land degradation to household welfare, migration and adaptation choices are limited in many regions — this constrains targeted interventions.

National Policy, Programs and Institutional Responses

1. Policy frameworks:

a. National Action Programme (NAP) to Combat Desertification and Land Degradation: India's NAP (updated documents and implementation plans) outlines integrated land restoration through forestry, agroforestry and watershed approaches and aligns with UNCCD commitments.

b. International commitments: India engaged actively in UNCCD processes (e.g., COP-14 New Delhi), and reports SDG indicator 15.3.1 metrics via the UNCCD data platform.

2. Flagship programs and instruments: Various central and state programs contribute to addressing degradation (e.g., watershed development, afforestation/Green India missions, MGNREGA investments in soil and water conservation infrastructure). However, many of these programs require better targeting, long-term maintenance funding, and stronger community ownership to be fully effective.

3. Science-policy linkages: The ISRO/SAC atlases and NBSS&LUP surveys provide technical baselines for planning; newer initiatives emphasize Land Degradation Neutrality (LDN) targets and landscape restoration as part of national climate and development strategies.

Best-Practice Management and Restoration Approaches

Integrated, context-sensitive interventions are essential. Key, evidence-backed strategies include:

1. Conservation agriculture: reduced tillage, residue retention and crop rotations to protect soil structure and increase SOC.

2. Watershed management and micro-catchment approaches: check dams, contour bunding, gully plugging and re-vegetation to reduce runoff and promote recharge.

3. Agroforestry and perennial integration: trees in agricultural landscapes stabilize soils, improve carbon sequestration and diversify incomes.

4. Soil health management: integrated nutrient management, organic matter application (compost, biochar where appropriate), correction of salinity/alkalinity and improved drainage.

5. Grazing management and rangeland restoration: controlled stocking rates, rotational grazing and reseeding degraded pasturelands.

6. Targeted reclamation: saline/sodic land reclamation (chemical amendments, planting salt-tolerant species), mine-site rehabilitation and stabilisation of abandoned quarries.

7. Socio-institutional measures: tenure security, incentive realignment (to reward conservation), extension services and community participatory institutions (watershed committees, JFMCs). Many of these practices are already demonstrated at scale in India; success depends on finance, technical advisory services and long-term monitoring.

Financing, Governance and Scaling Challenges

1. Sustained financing: restoration and maintenance require multi-year investments — short funding cycles under many programs impede long-term success.

2. Coordination: land degradation intersects agriculture, forestry, water, mining and urban development — institutional siloing often hinders integrated action.

3. Monitoring & incentives: scaling requires rigorous measurement frameworks (SDG 15.3.1) and payments or incentives for restoration outcomes (e.g., PES, carbon finance).

4. Local capacity: technical capacity at district and panchayat levels to design and implement landscape restoration must be strengthened.

Research Priorities and Knowledge Gaps

Priority areas for research and operational learning in India include:

1. High-resolution mapping of degradation drivers and trajectories using multi-sensor remote sensing and machine learning.

2. Economic valuation of local, regional and national costs of degradation and benefits of restoration (to strengthen investment cases).

3. Longitudinal studies linking soil health, crop productivity and household welfare under different restoration interventions.

4. Scalable models for rehabilitating saline, acidic and mined lands with locally available amendments and species.

5. Monitoring frameworks integrating remote sensing, citizen science and field data for continuous assessment of restoration success.

Conclusion

Soil erosion and land degradation in India require urgent attention, given their impact on food security, climate resilience, and rural livelihoods. To reverse these trends, India needs accurate and harmonized monitoring with transparent reporting, targeted landscape-scale restoration that combines ecological and livelihood objectives, innovative financing mechanisms, institutional integration across ministries and levels, and meaningful community engagement and capacity building. With concerted action, it's possible to arrest and reverse land degradation, restore productive land, safeguard biodiversity, and strengthen climate resilience.

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Harnessing Digital Ecosystems for Enhanced Farmer Socioeconomic Resilience

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Summary

Digital ecosystems—integrated networks of digital infrastructure, platforms, data services, and actors—are rapidly transforming the agricultural landscape. When inclusively designed and effectively governed, these ecosystems enhance the socioeconomic resilience of farmers by expanding access to information, markets, financial instruments, and risk-management tools. They foster productivity growth, promote diversification, and strengthen social capital and adaptive capacity within farming communities. However, the benefits of digitalization are not evenly distributed. Persistent barriers such as limited connectivity, inadequate digital literacy, high costs, unequal power dynamics, and weak data-governance frameworks can exacerbate existing inequalities. This review explores how digital ecosystems influence farmer resilience, highlighting the technological and institutional components that drive transformation. It also examines potential challenges, synthesizes empirical lessons from global experiences, and proposes strategic policy and research directions to ensure that digital ecosystems contribute equitably to the livelihoods and sustainability of smallholder and family farmers.

Introduction

Resilience in farming communities refers to the capacity of farmers and their households to cope with, adapt to, and transform in response to shocks and stresses (climatic, market, health, political). Socioeconomic resilience emphasises livelihoods, incomes, access to markets and services, and social protection. Digital ecosystems comprising physical infrastructure (broadband, mobile networks), digital platforms (marketplaces, advisory platforms), data flows (sensors, satellite, administrative records), service providers (fintech, insurers, extension agents), and governance arrangements are rapidly reshaping agricultural value chains and rural livelihoods. This review examines how digital ecosystems affect farmer socioeconomic resilience: mechanisms of impact, evidence of outcomes, risks and inequalities, and policy/technical pathways to realize inclusive resilience gains.

Defining “Digital Ecosystems” in Agriculture

A “digital ecosystem” is an interdependent system of digital actors and components that create value through data exchange and platform-mediated interactions. In agriculture this includes:

1. Connectivity and hardware: mobile phones, IoT sensors, drones, edge devices and cloud infrastructure.
2. Data sources: remote sensing (satellite), farm sensors, farmer-entered data, market prices, weather and supply-chain traces.
3. Platforms & services: e-extension, digital marketplaces, input/advisory services, precision-agriculture analytics, traceability, and digital identity.
4. Financial & risk services: mobile-money, micro-insurance, input/credit delivery and pay-as-you-go models.
5. Institutions & governance: standards, interoperability protocols, data-rights, privacy frameworks, and public policies that shape market structure and inclusion.

This system view is crucial because effects on farmers are mediated by interactions among technical, commercial and institutional elements rather than by single tools in isolation (Wolfert et al., 2017; Klerkx et al., 2019).

Pathways from Digital Ecosystems to Farmer Socioeconomic Resilience

Digital ecosystems can strengthen resilience through multiple, interacting pathways:

1. Information and knowledge flows — timely weather, pest alerts, and market price information reduce uncertainty, enabling better decisions on planting, selling and postharvest actions. Mobile phones and SMS platforms have demonstrably reduced-price dispersion and waste in markets.
2. Market access and value-chain integration — digital marketplaces and traceability systems connect farmers to buyers, improve price discovery, and lower transaction costs, enabling diversification and higher returns.
3. Access to finance and risk management — mobile money, digital credit scoring, e-collateralization, and parametric insurance enable liquidity and buffer incomes against shocks, while new business models (e.g., pay-as-you-go inputs) lower up-front costs.
4. Productivity and efficiency gains — precision-agriculture analytics, irrigation and input optimisation from IoT and big-data analytics can raise yields and reduce input waste. Wolfert et al. (2017) synthesize evidence that big-data applications reach beyond production into supply chains, with potential productivity and sustainability gains.
5. Social capital and collective action — platforms can enable farmer groups, aggregation services, and peer learning, improving bargaining power and shared investments (e.g., equipment hiring).
6. Governance, safety nets and public services — digital IDs and registries can streamline targeting for subsidies and social protection, improving the ability to receive timely assistance after shocks.

These pathways interact: for example, better information increases uptake of credit and insurance; improved finance expands capacity to adopt productivity-enhancing tools.

Empirical Evidence and Case Examples

Evidence is growing but heterogeneous across regions, crops and farm scales.

1. Market efficiency via mobile phones: Aker & Mbiti (2010) document how mobile phones reduced price dispersion and improved market integration in African contexts, benefiting producers who could more easily access price information and reduce local market inefficiencies.
2. Big Data and precision farming: Wolfert et al. (2017) review technical applications—IoT, remote sensing, decision-support systems—and discuss socio-economic challenges such as data ownership and business models. They highlight that while large commercial farms capture many gains, smallholders face access barriers.
3. Digital innovations and resilience: Recent analyses (Finger et al., 2023; OECD 2022) show that digital innovations can improve sustainability and resilience, but require complementary investments (skills, regulation, infrastructure) and appropriate policy to avoid reinforcing inequalities. Empirical studies of digital ecosystems in LMICs (e.g., rapid assessments in Zambia/Kenya) show market platforms and fintech providing income opportunities but also reveal fragmentation, low interoperability and vendor lock-in risks.

Distributional Effects, Risks and Constraints

Digital ecosystems are not a panacea; they create winners and losers through the following mechanisms:

1. Digital divide: connectivity, smartphone ownership, and digital literacy are uneven within rural populations (by gender, age, landholding), which can exacerbate inequality.
2. Platform capture and power asymmetry: dominant platforms may extract value (data, commissions), set opaque prices or lock farmers into unfavourable terms.
3. Data governance and privacy: unclear ownership rights and weak regulation can lead to misuse of farmer data (profiling, discriminatory pricing). Wolfert et al. (2017) raise governance as a central socio-economic issue limiting broad benefit-sharing.
4. Interoperability & fragmentation: many siloed apps and pilot projects prevent scale; farmers bear switching costs.

5. Affordability and sustainability of business models: services dependent on subsidies or short grants may collapse, leaving farmers exposed.

Bias and exclusion: algorithmic decision systems (for credit-scoring or yield predictions) may be biased by historical data, disadvantaging marginalised groups.

Institutional & Policy Dimensions for Inclusive Resilience

Realizing resilience gains requires public policy and institutional design across several domains:

1. Connectivity & infrastructure — public–private investments to expand last-mile connectivity (including community networks and subsidised access in sparse areas).
2. Digital literacy & capacity building — extension services and community programs must build farmer skills to use and evaluate digital tools; gender-sensitive training is essential.
3. Data governance frameworks — clarify data ownership, consent, portability and privacy; promote open-data standards for public goods (e.g., weather, soil maps) while protecting personal data.
4. Interoperability & standards — incentivise APIs, common data schemas and modular services so farmers can combine services without vendor lock-in.
5. Inclusive business models & financing — support blended finance, public procurement and aggregation models that enable smallholders to benefit (e.g., cooperatives as digital intermediaries).
6. Regulation of platforms and competition policy — ensure market competitiveness, transparent pricing, and mechanisms for dispute resolution.
7. Linking digital ecosystems with social protection — use digital IDs and payment systems to deliver targeted safety nets and rapid disaster response.

OECD and FAO analyses stress that policy coherency across agriculture, telecoms and finance sectors is critical to avoid contradictory incentives and maximize resilience outcomes.

Design Principles for Farmer-Centric Digital Ecosystems

Based on empirical lessons and synthesis of the literature, the following design principles increase the likelihood that digital ecosystems boost socioeconomic resilience:

1. Farmer agency & co-design: involve farmers (especially women and marginal groups) in design and governance decisions.
2. Modularity and interoperability: design services that compose easily (marketplace + fintech + advisory) via open APIs.
3. Affordability & flexible payment: pay-as-you-go and micro-payments lower barriers.
4. Transparent data practices: clear consent, understandable terms, and data-sharing benefit architectures (e.g., farmer coops share revenue).
5. Local intermediaries & aggregation: support community aggregators/cooperatives to bridge digital and physical markets.
6. Sustainability & business viability: prioritize models that can survive beyond pilot funding—commercial pathways for scale combined with targeted public support where markets fail.

Measurement and Evaluation Approaches

To understand whether digital ecosystems strengthen resilience, rigorous mixed-methods evaluation is needed:

1. Outcome metrics: income volatility, yield stability, market prices received, uptake of credit/insurance, diversification indices, coping/adaptive behaviours, and welfare indicators.
2. Process metrics: platform usage patterns, equity of access (gender/distribution), data flows, and interoperability.

3. Causal identification: randomized trials, phased rollouts, and quasi-experimental designs (diff-in-diff, instrumental variables) to establish causal effects on resilience. Aker & Mbiti's empirical approach to market integration via mobile coverage provides a model for evaluating market effects.

4. Qualitative inquiry: user narratives, governance mapping, and power analyses to detect exclusionary effects and unintended harms.

Future Research Directions

Key research gaps in digital agriculture include the need for longitudinal studies on the impact of digital interventions on income volatility and adaptive capacity under climate shocks, as well as distributional analyses to track inclusion and exclusion dynamics among vulnerable groups like women, youth, and landless laborers. Other promising research areas include data governance experiments to compare models for equitable value capture, interoperability pilots to explore composable service architectures, and algorithmic fairness research to prevent structural bias in credit-scoring and advisory algorithms. Additionally, cost-benefit analyses of public investments in digital agriculture and studies on scaling pathways and business models for sustainable services that serve smallholders are crucial for advancing the field and ensuring that digital agriculture benefits all stakeholders.

Recommendations for Practitioners and Policymakers

To effectively promote digital agriculture, it's crucial to invest in last-mile connectivity and complementary digital literacy programs with measurable inclusion targets, ensuring that all farmers can access and utilize digital tools. Prioritizing interoperable, open standards and public data goods, such as weather, soil, and cadastral data, can lower costs for entrepreneurs and farmers, fostering innovation. Supporting farmer aggregation through cooperatives or producer organizations can improve bargaining power and enable bundled services. Clear, enforceable data-protection and data-ownership rules are essential to protect farmers' interests and enable data portability. Regulatory sandboxes can provide a safe space for innovation while monitoring for potential harms like price gouging and data misuse. Finally, blended finance and procurement mechanisms can help make early-stage services commercially viable for rural markets, driving growth and sustainability in digital agriculture.

Conclusion

Digital ecosystems hold significant promise for enhancing farmer socioeconomic resilience by reducing information asymmetries, expanding market access, enabling finance, and improving productivity. Yet their potential will only be realized if technical innovations are paired with robust governance, inclusive design, interoperable standards and targeted public investments. The literature (e.g., Aker & Mbiti 2010; Wolfert et al. 2017; Finger et al. 2023) emphasizes that technology alone cannot substitute for institutions: policy choices determine whether digitalization mitigates or exacerbates vulnerability. Thoughtfully governed digital ecosystems centered on farmer agency, equity and sustainability can help farming households better withstand shocks, adapt to change, and secure more stable livelihoods.

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Nanosilica: A Promising Tool for Mitigating Drought Stress in Crops

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Introduction

Drought stress is one of the most severe abiotic factors limiting agricultural productivity worldwide. Reduced water availability negatively affects plant growth, nutrient uptake, photosynthesis, and ultimately yield. With the increasing frequency of drought events under climate change, it has become necessary to explore innovative, sustainable solutions for improving plant resilience. Among these, the application of nanosilica (SiO₂ nanoparticles) has gained significant attention due to its unique physicochemical properties and enhanced efficiency compared to conventional silicon sources.

Role of Silicon in Plants

Silicon, though not classified as an essential element, is recognized as a beneficial element for many crops, particularly grasses like rice, wheat, and maize. Its major functions under drought stress include:

Structural reinforcement: Silicon accumulates in epidermal tissues, improving leaf rigidity and reducing transpiration losses.

Physiological regulation: Enhances stomatal regulation, maintains photosynthetic activity, and improves water use efficiency.

Biochemical defense: Reduces oxidative damage by enhancing antioxidant enzyme activities. **Nutrient management:** Facilitates uptake and distribution of essential nutrients even under water-limited conditions.

These functions collectively contribute to improved drought tolerance and crop performance.

Why Nanosilica?

The nanoscale size of silica particles (1–100 nm) provides distinct advantages over bulk silicon fertilizers:

1. Higher solubility and reactivity → better availability to plants.
2. Rapid uptake and translocation → efficient movement through xylem and phloem.
3. Lower dosage requirement → reduced application rates with greater impact.
4. Enhanced interaction with biomolecules → improved stress signalling and protective responses

Thus, nanosilica represents a more effective and sustainable option for silicon delivery.

Advantages of Nanosilica in Mitigating Drought

Stress Numerous studies have reported the beneficial effects of nanosilica on plants exposed to drought stress:

Improved photosynthetic efficiency – Maintains chlorophyll stability and delays leaf senescence. **Enhanced root development** – Promotes deeper root systems for better water acquisition.

1. Osmotic adjustment – Helps maintain higher relative water content and cell turgor.
2. Activation of antioxidant defense – Increases the activity of superoxide dismutase, Catalase, and peroxidases, thereby reducing oxidative stress.

Yield stabilization – Minimizes drought-induced yield losses in cereals, pulses, and vegetables. **Environmental sustainability** – As nanosilica can be synthesized from agricultural residues like rice husk, it supports circular economy practices.

Relevance and Future Perspectives

With global water scarcity expected to intensify, nanosilica provides a promising approach for enhancing crop resilience to drought. However, further research is required to:

Optimize concentration and mode of application (soil vs. foliar).

1. Understand long-term soil–plant–environment interactions.
2. Evaluate biosafety and potential ecological impacts.
3. Develop cost-effective production methods for large-scale use.

Conclusion

Nanosilica application represents a novel and sustainable strategy to mitigate drought stress in crops. By reinforcing structural, physiological, and biochemical processes, nanosilica enhances drought tolerance and contributes to stable agricultural production under water-limited conditions. Its dual advantage of efficiency at low doses and eco-friendly synthesis from agricultural waste positions nanosilica as a valuable input in climate-smart agriculture.

Quinoa: Your Next Nutrient-Dense Supergrain

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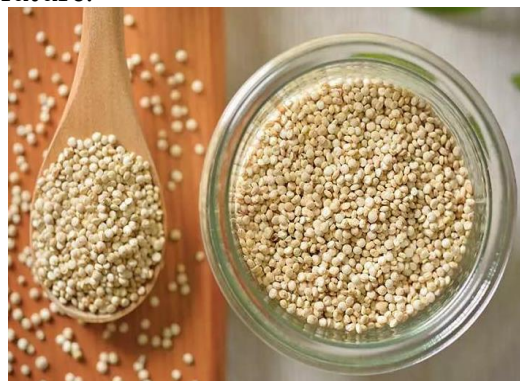
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Abstract

Quinoa (*Chenopodium quinoa willd.*), though technically a seed, functions as a whole grain pseudocereal, earning its title as a 'supergrain' due to its exceptional nutritional profile. It is one of the few plant foods that is a complete protein, containing all nine essential amino acids. Beyond protein, quinoa is rich in dietary fiber, essential minerals (like magnesium, iron, and zinc), and powerful antioxidants. This abstract highlights quinoa's multifaceted benefits, including its role in improving metabolic health, its suitability for gluten-free diets, and its remarkable climate resilience, positioning it as a key staple for sustainable nutrition in a changing world.

Introduction

Quinoa (*Chenopodium quinoa willd.*), often called a 'supergrain,' is an ancient food that has transitioned from a sacred staple of the Inca Empire to a globally recognized nutritional powerhouse. Despite its common use as a grain, quinoa is technically a pseudocereal a seed related to spinach and beets making it naturally gluten-free. Its rise to fame is justified by an exceptional nutrient profile: it is one of the very few plant-based foods that offers a complete protein, containing all nine essential amino acids necessary for human health. Beyond its high-quality protein, quinoa is an excellent source of dietary fiber, minerals like magnesium, iron, and zinc, and powerful antioxidants. This versatility and density of nutrition, coupled with the crop's remarkable resilience to harsh growing conditions, positions quinoa as a key player for not only enhancing modern health-conscious diets but also for promoting global food security. It truly is the nutrient-dense supergrain of the future.



Nutritional Composition

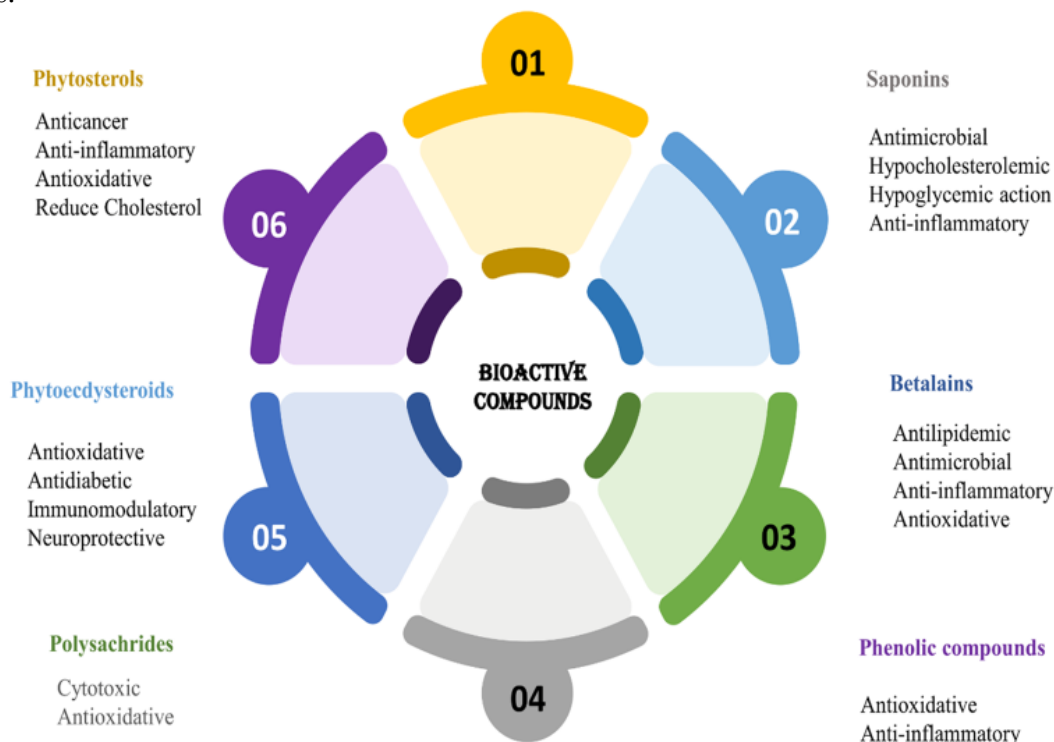
Recognized as a highly valuable food source for global health and food security, Quinoa provides an exceptional nutritional profile through its seeds (grains) and edible plant parts (leaves/sprouts). These components are rich in protein, essential amino acids, fiber, healthy fats, and minerals. Nevertheless, the precise levels of these nutrients are highly dependent on the cultivar, climate, and the specific section of the plant being analyzed.

Bioactive Compounds

Quinoa is rich in phenolics, flavonoids, and saponins, contributing to antioxidant, anti-inflammatory, and potential disease-preventing properties. Both grains and greens are gluten-free and suitable for celiac diets.

Variation by Variety, Color, and Environment

1. Protein, fiber, and mineral content vary widely among quinoa varieties and are influenced by genetic and environmental factors
2. Colored quinoa (black, red) often has higher fiber, phenolics, and antioxidant activity than white varieties
3. Leaves generally contain more protein and minerals than grains, while grains are higher in carbohydrates.



Macronutrient and Micronutrient Profile

Components	Grains (per 100g)	Greens (per 100g dry weight)	Feature and References
Carbohydrate	55 to 77g	Lower than grains	Main energy source Nowak, V., Du, J., & Charrondière, U. R. (2016).
Fat	4 to 8g	Lower than grains	Rich in unsaturated fatty acids Pathan, S., & Siddiqui, R. A. (2022).
Protein	9 to 21g (depends on variety)	>35g (leaves)	High-quality, complete protein (Gómez <i>et al.</i> 2021)
Dietary Fiber	8 to 23g	Higher in colored varieties	Supports digestive health (Arguello-Hernández <i>et al.</i> 2024)
Vitamins	B, E, folate	B, E, provitamin A, folate	Antioxidant and metabolic roles (Gaikwad <i>et al.</i> 2021)
Minerals	High in K, Mg, P, Fe, Zn	Higher in leaves	Essential for health (Villacrés <i>et al.</i> 2022)
Antinutrients	Saponins, oxalates	Saponins, nitrates, oxalates	Can be reduced by processing (Brito <i>et al.</i> 2022)

Key Benefits

1. **Complete Protein Source:** Quinoa is one of the few plant-based foods considered a complete protein, meaning it contains all nine essential amino acids that the human body cannot produce on its own. This makes it an excellent protein source for vegetarians, vegans, and athletes.

2. High in Antioxidants: Rich fiber aids digestion and heart health by promoting regularity and lowering LDL cholesterol. Its low glycemic index and mix of protein and fiber help effectively manage blood sugar.
3. Supports Weight Management: The combination of high protein and fiber promotes a feeling of fullness (satiety), which can help reduce overall calorie intake and support healthy weight loss or maintenance.
4. Naturally Gluten-Free: It is a safe and highly nutritious whole grain alternative for people with celiac disease or gluten sensitivity
5. Rich in Essential Micronutrients: It is an excellent source of several important vitamins and minerals, including:
6. Manganese: Essential for metabolism and antioxidant function.
7. Magnesium: Important for muscle and nerve function, blood pressure, and bone health.
8. Iron: Crucial for transporting oxygen in the blood.
9. Folate (Vitamin B9): Essential for cell function and tissue growth, particularly important during pregnancy.

Environmental and Agronomic Sustainability

Quinoa is highly adaptable to diverse and challenging environments, including drought, salinity, and poor soils, making it a strategic crop for climate change adaptation and land restoration (Dehghanian *et al.* 2024). Its cultivation requires relatively low water and can thrive with fewer inputs compared to many staple crops (Cui *et al.* 2024). Life cycle assessments show quinoa's global warming potential is lower than rice and animal-based foods, though excessive fertilizer use and mechanization can reduce eco-efficiency and increase environmental impacts (Lotfalian Dehkordi, A., & Forootan, M. 2020). Sustainable practices such as proper seed management, crop rotation, and reduced agrochemical use are essential to maintain soil health and biodiversity (Calizaya *et al.* 2023).

Quinoa's Contribution to Climate-Smart Farming

Quinoa is an ideal crop for areas struggling with climate change, as it thrives in a wide variety of harsh conditions, including drought, high salinity, heat, and poor soils. Its genetic diversity enables the development of new varieties specifically tailored for different environments, promoting successful adaptation globally from its native Andes to Africa, Asia, and Europe. Quinoa's proven ability to maintain yields and nutritional quality despite water and heat stress makes it a valuable addition to existing cropping systems for diversifying production and reducing risk.

Contribution	Details & Benefits	References
Stress Tolerance	Drought, salinity, heat, poor soils	Ruiz, K. E. F. (2013).
Sustainable Intensification	Low input, land restoration, reduced emissions	Dehghanian <i>et al.</i> (2024)
Food Security	High nutrition, stable yields, smallholder support	Kakabouki <i>et al.</i> (2021)

Conclusion

Rich in complete protein, fiber, and micronutrients, it significantly boosts human health (benefiting digestion, cardiovascular function, and blood sugar control). More importantly, its impressive resilience to challenging environments like drought, heat, and poor soil makes it essential for building climate-resilient agriculture and ensuring global food security. With the implementation of sustainable farming and fair trade policies, quinoa can both sustain human populations and strengthen agricultural systems globally.

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Underutilized Fruits of Northeast India: Hidden Treasures for Nutrition and Economy

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Introduction

Adequate nutrition for all remains one of the foremost priorities of developing nations, yet malnutrition continues to be a pervasive global challenge intricately associated with poverty and food insecurity. Malnutrition, defined as a physiological condition resulting from an imbalanced diet wherein essential nutrients are deficient or consumed in inappropriate proportions, affects approximately one in every three individuals worldwide. In India, the prevalence of malnutrition is particularly alarming, with more than one-third of the world's malnourished children residing in the country. The Global Hunger Index (2017) ranked India 100th among 119 nations, and it is estimated that nearly half of the country's children are undernourished—about 43% of children under five are underweight and 48% are stunted (IFPRI, 2016). Such statistics underscore the urgency to address malnutrition and ensure equitable access to adequate and balanced nutrition.

Food security, as defined by the Food and Agriculture Organization (FAO, 2002), ensures that all people, at all times, have physical, social, and economic access to sufficient, safe, and nutritious food that meets their dietary needs and preferences for an active and healthy life. In the Indian context, food and nutritional security are the cornerstone of national food policy, where conserving and utilizing available food and natural resources must take precedence. With rising health awareness, consumers are now shifting away from chemically processed foods toward organic and naturally derived sources of nutrition. Within this paradigm, fruits and vegetables occupy an indispensable role as they provide essential vitamins, minerals, fibers, carbohydrates, organic acids, and bioactive compounds that sustain human health. Regular consumption of fruits has been scientifically linked to reduced incidence of chronic ailments such as cardiovascular diseases and cancer (Hall et al., 2009), whereas inadequate intake contributes to nutritional imbalances and associated disorders.

Underutilized edible crops, especially fruit species, have historically served as vital nutritional resources since the dawn of civilization. Despite their abundance and cultural significance, many of these fruits have received minimal scientific attention and remain neglected in commercial agriculture. These underutilized fruits are rich in carbohydrates, proteins, fats, vitamins, minerals, and fibers (Narzary et al., 2013), and valuable phytochemicals such as flavonoids, phenolics, carotenoids, and antioxidants (Deshmukh and Waghmode, 2011). They are also deeply embedded in traditional medicine systems like Ayurveda and Unani, where they have been used for their healing and curative properties. Consequently, underutilized fruits can play a pivotal role in mitigating malnutrition, combating hidden hunger, and addressing micronutrient deficiencies in vulnerable populations.

Jaenicke and Hoshle-Zeledon (2006) defined underutilized crop species as those representing an enormous wealth of agro-biodiversity with potential contributions to food security, nutrition, health, income generation, and ecological sustainability. These fruit species are often found growing wild in forests and home gardens with minimal care. They are rarely cultivated commercially, poorly documented, and largely unknown beyond local communities. Despite their limited market presence, their nutritional and economic potential remains untapped.

In India, around 800 underutilized edible crop species have been identified, of which nearly 300 are predominantly used by indigenous and tribal populations of the North-Eastern Region (Nath et al., 2013). The North-East, comprising Arunachal Pradesh, Assam, Manipur, Meghalaya, Mizoram, Nagaland,

Tripura, and Sikkim, represents a major part of the Indo–Myanmar biodiversity hotspot, one of the 25 global biodiversity hotspots (Myers et al., 2000). Owing to its diverse agro-climatic conditions, rich forest cover, and high rainfall, the region provides an ideal habitat for the evolution and distribution of numerous wild and underutilized fruit species (Rymbai et al., 2016). These fruits are integral to the traditional diets and livelihoods of several tribal communities, who have preserved knowledge on their harvesting, processing, and medicinal uses. Beyond their cultural and economic importance, many of these fruits possess potent antioxidant and therapeutic properties, contributing to immunity enhancement and disease prevention (DeFelice, 1996).

Garcinia morella (Gaertn.) Desr.

Family: Clusiaceae

Common name: Indian Gamboge

Vernacular name: Kuji-thekera (Assamese)

Garcinia morella (Gaertn.) Desr., commonly known as Indian gamboge, is an evergreen, medium-sized tree attaining a height of up to 18 meters. The species exudes a characteristic deep yellow, sticky latex upon injury. Leaves are simple, opposite, and elliptic to obovate in shape, measuring approximately 10–15 cm in length and 4–8 cm in breadth. The midrib is distinctly prominent, while the lateral veins are slightly raised, imparting a leathery texture to the lamina.

The species exhibits a polygamous floral condition, bearing both male and hermaphroditic flowers. The flowers are tetramerous, with the male flowers typically arranged in clusters within the axils of fallen leaves, whereas the hermaphroditic flowers are solitary. The fruit is sub-globose to globose, turning bright yellow upon ripening, and contains four seeds that are ovoid-reniform, laterally compressed, and dark brown in color.

Spondias cytherea Sonn.

Family: Anacardiaceae

Common Name: Ambarella / Golden Apple

Vernacular Name: Amra (Bangla)

Description: *Spondias cytherea* is a fast-growing, deciduous tree that typically reaches a height of 9–12 meters, exhibiting an erect and sturdy growth habit. The leaves are pinnate, ranging from 20–60 cm in length, and comprise 9–25 glossy, elliptic to obovate-oblong leaflets with finely serrated margins near the apex.

The species produces small, whitish, inconspicuous flowers arranged in large terminal panicles. The fruits develop on long peduncles, occurring in clusters of a dozen or more, and are oval to irregularly knobby in shape. The flesh of the immature fruit is crisp, juicy, and sub-acidic, making it suitable for pickles and salads. Upon ripening, the pulp turns golden-yellow, becoming fibrous due to the presence of prominent fibres radiating from the woody, five-celled stone that encloses 1–5 flattened seeds.

Ficus semicordata Buch.

Family: Moraceae

Common Name: Drooping Fig

Vernacular Name: Tapang (Adi)

Description: *Ficus semicordata* is a small to medium-sized deciduous tree, attaining a height of up to 15 meters, characterized by a spreading, irregular crown. The trunk measures up to 2 meters in circumference and typically lacks aerial roots. The leaves are elliptic to oblong-lanceolate, with a distinctly unequal base where the larger lobe overlaps the petiole. Branches are pendulous, often extending prostrate along the ground, giving the tree its characteristic drooping appearance. The syconia (figs) are spherical to pyriform, measuring 1.2–2 cm in diameter, and exhibit a pink to dull reddish-brown coloration with white speckles and fine pubescence. The fruits are borne on leafless branches and serve as a valuable food source for both wildlife and local communities.

Flacourtia jangomas Lour.

Family: Salicaceae

Common Name: Governor's Plum / Indian Coffee Plum

Vernacular Name: Poniol (Assamese)

Description:

Flacourtia jangomas is a small, evergreen tree notable for the presence of compound spines along its trunk. The leaves are alternate, spirally arranged, deciduous, and exhibit long, finely serrated apices. The species is dioecious, producing axillary racemose inflorescences that measure 1.0–2.0 cm in female plants and 1.5–3.0 cm in male plants. The flowers are white to greenish, with 4–5 ovate-triangular petals that emit a subtle, honey-like fragrance. Male flowers are glabrous, solitary or clustered, while female flowers are solitary. The fruit is an ellipsoid to sub-globose berry, 1.5–2.5 cm in diameter, exhibiting a purplish exterior with greenish-yellow pulp that encases 5–10 flattened seeds. The fruits retain persistent stigmatic remnants at maturity.

Myrica nagi Thunb.

Family: Myricaceae

Common Name: Box Myrtle

Vernacular Name: Sohpie Nam (Khasi)

Description: Myrica nagi is an evergreen, dioecious tree reaching 12–15 meters in height, with a spreading growth habit. The leaves are concentrated toward the distal ends of branches, lanceolate, measuring 8–9 cm in length and 2.5–3.5 cm in breadth, with a dark green adaxial surface and a pale green abaxial surface. Pistillate flowers are very small, sessile, solitary, and subtended by bracts. The male catkin inflorescence is compound, 3–3.5 cm long, and bears approximately 20–25 flowers. The fruit is an ellipsoid to ovoid drupe, cherry-sized, tuberculate, and turns reddish upon ripening. The fruits have a limited shelf life, and the seeds are light green, ridged, and enclosed within the pulp.

		
<i>Garcinia morella</i>	<i>Spondias cytherea</i>	<i>Ficus semicordata</i>
		
<i>Flacourtia jangomas</i>	<i>Myrica nagi</i>	

Nutritional and Medicinal Value

Underutilized fruits of North-East India are rich in vitamins, minerals, dietary fibers, and bioactive compounds such as flavonoids, phenolics, and antioxidants, contributing to antioxidant, anti-inflammatory, and immunity-boosting effects.

Fruit	Key Nutrients	Traditional / Medicinal Uses	Economic Potential
<i>Garcinia morella</i>	Vitamin C, fiber	Used in treating dysentery, gastritis, fatigue, boils, burning sensations, and dizziness. The dried pulp is used as a home remedy for stomach ailments and inflammatory disorders	Latex, juice, dye, and medicinal products
<i>Spondias cytherea</i>	Vitamin C, potassium	Used in treating wounds, sore throats, mouth infections, cataracts, dysentery, coughs, fever, and stomach pain	Fresh fruit, jams, juice
<i>Ficus semicordata</i>	Vitamin A, calcium	Used in treating jaundice, stomach disorders, wounds, scabies, leprosy, indigestion, liver ailments, and skin diseases	Fresh fruit, wildlife food
<i>Flacourtia jangomas</i>	Vitamin C, iron	Used in treating diarrhea, diabetes, blood purification, fever, and digestive problems.	Juice, jams, nutraceuticals
<i>Myrica nagi</i>	Vitamin C, calcium	Used in treating fever, cold, hemorrhage, leucorrhea, intestinal disorders, asthma, bronchitis, teeth, wounds, and ulcers.	Medicinal extracts, local consumption

Ethnobotanical and Medicinal Uses

Indigenous communities in North-East India have long relied on these fruits for both nutrition and traditional medicine. For example:

1. *Garcinia morella* latex is used as an antimicrobial agent, and its fruit pulp for digestive health.
2. *Spondias cytherea* fruits are consumed raw, pickled, or processed into jams to improve appetite and digestion.
3. *Ficus semicordata* figs are a source of natural tonic, improving immunity and serving as wildlife fodder.
4. *Flacourtia jangomas* fruits are used to treat digestive ailments, diabetes, and hypertension.
5. *Myrica nagi* drupes are used in managing gastric disorders and skin ailments in traditional medicine systems.
6. Economic and Livelihood Potential
7. The commercialization of underutilized fruits presents significant opportunities for income generation in rural and tribal communities:
8. Fresh consumption: Many fruits can be sold locally or in regional markets.
9. Value addition: Fruits can be processed into juices, jams, pickles, dried products, or nutraceutical formulations.
10. Agroforestry integration: Cultivation in home gardens and orchards ensures continuous availability and biodiversity conservation.
11. Cultural tourism and specialty products: Local festivals and markets can promote underutilized fruits as part of a heritage-based economy.

Conclusion

Underutilized fruits of North-East India are nutrient-rich, containing vitamins, minerals, fibers, and bioactive compounds with significant health-promoting and medicinal properties. Deeply embedded in traditional ethnomedicine, they offer cost-effective remedies while also supporting nutrition security.

Despite their potential, limited awareness, short shelf life, and lack of market infrastructure hinder their widespread use. Sustainable cultivation, value addition, and community engagement can enhance their role in rural livelihoods, biodiversity conservation, and dietary diversification. Harnessing these fruits can thus transform them into powerful tools for health, economy, and sustainable development.

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Vermicompost and Biofertilizers: A Boon for Vegetable Farming

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Introduction

Vegetable farming plays a vital role in providing nutritional security and livelihood to millions of farmers in India. However, the indiscriminate use of chemical fertilizers has led to soil degradation, reduced microbial activity, and decline in crop quality. In this context, organic inputs like vermicompost and biofertilizers have emerged as eco-friendly alternatives that not only enhance soil fertility but also improve vegetable yield and quality.

Vermicompost: Black Gold Farming

Vermicompost is an organic manure produced by earthworms through the breakdown of organic waste. It is rich in macro- and micro-nutrients, plant growth-promoting hormones (auxins, gibberellins, cytokinin's), and beneficial microbes.

Benefits in Vegetable Farming

1. Improves soil structure, aeration, and water-holding capacity.
2. Supplies readily available nutrients (N, P, K, Ca, Mg, micronutrients).
3. Enhances germination, flowering, and fruiting in crops like tomato, brinjal, okra, and chilli.
4. Reduces dependence on chemical fertilizers.
5. Promotes sustainable soil health.

Biofertilizers: Living Fertilizers

Biofertilizers are preparations containing beneficial microorganisms that promote nutrient availability in the soil. Commonly used biofertilizers in vegetable farming include:

1. Rhizobium – fixes atmospheric nitrogen in leguminous vegetables like beans and peas.
2. Azotobacter & Azospirillum – non-symbiotic nitrogen fixers for solanaceous and cucurbit crops.
3. Phosphate-Solubilizing Bacteria (PSB) – release phosphorus from insoluble forms.
4. Trichoderma & Pseudomonas – act as bio-control agents against soil-borne diseases.
5. Mycorrhizal fungi – improve nutrient absorption, especially phosphorus and micronutrients.

Benefits in Vegetable Farming

1. Reduce chemical fertilizer requirement by 25–50%.
2. Enhance root development and nutrient uptake.
3. Increase resistance against diseases and abiotic stresses.
4. Improve vegetable quality in terms of taste, aroma, and nutrient content.

Effects of Vermicompost and Biofertilizers on Soil Health

1. Improvement in Soil Physical Properties:

- a. Vermicompost enhances soil aggregation, porosity, and aeration, which promotes better root penetration in vegetable crops.
- b. Increases water-holding capacity, reducing the need for frequent irrigation in sandy soils.
- c. Helps in reclaiming degraded and compacted soils.

2. Enrichment of soil chemical properties:

- a. Supplies a balanced proportion of macro- (N, P, K) and micronutrients (Zn, Fe, Mn, Cu) in available form.
- b. Increases cation exchange capacity (CEC) of the soil, improving nutrient retention.
- c. Enhances soil buffering capacity, preventing pH fluctuations.
- d. Reduces dependency on synthetic fertilizers, thus minimizing soil toxicity.

3. Boost in soil biological properties:

- a. Vermicompost is rich in beneficial microbes like *Azotobacter*, *Rhizobium*, *Actinomycetes*, and *Trichoderma*, which support nutrient cycling.
- b. Biofertilizers inoculate the soil with specialized microorganisms that fix nitrogen, solubilize phosphorus, and mobilize potassium.
- c. Application of *Trichoderma* and *Pseudomonas* through biofertilizers suppresses soil-borne pathogens, improving soil health and reducing pesticide use.
- d. Stimulates microbial biomass and enzyme activities such as dehydrogenase, urease, and phosphatase, which are indicators of soil health.

4. Soil organic carbon enhancement:

- a. Vermicompost increases the organic carbon content of soil, which is the backbone of soil fertility.
- b. Higher soil organic carbon improves nutrient availability and promotes sustainable soil fertility.
- c. Biofertilizers accelerate the decomposition of organic matter and stabilize soil organic carbon pools.

5. Restoration of soil ecosystem:

- a. Improves soil biodiversity by enhancing populations of earthworms, beneficial nematodes, and microbes.
- b. Reduces soil salinity and heavy metal toxicity by binding and immobilizing harmful ions.
- c. Promotes ecological balance in the rhizosphere, ensuring healthier vegetable production systems.

Synergistic Role of Vermicompost and Biofertilizers

When used together, vermicompost and biofertilizers complement each other: Vermicompost improves soil conditions and provides organic matter, which supports microbial growth. Biofertilizers enhance nutrient mobilization, which works effectively in the organic-rich environment created by vermicompost. The integrated use results in higher yield, better quality, and long-term soil fertility.

Conclusion

Vermicompost and biofertilizers represent a sustainable, eco-friendly, and cost-effective solution for vegetable farming. Their combined application acts as a soil conditioner, nutrient reservoir, and microbial stimulator, ultimately restoring degraded soils and making them more productive and resilient. It improves soil fertility, enhances crop productivity, and ensures safe, nutritious food for consumers. Promoting their use is a step toward achieving sustainable agriculture, healthy soils, and healthier lives.

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Heat Unit Concept of Crop Maturity

Article ID: 72238

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Abstract

The heat-unit system also known as growing degree days (GDD) involving the sum of daily mean temperatures above a given base temperature, is used with processing pea (*Pisum sativum* L.) to predict relative maturity during the growing season and to schedule planting dates based on average temperature data. It quantifies the accumulated thermal time required for a crop to transition through its growth stages. This approach integrates daily temperature variations, using a base temperature threshold specific to each crop. By considering base temperatures and daily variations, it predicts growth stages and maturity. This framework is vital for optimizing planting schedules, harvesting time, forecasting yields, and resource allocation in agricultural and horticultural crops, ensuring efficient crop management and enhanced agricultural productivity.

Keywords- Heat unit, Growing degree days, Temperature.

Introduction

Crop growth and development are mainly influenced by environmental factors. The **heat unit concept**, also known as **growing degree days (GDD)**, serves as a scientific approach to measure and quantify the effect of temperature on crop growth and development. It calculates the cumulative thermal energy required for crops to progress through different morphological stages, such as germination, vegetative growth, flowering and maturity. Each crop has a specific base temperature, below which no growth occurs. By addition of the daily differences between the average temperature and the base temperature, the concept provides a effective way to predict the timing of critical growth stages. This method is particularly valuable for improving planting schedules, optimizing resource allocation, and forecasting crop yields. It also helps farmers and agronomists manage agricultural practices more efficiently by ensuring crops are harvested at optimal maturity.

The heat unit concept has broad applications in modern agriculture, including pest and disease management, selection of crop varieties, and adaptation to climate change. However, the method does have certain limitations, such as variability in base temperatures among crops and the influence of non-temperature factors like photoperiod and soil moisture. Despite these challenges, the heat unit concept remains a widely accepted and practical tool in agronomy. It provides a robust framework for enhancing crop productivity and sustainability in a rapidly changing agricultural landscape.

Reported Base Temperatures for GDD Computations

Base Temperatures for Crops:

Base Temp	Crop
40° F	wheat, barley, rye, oats, flaxseed, lettuce, asparagus
45° F	sunflower, potato
50° F	sweet corn, corn, sorghum, rice, soybeans, tomato

Base Temperatures for Insects:

Base Temp	Insect
44° F	Corn Rootworm
48° F	Alfalfa Weevil
50° F	Black Cutworm, European Corn Borer

52° F

Green Cloverworm

What are Heat Units?

Heat unit is a daily estimate of the amount of contributory heat that will contribute to growth and development.

A proper thermal environment is essential to the survival of all biological organisms. The thermal environment is especially critical to “cold-blooded” organisms such as plants and insects because their internal temperature is dictated by the surrounding environment. If the outer temperature exceeds some upper limit or declines below some lower limit, growth and development of “cool-blooded” organism are impaired or halted. However, when these organisms are exposed to temperature within some optimal range, growth and development typically increase with temperature.

Growing Degree Days

Growing Degree Days (GDD) are used to estimate the growth and development of plants and insects during the growing season. The basic concept is that development will only occur if the temperature exceeds some minimum development threshold, or base temperature (T_{BASE}). The base temperatures are determined experimentally and are different for each organism.

Procedure to Calculate GDDs

1. First find the mean temperature for the day. The mean temperature is found by adding together the high and low temperature for the day and dividing by two.
2. If the mean temperature is at or below T_{BASE} , then the Growing Degree Day value is zero.
3. If the mean temperature is above T_{BASE} , then the Growing Degree Day amount equals the mean temperature minus T_{BASE} .
4. For example, if the mean temperature was 75° F, then the GDD amount equals 10 for a T_{BASE} of 65° F.

In equation form:

$$GDD = T_{MEAN} - T_{BASE}, \text{ if } T_{MEAN} \text{ is greater than } T_{BASE}$$

$$GDD = 0, \text{ if } T_{MEAN} \text{ is less than } T_{BASE}$$

Where:

$$T_{BASE} = \text{Growing Degree Day base temperature}$$

$$T_{MEAN} = \text{mean temperature, } (T_{MAX} + T_{MIN}) / 2.$$

Growing Degree Units (GDUs): are accumulated by adding each day’s GDs contribution as the season progresses.

Crop Heat Units (CHUs): Crop specific indices that employ separate equations for the influence of the daily minimum (nighttime) and the maximum (daytime) temperatures on growth are called crop heat units.

Daily crop heat units are calculated by using the average of the two daily values from the equation.

Calculating Daily CHU

The following equation is used to calculate a daily CHU for a site:

$$\text{Daily CHU} = (Y_{max} + Y_{min}) \div 2$$

where:

$$Y_{max} = (3.33 \times (T_{max} - 10)) - (0.084 \times (T_{max} - 10)^2) \text{ (If values are negative, set to 0)}$$

Heat unit efficiency (HUE) or thermal time use efficiency (TTUE) - amount of dry matter produced per unit of thermal time or growing degree day. It is expressed in $gm^* day^{-1} ^\circ C$.

$$HUE = \frac{\text{Dry matter production (g/m}^2\text{)}}{\text{Growing degree day base temperature of cotton}}$$

Baseline temperature:

- a. Base Temperature (T_{BASE}): The base temperature is that temperature below which plant growth is zero.

b. Baselines: 10 °C is the most common base for GDD calculations, however, the optimal base is often determined experimentally based on the lifecycle of the plant or insect.

GDDs may be calculated using either Celsius or Fahrenheit:

5.5 °C: wheat, barley, rye, oats, flaxseed, lettuce, asparagus
6 °C: Stalk Borer
7 °C: Corn rootworm
8 °C: sunflower, potato
9 °C: Alfalfa weevil
10 °C: Maize, sorghum, rice, soybeans, tomato, Black cutworm, European Corn Borer, Coffee, insect and mite pests of woody plants
11 °C: Green Clover worm
12 °C: many other crop calculations

Significance

Heat Units on physiological process: The heat units or thermal time are involved in the physiological process of plants. The specific amount of heat units required for the plant at each stage from its germination to harvest of the crop would vary and the important processes are listed below:

1. Growth and development
2. Growth parameters
3. Nitrification
4. Biomass
5. Physiological maturity
6. Yield.

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Sustainable Pest and Disease Management through Botanicals in Vegetables

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Introduction

Botanicals are plant-derived extracts or preparations, such as oils, powders, meals, or decoctions, obtained from fresh or dried plants or their parts. These formulations influence pest and disease management as well as crop growth. They are primarily composed of secondary metabolites synthesized by plants as defense mechanisms, many of which exhibit toxicity to insect pests. Such botanicals, also referred to as botanical pesticides or plant-based pesticides, are increasingly recognized as eco-friendly alternatives to synthetic chemicals. Typically, they are extracted from various plants or plant parts and used directly for controlling insects and other agricultural pests. Examples include neem (*Azadirachta indica*, source of azadirachtin), pyrethrum (derived from chrysanthemum flowers), essential oils (eucalyptus, clove), and spice extracts (garlic, chilli). In vegetable crop production, the most widely applied botanicals include neem oil or leaves, pyrethrum, pongamia extract, garlic extract, jojoba oil, cinnamon extract, Ecogold, Alata soap, exotic garlic, papaya leaves, and wood ash, particularly in crops such as okra and eggplant.

Unlike synthetic pesticides, botanicals generally degrade more rapidly in the environment and, when properly prepared and applied, pose minimal risk to consumers and non-target organisms. Each botanical pesticide possesses a distinct mode of action, functioning as natural bioactive products with activity against bacteria, fungi, nematodes, viruses, and insect pests, while typically sparing beneficial insects. Their major advantages include environmental safety, reduced toxicity, and cost-effectiveness compared to synthetic chemicals.

Phytochemical investigations have reported a diverse range of bioactive compounds in several plant families, including Myrtaceae, Lauraceae, Rutaceae, Lamiaceae, Asteraceae, Apiaceae, Cupressaceae, Poaceae, Zingiberaceae, Piperaceae, Liliaceae, Apocynaceae, Solanaceae, Caesalpinaceae, and Sapotaceae. These compounds exhibit multiple biological activities such as insect growth regulation, antifeedant properties, and antifungal effects. Notable examples include pyrethrins from *Tanacetum cinerariifolium*, parthenin from *Parthenium hysterophorus*, azadirachtin from *Azadirachta indica*, and bioactive constituents of garlic (*Allium sativum*), turmeric (*Curcuma longa*), rosemary (*Rosmarinus officinalis*), ginger (*Zingiber officinale*), and thyme (*Thymus vulgaris*). Limonoids from *Khaya ivorensis* have been shown to possess antifungal activity, while azadirachtin analogues such as Aza-A and Tetrahydro Aza-A exhibit strong insect growth regulatory and antifeedant effects against *Helicoverpa armigera*.

Need of Botanicals

Botanical pesticides are increasingly regarded as environmentally safer alternatives to synthetic agrochemicals. They are characterized by novel modes of action, chemical diversity, and a rich reservoir of biologically active compounds. Despite their demonstrated potential, large areas of botanical research remain unexplored, particularly with respect to their chemically complex structures and stereoisomeric variations, which contribute to reduced resistance development in pests. Beyond their role in agriculture, several botanical compounds have also exhibited promising pharmacological activities.

At present, botanicals are emerging as an integral component of Integrated Pest Management (IPM) programs across diverse cropping systems. Their adoption is attributed to multiple advantages, including:

1. High efficacy in managing a wide range of pests,
2. Eco-friendly nature and cost-effectiveness,

3. Environmental compatibility and safety for public health,
4. Abundant sources of bioactive natural compounds, and
5. Significant utility in organic and sustainable farming systems.

Botanical Pesticide Used in Different Vegetable Crops to Minimize Pest

Botanical used	Amount	Beneficial crop	Target
Neem Seed	5kg/ 30%	Brinjal /Okra	Whitefly, jassid ,Thrips / Aphids
Garlic extract	30%	Cucumber	Root-Knot nematode
Chrysanthemum Dry flower	500 g	Cabbage	Aphids

Impact of Botanical Pesticides on Environment

Botanical pesticides are environmentally friendly, biodegradable, and leave minimal residues. They are generally target-specific and safe for beneficial organisms such as pollinators, predators, and parasitoids. Moreover, they do not interfere with the growth and activity of natural enemies of pests, thereby reducing the need for repeated pesticide applications.

Conclusion

Botanical insecticides are naturally occurring plant-derived compounds with insecticidal properties and represent an excellent alternative to synthetic pesticides for sustainable crop protection. Unlike conventional chemicals, they possess diverse bioactive constituents and exhibit multiple modes of action, including repellency, feeding deterrence (antifeedant effects), toxicity, growth regulation, chemo sterilization, and attraction. Commonly used botanical insecticides, such as pyrethrum, neem, and nicotine, have demonstrated effectiveness against a wide spectrum of pests while minimizing risks to the environment and human health. Their eco-friendly nature and compatibility with organic farming systems make them especially valuable for modern agricultural practices. Consequently, botanical insecticides are increasingly recognized by organic crop producers in industrialized nations. It is therefore recommended to promote their wider use and to intensify research efforts aimed at identifying new botanical sources and improving their formulations for effective pest management.

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Hive Shield – Honeybee Defense Behaviour

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Abstract

Honeybees, like eusocial insects, rely on a well-coordinated defense system to protect their colonies from predators and pathogens. Their strategies include behavioral defenses, chemical defense using pheromones, physical defense with a sting and immune defense. Together these defenses form a highly effective shield for the hive. Guard bees play a major role in hive protection. Predators like wax moth, hornet, ants, rats, and lizards are also defended by honeybees.

Keywords: Colony, defense, guard bees, honey bees, predators

Introduction

Honeybees are eusocial insects as they live in socially structured colonies. Honeybees use multiple defense mechanisms, including behavioral, chemical, and physical defenses against predators and pathogens. Bee behaviour highlights a blend of cooperation, flexibility and structured organization reflecting the sophistication of their highly evolved social system.

Key behavioral defenses include guard bees initiating an alert and recruiting nestmates via alarm pheromones, and hygienic behaviors like grooming and removing infested brood to combat parasites. Chemical defenses involve releasing alarm pheromones to signal threats and, for direct attacks, the venom released from the sting. Physically, they can sting, and though it often results in the bee's death (autotomy), it delivers venom and the sting can continue to pump venom even after the bee has detached.

Colony Defense

Colony defense activity is one of the important behaviour of bees. A bee colony consists of one queen, drones, workers, brood, food such as honey and pollen and all these resources needed to be guarded by natural enemies by defending them through various mechanisms and behaviour. The bees that are involved in defending and guarding the beehive are called guard bees.

Honeybees are structured into discrete castes according to the principle of temporal polyethism such that bees of different ages take up different roles in the group. In the defensive activity, the colony depends on using two main castes of bees namely guard bees and soldier/stingers.

Various Types of Defenses in Honeybees

1. Behavioral and chemical defenses:

a. Guard bees: These are the first line of defense, triggering an alert posture, wing buzzing, and releasing alarm pheromones to recruit other bees.

b. Alarm pheromones: These chemicals are released by the sting apparatus and serve as an alarm to trigger an aggressive response from other bees. When a potential threat is detected, alarm pheromones are released by individual bees, especially during the process of guarding or when stinging. The alarm pheromones can be placed directly onto an intruder and thus the conspecifics can detect the host and focus their offensive attacks on the marked one.

c. Hygienic behavior: Hygienic behaviour involves specific workers of the colony removing and disposing of brood that is diseased or infested with parasites, like the Varroa mite.

d. Grooming: Grooming in bees is a vital behavioral defense mechanism and self-maintenance activity in which individual bees use their legs and mouthparts to remove ectoparasites (like *Varroa* mites), pollen, dust, and other debris from their bodies. This behavior is essential for both individual and colony health. Some bees groom mites off of other adult bees.

2. Physical defenses:

- a. Stinging:** A primary method for individual defense, where worker bee injects venom using a barbed stinger when danger exists.
- b. Sting autotomy:** The sting is often left behind in the target, and the venom apparatus continues to pump venom after the bee has flown away.
- c. Collective defense:** When a large predator is detected, the defensive response is escalated by the alarm pheromone, leading to a mass attack.

3. Immune defenses:

- a. Innate immune response:** Honeybees have an immune system that includes mechanisms like producing antimicrobial peptides, phagocytosis (cells engulfing pathogens), and melanization (a process of encapsulating pathogens).
- b. RNA interference (RNAi):** This is a key antiviral defense, although some viruses can suppress this pathway, making the bee more vulnerable.
- c. Physical barriers:** The cuticle and the gut epithelium act as physical barriers to block pathogens.

Defensive Behaviour and Intruders Detection in Guard Bees

Bees that are neither foragers nor nest workers but are younger than foragers, also called guarding entails a unique behavior. The process of behavior guarding begins on the seventh to the twenty-second days of adult life, which represent the age range of about two to three weeks.

At the openings of their colonies guard bees are continually seen in a stereotyped pose, with their forelegs raised and antennae frontal, and wings spread out ready to attack any hostile intruders who may have ventured into the nest. Guard bees can recognize their nestmates and non-nestmates using chemical cues, i.e. certain alkenes that are released by nestmates. The intruders are attacked with rigorous force and physically evicted through the entrance whereas the robber bees are also spotted and silenced by the guards.

Anti-Predator Adaptations in Bees

The guard bees show a stereotypic behaviour in the presence of ant invaders: at the first arrival of the ants guard bees first put an end to the contact with them, and then drive them out of the colony by fluttering their wings with the frequency of 275 Hz. To protect from Varroa mite they exhibit grooming and hygienic behaviour. Wax moth larva is bitten and pulled off away from the nest and intruding small beetles are also removed by bees.

When hornet enters the hive, the bees form a huge mass at the entrance of the hive and interlock their bodies to provide a protective cover known as carpet. They make attempts of seizing the hornet with their forelegs and mandibles, and when the hornet was successfully captured, it is trapped inside a dense ball of bees.



Fig.1 Dense bee ball defending hornet

When bees confront bigger predators like rats, lizards or birds, guard bees move into the hive abdomen upraised, and jut out their stingers as they fend off the attack with the help of their wings. These behaviors warn the nestmates of the threat about to happen and stimulate the discharge of alarm pheromones.

Conclusion

The defense mechanisms of honeybees represent a complex and well-coordinated system essential for colony survival. Honeybees utilize an integrated defense system involving behavioral, chemical, and physical strategies to protect their colony. These mechanisms, coordinated through social communication and collective action, are essential for colony survival and highlight the advanced social structure of honeybee communities.

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From Farm to Fork: How AI is Cutting the Food Supply Chain's Carbon Footprint

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From Farm to Fork: How AI is Cutting the Food Supply Chain's Carbon Footprint

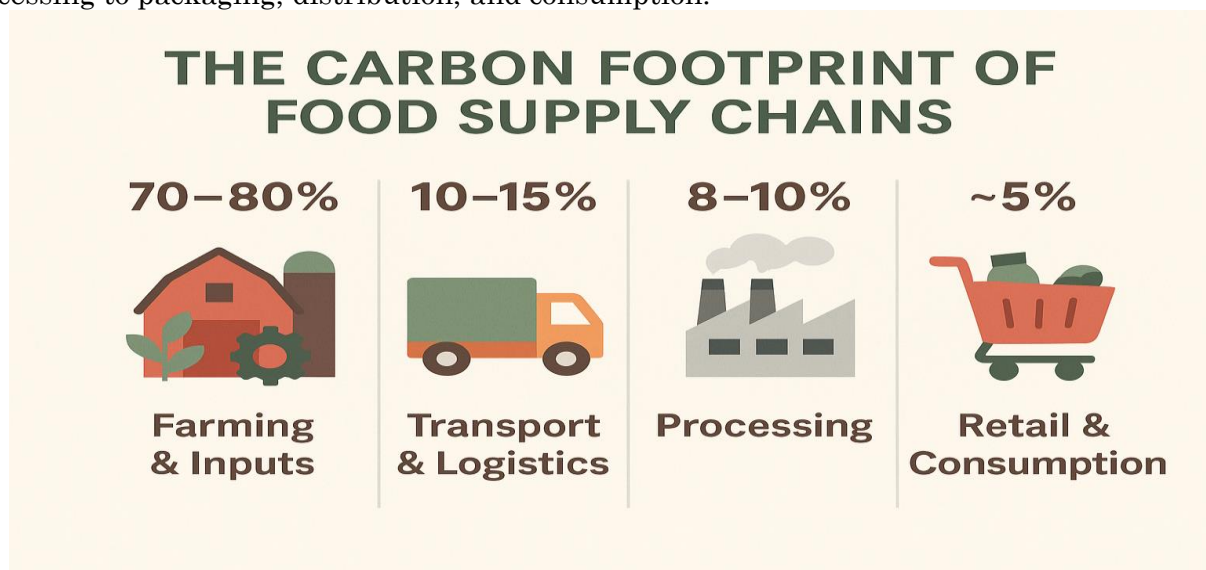
"One-third of all human-caused greenhouse gas emissions comes from the food we grow, transport, and eat."

Summary

The food system is a major contributor to climate change, accounting for one-third of all human-caused greenhouse gas (GHG) emissions. However, the journey from farm to fork is becoming greener thanks to the innovative application of Artificial Intelligence (AI). AI is tackling the substantial environmental impact of food production and delivery by optimizing farming, logistics, and processing, leading to a significant reduction in overall emissions.

Introduction: The Carbon Challenge of the Food System

The production, transportation, and consumption of food contribute significantly to global greenhouse gas (GHG) emissions. Every stage of the food supply chain adds to the overall carbon footprint — from farming and processing to packaging, distribution, and consumption.



The carbon footprint of the food supply chain is dominated by a few key stages:

- 1. Farming & Inputs:** This phase, which includes fertilizer-intensive fields, accounts for the vast majority of emissions—70–80%. Overusing resources like water and fertilizer not only wastes them but also releases potent GHGs.
- 2. Transport & Logistics:** This stage contributes 10–15% of emissions. While often blamed, transport's contribution is relatively small, especially for high-impact foods like beef, where it's only about 0.5%.
- 3. Processing:** This adds another 8–10%.

This substantial environmental impact means that what we choose to eat is one of the most powerful tools available to combat climate change, making the deployment of technologies like AI critical.

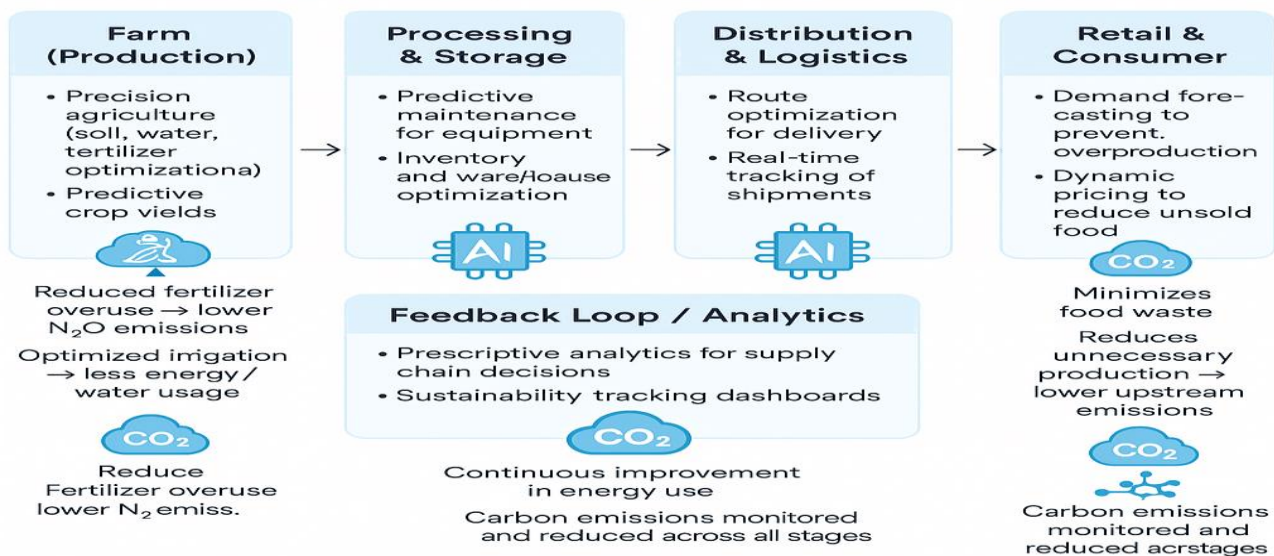
The Highest-Impact Foods: Not all foods contribute equally to greenhouse gas emissions. A landmark study revealed a striking disparity between different food types. **Beef from beef herds** produces the highest emissions—about **60 kg of CO₂-equivalent per kilogram of meat**—followed by **lamb and mutton (24 kg)** and **beef from dairy herds (21 kg)**. Cheese has a similar footprint of **21 kg**, while

chocolate (19 kg) and **coffee (17 kg)** also rank among high-impact foods. **Farmed prawns** generate around **12 kg**, and **palm oil** about **8 kg** per kilogram produced. In contrast, lower-emission foods include **pig meat (7 kg)**, **poultry meat (6 kg)**, **eggs (4.5 kg)**, and **rice (4 kg)**. Animal-based foods clearly dominate emissions, with **beef from beef herds** producing nearly **2.5 times more GHGs than lamb**. Most plant-based foods have a substantially lower carbon footprint, with **chocolate** being a notable exception at **19 kg**. This data underscores that **high-impact foods like beef drive the majority of emissions regardless of transport distance**, challenging the popular notion that eating locally produced food alone can significantly reduce climate impacts.

AI's Impact Across the Food Supply Chain

Artificial Intelligence is being implemented across the entire food supply chain, from the field to the consumer, to enhance efficiency and dramatically cut carbon emissions.

AI-Driven Food Supply Chain: Reducing Carbon Footprint from Farm to Fork



AI drives Precision Agriculture to tackle the major emission sources at the farm level.

1. Resource Optimization: AI leverages satellite imagery, weather data, and soil sensors to provide farmers with guidance on the exact amount of water and fertilizer required for each crop. This prevents the overuse of resources, which is responsible for releasing potent GHGs.

2. Real-World Success: In India, AI-driven approaches have successfully reduced both water and fertilizer use by 20–30%, leading to lower emissions and more efficient resource management.

3. Measuring Impact: Life Cycle Assessments (LCA) show that AI-driven agriculture can reduce GHG emissions by up to 25% while simultaneously boosting crop yields by up to 30%. Forecasts in India indicate a steady decline in carbon footprints from 2019 to 2030 due to this adoption.

Intelligent Logistics and Processing

AI is applied to transport and processing to optimize operations and reduce energy consumption.

1. Route and Maintenance Optimization: In logistics, AI plans fuel-efficient routes and predicts maintenance needs for vehicles. This prevents spoilage and can cut refrigeration energy use by up to 15%.

2. Inventory Management: In processing and storage, AI performs predictive maintenance for equipment and optimizes inventory and warehouse use.

Tackling Food Waste

AI helps tackle **food waste**, responsible for one-third of global food production and 8–10% of emissions. By enabling **demand forecasting** and **dynamic pricing**, it ensures inventory matches consumption and products are sold before expiry, reducing both waste and upstream emissions.

A Holistic Approach: Diet and Green AI

Transitioning to a sustainable food system requires both **technological innovation** and **behavioral change**. **Plant-based diets** play a key role—replacing even one weekly serving of beef with a plant-based option can save tens of kilograms of CO₂ annually. However, **AI itself has a carbon footprint**, with large model training and digital infrastructure contributing 330 million tons of CO₂. **Green AI** addresses this by using renewable energy and energy-efficient algorithms to ensure sustainability without creating new environmental costs.

Conclusion: A Smarter, Greener Future

AI is fundamentally transforming the food supply chain into a more climate-resilient system. By enabling precision farming, driving optimized logistics, and ensuring smart inventory management to reduce waste, AI provides the intelligence needed to drastically cut the food system's enormous carbon footprint. The combination of these technological breakthroughs and the growing consumer adoption of lower-impact, plant-based diets suggests a promising, greener future for the journey from farm to fork.

The ability of AI and supercomputing to provide high-resolution, national-scale predictions of agricultural GHG emissions is a critical step toward developing credible monitoring and verification of these emissions. This capability will further empower stakeholders to track progress and make data-driven decisions for a sustainable food system.

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Digital Footprints: From Your Online Life to Your Farm Fields

Article ID: 72242

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Summary

Digital footprints are no longer limited to our online activities—they have extended into agriculture. Just as individuals leave traces through their digital interactions, farmers now generate vast amounts of data through sensors, drones, and smart farming technologies. This digitalization footprint helps improve productivity, sustainability, and financial decision-making, but also raises challenges related to cost, data privacy, and accessibility. Managing these footprints wisely is key to building both a digitally empowered and environmentally sustainable future.

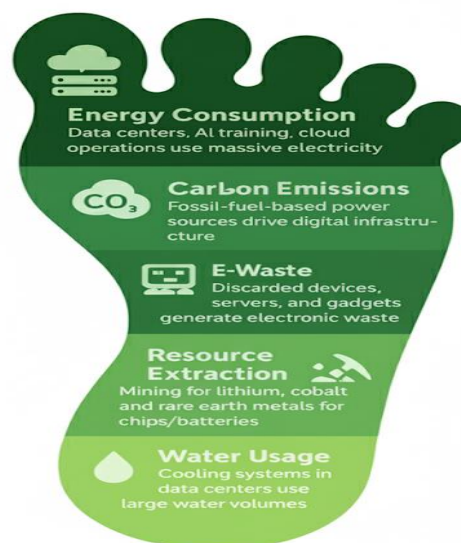
Introduction

When we think of digital footprints, we usually imagine our online lives—the websites we browse, the messages we send, and the posts we share. Each click leaves a mark, building our digital identity and, at times, exposing us to unseen risks. But the story doesn't end there. Beyond screens and social media, digital footprints have taken root in our **fields and farms**. Today's agriculture hums with technology—drones mapping crops, sensors tracking soil, satellites scanning skies, and software guiding every move. Together, these tools create a powerful **digitalization footprint**—evidence of how data is reshaping the way we grow food and transforming farming into a truly digital ecosystem.

A study of a 22-hectare corn field in Italy illustrates this evolution vividly. Between 2004 and 2020, the farm's data storage needs grew from less than 11 MB to over 18.5 GB, with projections suggesting it could exceed 40 GB by 2025. Much like personal digital activity, farm data also accumulates in layers—weather, soil, crop performance, drone imagery, and machinery data—where drone images account for the largest share, similar to how social media dominates personal digital footprints.

Digital Footprint in Agriculture

DIGITALIZATION FOOTPRINT



Green Digital Future



A study of a 22-hectare corn field in Italy tracked data collected between 2004 and 2020. Farmers used sensors, drones, satellites, and software to monitor crops, soil, machinery, and weather. The results were striking:

1. In 2004, the farm's digital footprint was less than 11 MB.
2. By 2020, it had grown to over 18.5 GB, with projections suggesting it could reach 40 GB by 2025.

Like personal online activity, farm data accumulates in layers such as weather, soil, crop, drone imagery, and machinery data. Among these, drone images dominate storage needs, similar to how social media dominates personal digital footprints.

Benefits of Agricultural Digital Footprints

The digital footprint in farming brings many advantages:

- 1. Enhanced productivity and efficiency:** Precision agriculture uses data to apply water, fertilizer, and pesticides only where needed, boosting yields and reducing waste. Predictive analytics powered by AI can forecast weather, crop performance, and disease outbreaks.
- 2. Improved sustainability:** Smart data use reduces overapplication of resources, protects soil health, minimizes environmental runoff, and supports biodiversity. Access to real-time climate insights also strengthens resilience to changing weather patterns.
- 3. Better financial management:** Digital record-keeping creates centralized farm dashboards that inform decisions about crops, resources, and markets. It helps cut costs, ensures regulatory compliance, and even supports access to credit and insurance.
- 4. Supply chain and market access:** Digital tools enable traceability, building consumer trust, and allow direct-to-consumer sales through e-commerce platforms, improving farmer profits.

Active and Passive Digitalization in Farming

Like personal footprints, agricultural data can be active or passive. Active digitalization occurs when farmers deliberately collect data, such as drone images, soil analyses, or yield logs. Passive digitalization happens when sensors, satellites, or automated software record data without direct input from the farmer. Recognizing both forms helps farmers manage their data more effectively.

Challenges in Managing the Digitalization Footprint

Despite the clear advantages, challenges remain:

1. The cost of advanced technologies like drones, sensors, and software is high, especially for small-scale farmers.
2. Limited internet connectivity and low digital literacy in rural areas restrict adoption.
3. Data ownership and privacy concerns make farmers cautious about cloud storage and sharing sensitive information.
4. The complexity of tools and lack of technical support can make it difficult to fully implement digital farming solutions.

The Takeaway

Digital footprints now extend beyond online activity to agriculture, driving smarter, more sustainable, and productive practices. Yet, they also require responsible management of cost, security, and environmental impact to truly support a sustainable future.

Conclusion

Digital footprints have grown from clicks and screens to crops and soil. Today, agriculture's digitalization footprint stands as both a symbol of innovation and accountability. When used wisely, farm data can fuel productivity, sustainability, and resilience—turning information into growth. Yet, realizing this promise depends on overcoming key hurdles in access, cost, and data governance, ensuring that technology truly cultivates a smarter, greener future.

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Feeding 9 Billion: The Role of Statistics, Agriculture, and Forests

Article ID: 72243

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Summary

By 2050, feeding 9 billion people will challenge food security, land use, and the environment. While agriculture occupies over a third of Earth's land, forest cover has declined 17% since 1850. Studies show that future food demand can be met without deforestation through higher yields, dietary shifts, reduced waste, and smarter land use. Integrating forests, precision agriculture, and data-driven planning can ensure food security while protecting biodiversity and climate stability.

Introduction: The Global Food Security Challenge

Feeding **nine billion people** by **2050** requires nearly **doubling global food production**, which, without **sustainable management**, could threaten **forests**, **biodiversity**, and **carbon sinks**. **Agriculture** already occupies over a third of the Earth's **land**, with **cropland** and **pastures** having expanded significantly at the expense of **forests**. **Forests** are vital to **food systems**, providing **wild foods**, **ecosystem services**, and supporting **resilient, nutritious diets**. Protecting them is essential for both **environmental health** and **sustainable agriculture**. **Sustainable intensification**, **precision farming**, and **technological innovations** can increase **yields** without further **deforestation**. **Policy measures** and **dietary shifts** are also crucial to reduce pressure on **land**. **Coordinated global action** is needed to balance **food security** with **ecological conservation**.

Forests and Food Security

Forests are no longer just "land banks" for agriculture; they are essential for **food security**. They provide **wild foods**, **fruits**, **nuts**, **bushmeat**, and **micronutrients**, while offering **ecosystem services** like **pollination**, **water regulation**, **soil protection**, and **carbon storage** that support productivity. Communities near forests enjoy more **diverse, nutritious diets**, and **agroforestry** helps stabilize yields, enhance **climate resilience**, and conserve **biodiversity**. Integrating forests into food systems is therefore crucial for **sustainable nutrition**, **ecological health**, and **climate mitigation**.

Agriculture–Forest Trade-Offs

1. Nearly two-thirds of future food production can be achieved without deforestation if sustainable measures are adopted.
2. Key levers include higher yields, dietary shifts (less livestock consumption), and expanding cropland into pastures rather than forests.
3. Policy limits: Yield growth alone may reduce land expansion, but market forces, trade, and biofuel demand constrain its impact.
4. Tropical forest clearing offers minimal food gains but causes large GHG emissions; combining productivity, conservation, and demand-side measures is more effective.
5. Rising biofuel demand could add 25% more cropland by 2050, often at the expense of forests and grasslands.

Climate and Environmental Impacts

Land-use change contributes **10–15% of global greenhouse gas emissions** and accounts for roughly **40% of radiative forcing**. Agriculture already pushes the Earth beyond **planetary boundaries** for land and freshwater. Unchecked expansion would compromise forests' role as **carbon sinks**, exacerbate climate change, and lead to **soil degradation**, **biodiversity loss**, and **altered hydrological cycles**. Modeling

indicates that combining **REDD+ incentives, carbon credits, sustainable intensification, and demand-side measures** (diet shifts, waste reduction) can meet food demand while minimizing deforestation. Restoration of degraded lands, agroforestry adoption, and preservation of biodiversity can further enhance **carbon sequestration, climate resilience, and long-term agricultural productivity**.

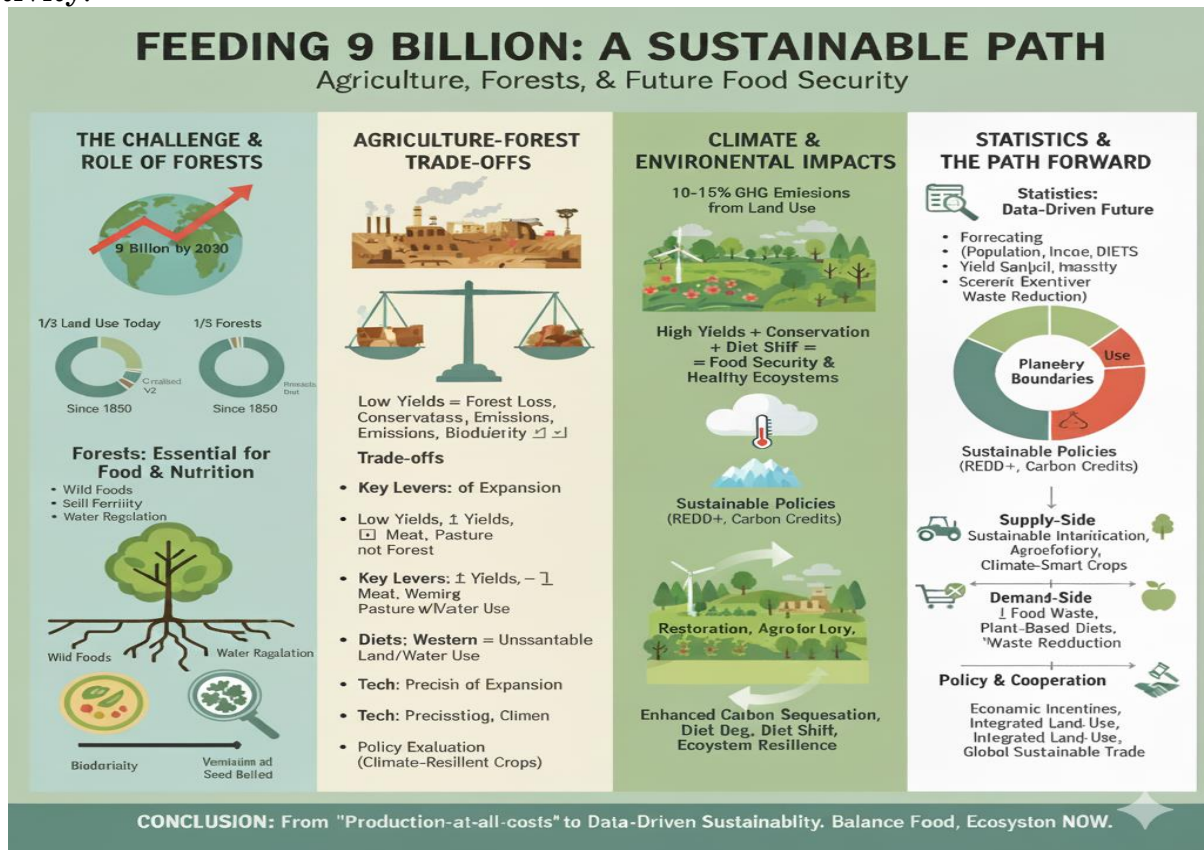


Fig.1: Agriculture-Forest Trade-offs: Statistical Levers for Sustainable Food Production

Role of Statistics in Navigating the Future

Statistics serve as the **bridge connecting agriculture, forestry, and sustainability**. They enable **forecasting food demand** by modeling population growth, income changes, and dietary trends. **Yield gap analysis** identifies regions where productivity can be increased **without additional land conversion**, reducing pressure on forests. **Scenario modeling** evaluates land-use change impacts under business-as-usual versus sustainable pathways, including trade-offs between food, forest, and climate outcomes. Statistics also support **policy evaluation**, such as assessing carbon stock conservation incentives, dietary shifts, or waste reduction strategies. They are essential for **quantifying synergies and conflicts**, informing evidence-based decisions, and guiding integrated, sustainable land-use planning.

Pathways Forward

- 1. Supply-side strategies:** Sustainable intensification, agroforestry, precision agriculture, closing yield gaps, and climate-resilient crop varieties.
- 2. Demand-side strategies:** Reducing food waste, shifting diets away from high-emission foods, promoting plant-based diets, and improving equitable food distribution.
- 3. Policy levers:** Economic incentives for forest and carbon conservation, integrating forestry into food security strategies, cross-sectoral land-use planning, regulation of biofuel expansion, and global cooperation on sustainable trade and investment.
- 4. Technological integration:** Digital agriculture, remote sensing for monitoring land-use change, and AI-driven optimization can improve productivity and environmental outcomes.

Conclusion

Feeding 9 billion people will inevitably reshape land use, and without intervention, forests—and the biodiversity and climate services they provide—will be at risk. However, **integrated land-use models, statistical analyses, and technological innovations** show that it is possible to meet global food demand while conserving forests, **provided agricultural and forestry policies are aligned**. Achieving this requires **coordinated action across supply, demand, policy, and technology pathways**, moving from a “production-at-all-costs” mindset to a **data-driven, sustainable framework** that balances food security, ecosystem health, and climate stability.

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From Pixels to Ploughs: Deep Learning Detectives Spot Crop Threats from Space

Article ID: 72244

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Summary

Deep Learning (DL), combined with satellite and drone imagery, is revolutionizing crop monitoring by **detecting diseases**, pests, and nutrient deficiencies before they become visible to the human eye. Using **Convolutional Neural Networks (CNNs)** and Object Detection models, these systems analyze multi-spectral and hyperspectral data to provide per-plant or per-field insights, enabling targeted interventions. This approach reduces crop losses, optimizes resource use, and promotes **sustainable** agriculture. **Early warning systems**, precision fertilization, optimized irrigation, and real-time yield estimation are transforming how farmers manage crops globally, supporting both productivity and environmental sustainability.

Introduction: The Invisible Enemy, The Watchful Eye

A daily, yet often unseen, challenge for farmers is the silent threat creeping across their fields: diseases, pests, and **nutrient deficiencies**. These issues often remain invisible to the human eye until they are severe, resulting in significant yield losses and forcing farmers to rely more heavily on costly, environmentally harmful chemicals. The solution lies in the ability to see the invisible. This is where DL, combined with **satellite** and **drone-based** remote sensing, steps in, acting as a **superhuman detective**. These DL Detectives can analyze spectral data to identify crop threats days or even weeks before symptoms become visible to a human, completely transforming crop monitoring. By shifting agriculture from reactive guesswork to proactive, precision interventions, this technology is actively safeguarding harvests and strengthening global food security.

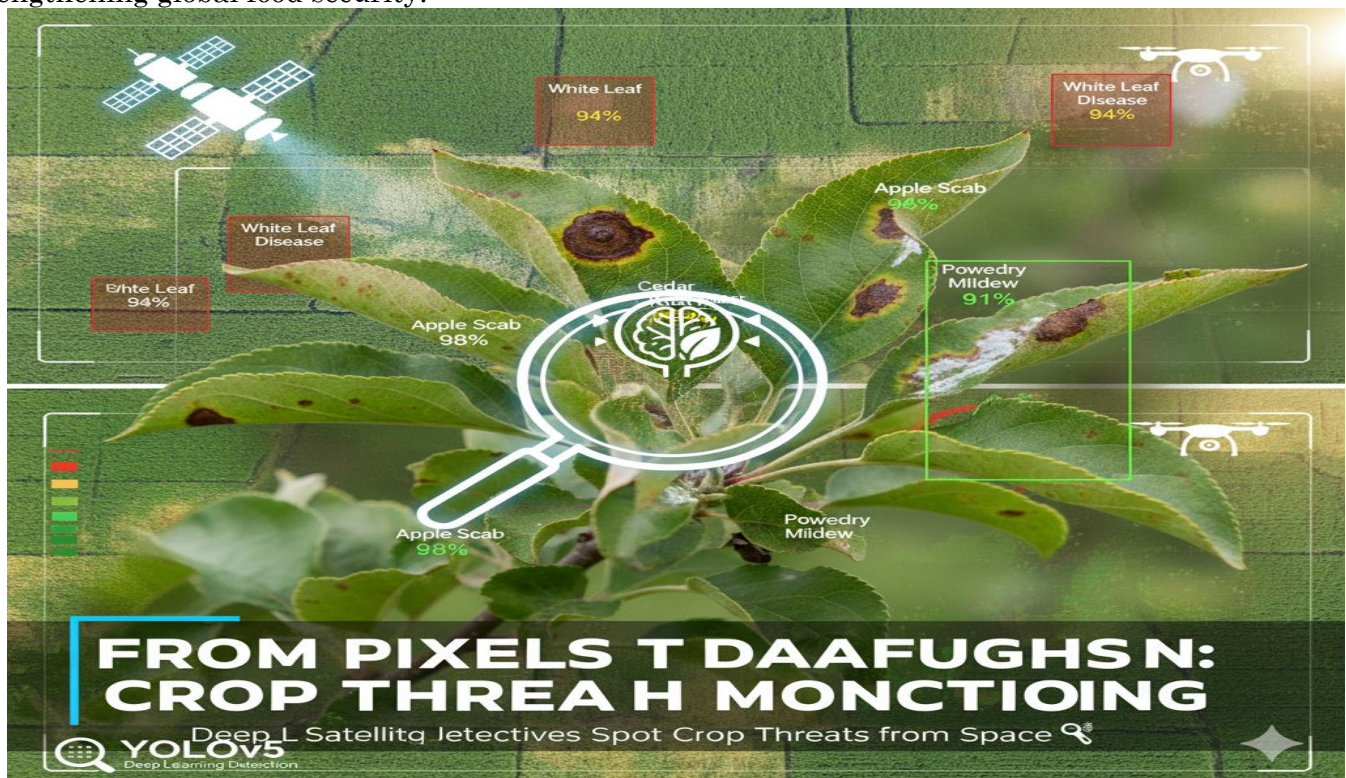


Image 1: Satellite and Deep Learning for Crop Threat Detection

The All-Seeing Eye: Remote Sensing and Deep Learning

Smart agriculture relies on **satellites** and **drones** to gather vast quantities of **multi-spectral and hyperspectral data**. These **spectral signatures** offer a unique, detailed health fingerprint of the crop. The core challenge is converting these **petabytes of raw data** into actionable insights, a necessity fulfilled by **Deep Learning models**, specifically **CNNs** and **Object Detection** architectures.

CNNs: Learning to See the Unseen

At their core, CNNs excel at visual pattern recognition. Trained on millions of images, they learn to identify incredibly subtle features that indicate specific problems.

1. Input: Multi-spectral satellite images and drone-captured RGB (Red, Green, Blue) and NIR (Near-Infrared) imagery serve as the primary input. These different light bands reveal details about plant physiology not visible in a standard photograph.

2. Feature Extraction: CNNs use multiple layers of filters to automatically extract increasingly complex features from these images. They can distinguish the unique spectral signature of a fungal infection from a bacterial one or differentiate the distinct pattern of water stress from a nitrogen deficiency.

3. Classification & Segmentation: Once trained, a CNN can classify entire pixels or regions as "diseased," "healthy," or "stressed." More advanced techniques, like **semantic segmentation**, can precisely outline the exact area of a leaf or a field affected by a specific issue.

This capability moves beyond simple overall crop health indices (like NDVI) to highly granular diagnostics, providing "per-plant" or "per-square-meter" insights.

Object Detection: Pinpointing the Problem

Building on CNNs, specialized **Object Detection** models (like YOLO – "You Only Look Once," or Faster R-CNN) are designed to not only identify *what* a problem is but also *where* it is within an image.

1. Function: These models can draw bounding boxes around specific anomalies in the field. For instance, they can detect individual weeds among crops, quantify the severity of a localized pest infestation, or even count emerging seedlings to assess planting density.

2. Actionable Insights: This precise localization is critical for "spot treatment," enabling farmers to apply pesticides or fertilizers only to the affected areas, reducing chemical use and environmental impact.

Unsupervised Learning: Discovering the Unknown Threat

While supervised learning handles known issues, **Unsupervised Learning** is crucial for **discovering unknown threats**. Specifically, **anomaly detection models** learn the spectral and growth patterns of a "normal" crop in a given region. Any significant and unexpected deviation from this established baseline is immediately flagged as an **anomaly**. This capability allows the AI system to provide **early warning** for novel or rare problems that haven't been pre-programmed, enabling the system to act as a true "detective" for unprecedented threats to the crop.

Applications: From Pixels to Ploughs

1. Early Warning Systems: Detect crop diseases and pest outbreaks days or weeks before visible symptoms, enabling timely, localized interventions.

2. Precision Resource Management: AI's diagnostic power enables **precision resource management**. It facilitates **Variable Rate Fertilization**, applying nutrients only where needed, and **Optimized Irrigation**, targeting water use based on real-time soil moisture and plant stress, thereby reducing waste and conserving resources.

3. Yield Estimation & Anomaly Detection: AI refines harvest predictions, integrates crop health with weather data, and flags unexpected growth deviations for human inspection.

Global Case Studies

Deep Learning is driving specialized agricultural advancements globally to optimize resource use and provide critical early warnings. In the U.S. Corn Belt, drone-based CNNs detect nitrogen stress,

significantly improving fertilizer efficiency. Similarly, Australian Wheat Fields use satellite-driven DL models to map weeds, reducing herbicide use by roughly 20%. In Southeast Asia's Rice Paddies, AI alerts farmers to pest outbreaks via mobile apps, protecting yields. Furthermore, in Sub-Saharan Africa, Satellite-DL systems offer early warnings for remote crops, which is vital for guiding humanitarian food aid.

Conclusion

Deep Learning detectives are transforming agriculture by providing **early, precise, and actionable insights**. From **satellite pixels to ploughed fields**, these AI systems reduce crop losses, optimize resource use, and promote **sustainable farming**. While challenges like labeled data scarcity remain, integrating DL with real-time sensor data and precision agriculture tools will continue to enhance **resilience, productivity, and environmental sustainability**, making AI an essential guardian of global food security.

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Farming's New Guardians: How Statistics are Shielding Our Harvests

Article ID: 72245

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Summary

Climate change poses a major threat to global agriculture, with rising temperatures and extreme weather events destabilizing crop yields. Advanced statistical methods, including Panel Data Analysis and Time Series Models, allow researchers to isolate the impact of climate from other factors like technology and policy. These models quantify the risks of temperature extremes, regional vulnerabilities, and economic losses, providing actionable insights for farmers and policymakers. Findings highlight that developing countries in low latitudes are most at risk, while some high-latitude regions may see minor benefits. Evidence-based adaptation strategies are essential to safeguard food security and water resources globally.

Introduction

Global agriculture faces mounting climate risks—rising temperatures, erratic rainfall, and extreme weather threaten crop productivity. Panel data and time series analyses, using methods like Fixed Effects and Spatial First Differences, help isolate climate impacts from technological and local factors. Models such as Just-Pope and Dynamic Panels quantify both average yields and risks, identifying temperature thresholds and regional vulnerabilities. These insights guide targeted, evidence-based interventions for resilient and sustainable agriculture, ensuring food security in a changing climate.

The Statistical Arsenal: Panel Data and Time Series Analysis

Disentangling correlation from causation is a key challenge in climate-agriculture research, as yields rise due to both technological progress and changing temperatures. **Panel data**—combining time-series (annual yields) and cross-sectional (districts) data—helps address this. **Fixed Effects (FE) models** control for unobserved factors, account for regional differences and time trends, and use **Spatial First Differences** to strengthen causal links between climate and yield.



Fig.1: The Data Harvest: Merging Statistical Modeling with Agricultural Fields

Time Series and Distributional Analysis

Beyond average impacts, models also assess yield variability and risk: **Just-Pope Production Functions** evaluate how climate extremes affect both mean yields and their variance, while **Dynamic Panel Models**

examine short- and long-term effects, showing, for example, that Japanese rice yields drop 5.8% short-term but only 3.9% long-term, indicating farmer adaptation.

Key Global Findings: What the Data Reveals?

The application of these statistical models has moved the climate-agriculture debate from speculation to quantification, revealing several critical, nuanced findings:

- 1. Temperature Extremes:** Rising temperatures severely reduce crop yields, with each 1°C increase cutting Maize 7.4%, Wheat 6.0%, Rice 3.2%, and Soybean 3.1%.
- 2. Geographical Variations:** Low-latitude developing regions suffer most, while cooler high-latitude areas gain slightly; in India, heat generally harms rice and maize, threatening water and food security.



Fig.2: Climate's Shadow: Visualizing Impact and Resilience in Agriculture

- 3. Economic Cost of Inaction:** Econometric models show that climate change significantly reduces agricultural revenue, with studies in regions like Argentina's Pampas and parts of Africa estimating billions in losses, highlighting the urgent need for adaptation investments.

Conclusion: Data-Driven Adaptation Strategies

Statistical analyses have transformed climate-agriculture research from speculation to quantification, highlighting the outsized effect of temperature extremes and regional disparities in crop vulnerability. Econometric models reveal the economic costs of inaction, emphasizing the need for proactive measures. Evidence-based strategies, including **heat- and drought-tolerant crops, improved irrigation, and region-specific policies**, are crucial. By combining rigorous data analysis with technological and policy interventions, the global community can better protect food security. Ultimately, these methods provide the foundation for **adaptive, resilient, and sustainable agricultural systems** in the face of climate change.

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AI's Crystal Ball: How Deep Learning Predicts the Perfect Harvest

Article ID: 72246

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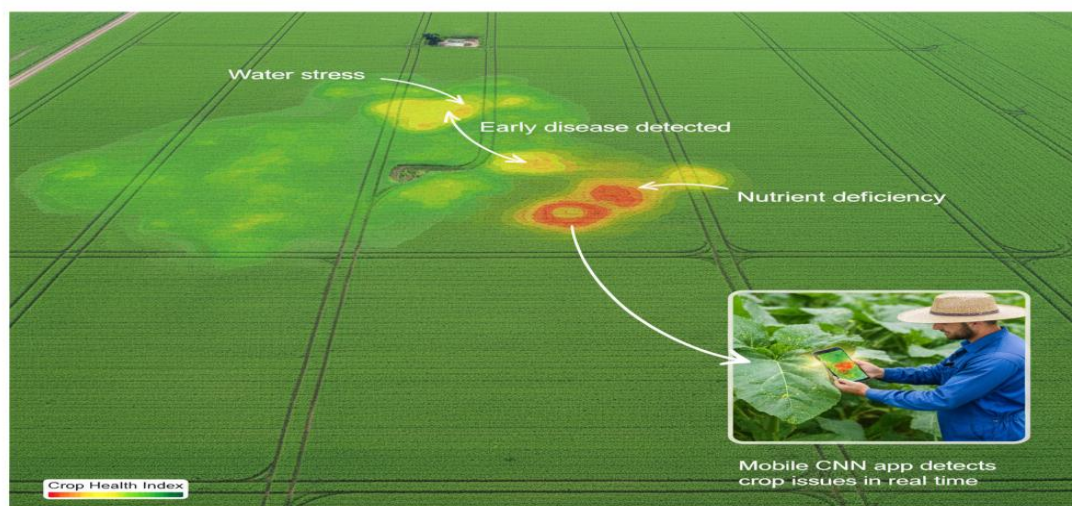
Summary

The **global agricultural** sector is shifting from guesswork to data-driven strategies to feed a projected 10 billion people by 2050 amid climate change and resource scarcity. Deep Learning (DL), including CNNs and RNNs, analyzes satellite imagery, climate records, and soil data to predict yields, detect diseases, and **forecast extreme weather**, enabling proactive farming and resource optimization. These technologies support precision **fertilization** and irrigation, reducing environmental impact and paving the way for smarter, more resilient, and sustainable agriculture.

Introduction: From Guesswork to Precision

For centuries, farming relied on **guesswork**—when to sow, irrigate, or expect yields. Today, with a growing population, shifting diets, climate extremes, and limited land and water, guesswork is risky. By 2050, the world must feed nearly **10 billion people** while coping with **rising temperatures** and **erratic rainfall**. **Artificial intelligence (AI)**, powered by **deep learning**, transforms vast datasets—**satellite imagery**, **climate records**, **soil maps**, and **historical yields**—into actionable forecasts. It can **predict yields**, **detect pests and diseases early**, and model **weather impacts**, enabling agriculture to shift from reactive decisions to **proactive, data-driven strategies**. These tools also support **precision resource management**, reducing waste and environmental impact. As AI systems continue to advance, they promise **more resilient, efficient, and sustainable farming** worldwide.

The Deep Learning Toolbox for Agriculture



AI analyzes aerial imagery to detect crop stress and disease before visible symptoms appear.

Image 1: AI in Action – Crop Monitoring & Disease Detection

Deep Learning (DL) models are transforming agriculture through integrated temporal and spatial analysis. **Convolutional Neural Networks (CNNs)** act as the "**eyes of agriculture**," specializing in spatial analysis of imagery to detect subtle spectral signatures of stress. CNNs can diagnose plant diseases with over 90% accuracy, providing smallholder farmers with instant, mobile advice. Meanwhile, **Recurrent Neural Networks (RNNs)** and **Temporal Convolutional Networks (TCNs)** analyze seasonal and sequential data (like temperature and rainfall) to accurately predict crop yields weeks or months in advance, achieving national-scale forecasts comparable to official statistics. Finally, new

Transformer models integrate diverse, **multimodal data** to capture complex long-term dependencies and deliver scalable, system-level forecasts essential for food security monitoring.

What AI Predicts in Today's Fields

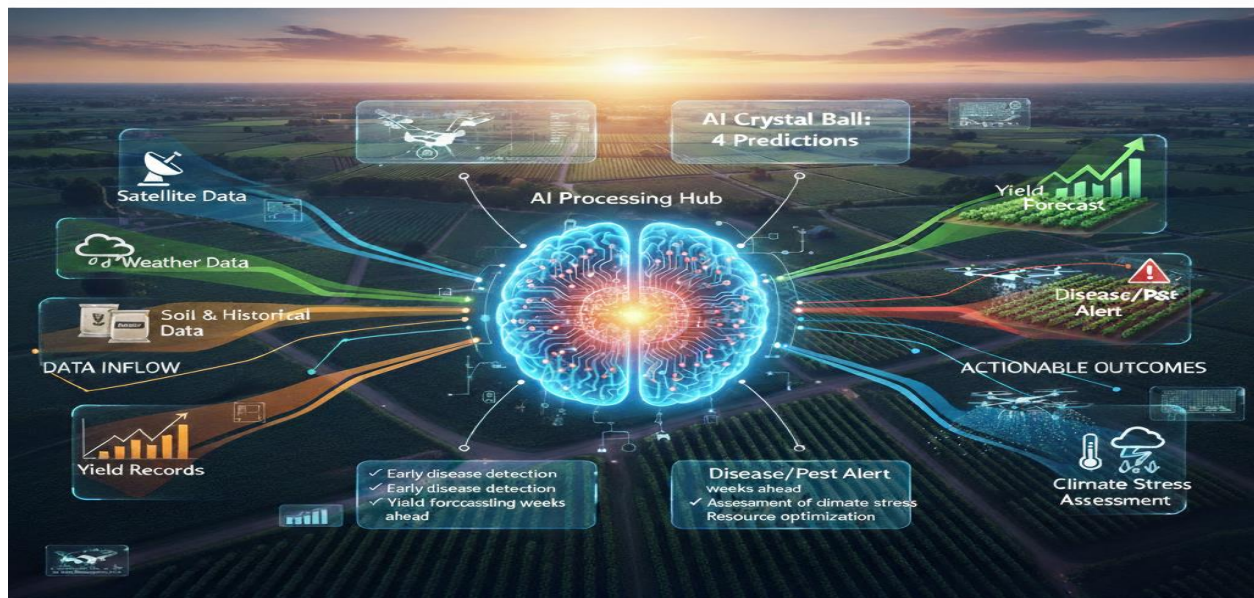


Image 2: Forecasting & Decision-Making – AI Predictive Analytics

- 1. Yield Prediction:** DL forecasts crop yields using weather, soil, and satellite data for early warnings and food security planning.
- 2. Disease & Pest Detection:** CNN apps spot diseases early, reducing losses and pesticide use.
- 3. Weather Risk Forecasting:** AI predicts extreme events affecting yields for insurance and resilience.
- 4. Resource Optimization:** AI guides efficient irrigation, fertilization, and pest control.

Case Studies: AI in Action

AI-driven case studies demonstrate immediate, real-world impact across the globe. In the United States, Deep CNN–RNN models accurately predict **county-level** corn yields weeks ahead of harvest, directly influencing both commodity markets and farm-level decisions. In India, AI empowers smallholder farmers via a "**Mobile Plant Doctor**," where CNN-powered apps instantly diagnose pests and diseases in crops like rice and maize, successfully reducing losses and input costs. On a larger scale, international organizations are using AI-driven satellite monitoring for **Global Food Security** Monitoring, estimating crop production in data-scarce regions to help anticipate and guide aid efforts for crises such as drought-induced shortages in Sub-Saharan Africa.

Strengths and Limitations of the AI Crystal Ball

Strengths: The primary strengths of AI models are their capacity to process enormous, **complex datasets** across scales and their ability to detect nonlinear relationships (e.g., sudden yield collapse beyond temperature thresholds). Furthermore, these models are **highly efficient**, as they can be scaled cheaply once initially trained.

Limitations: Despite its promise, AI in agriculture faces **data gaps**, **bias** from models trained on high-input systems, **limited explainability**, and **access inequality**, especially in developing regions, which can hinder adoption and widen the digital divide.

Conclusion: From Data to Security

Deep learning is not replacing the farmer—it's giving them superpowers. By analyzing massive datasets of weather, soil, and satellite imagery, AI provides farmers with **actionable foresight** into the future of their fields. In an age defined by escalating climate shocks and population pressures, this foresight is no longer a luxury but a fundamental necessity for survival. If harnessed wisely and equitably, AI's ability to see into the future of farming could be the "crystal ball" humanity needs to achieve the daunting task of feeding billions of people while simultaneously protecting critical ecosystems. Ultimately, the future of agriculture won't be about guessing or reacting, but about **knowing**—and taking decisive action **before crisis strikes**.

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Crop Yield Prediction in Agriculture: How Technology is Shaping the Future of Farming

Article ID: 72247

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Summary of Article

The article discusses how Artificial Intelligence (AI), Machine Learning (ML), and Deep Learning (DL) are revolutionizing crop yield prediction, transforming it from a guesswork-based process into a precise, data-driven science. Accurate yield forecasting is essential for optimizing farm inputs, guiding policy decisions, stabilizing markets, and ensuring food security—especially in regions like India, where agriculture depends heavily on variable climate conditions. ML and DL models, using diverse data sources such as soil parameters, weather records, and satellite imagery, can detect complex patterns and predict yields with high accuracy. Hybrid models that combine multiple algorithms further enhance performance, enabling smarter resource management and risk mitigation. As AI-driven systems continue to evolve, they are paving the way for sustainable, efficient, and predictable farming, ensuring the world's growing population can be fed more reliably.

Introduction

Feeding a growing global population is one of the biggest challenges of the 21st century. Farmers need to know **how much food their fields will produce**, not just for their own livelihoods, but also to ensure food security for entire nations. Traditionally, estimating crop yields depended on experience, intuition, and visual observation—a method that often led to errors, wasted resources, or shortages. Today, **technology is transforming how we predict harvests**, making agriculture smarter, more efficient, and more reliable.

Why Predicting Crop Yields Matters?

Crop yield prediction is vital for farmers, policymakers, and markets. For farmers, knowing the expected yield helps optimize **water, fertilizer, and pesticide use**, reducing costs while maximizing output. For policymakers, accurate predictions support **timely import/export decisions**, contributing to national food security. At the market level, reliable yield forecasts help stabilize prices and prevent unnecessary food waste.

In countries like India, where **agriculture is highly dependent on rainfall and environmental conditions are unpredictable**, accurate crop prediction is crucial. Poor yield estimates can directly impact farmers' income and threaten regional food supply.

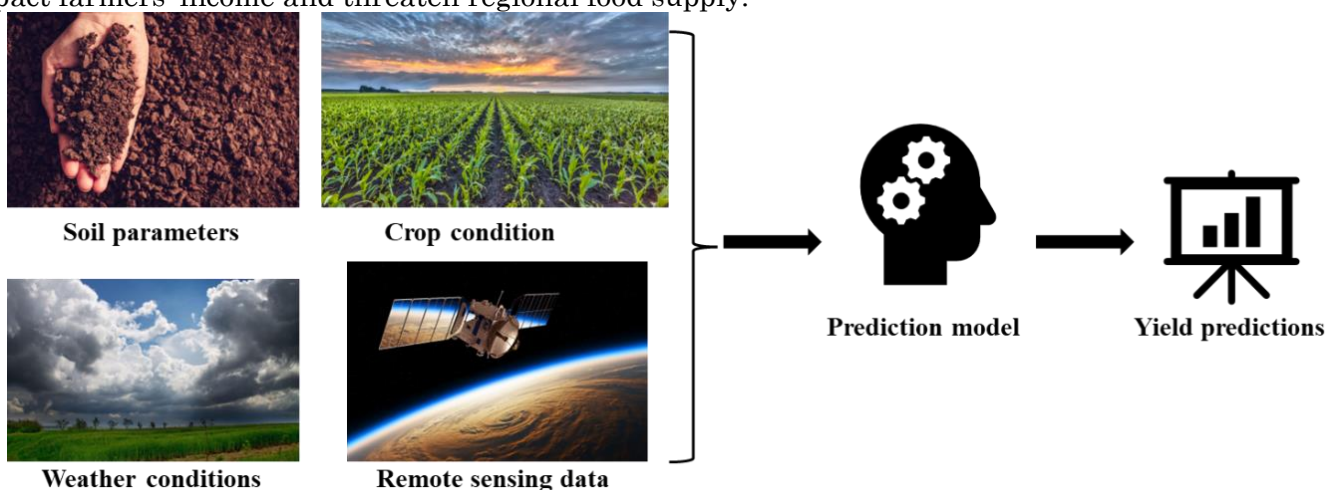


Figure 1: Representation of yield prediction using a prediction model

The Rise of Machine Learning in Agriculture

Machine learning, a branch of artificial intelligence, is revolutionizing crop yield prediction. Unlike traditional rule-based methods, ML analyzes **patterns in large datasets** to forecast outcomes. Data from **soil tests, weather records, irrigation schedules, crop types, and satellite imagery** can all feed into these models.

Popular ML techniques in agriculture include:

1. **Random Forest (RF):** Efficient at processing complex datasets.
2. **Support Vector Machines (SVM):** Effective when combining weather and vegetation indices.
3. **Artificial Neural Networks (ANN):** Detect nonlinear patterns between crop growth and environmental factors.

By analyzing historical and real-time data, ML models can guide **decision-making on planting, irrigation, fertilization, and harvesting**, helping farmers increase productivity while reducing resource waste.

Deep Learning: Unlocking More Insights

Deep learning, a more advanced subset of ML, excels at analyzing **large and unstructured datasets**, such as drone images or satellite photos. Key DL techniques for crop yield prediction include:

1. **Convolutional Neural Networks (CNN):** Analyze images to assess plant health and predict yields.
2. **Long Short-Term Memory (LSTM):** Capture time-dependent effects, such as weather changes across a growing season.
3. **Deep Neural Networks (DNN):** Extract complex patterns from multiple variables, including soil, climate, and crop type.

DL models can **discover subtle correlations** that traditional models may miss, leading to more accurate yield predictions across different regions and crops.

Data is the Heart of Prediction

The accuracy of crop yield prediction depends on **quality and diversity of data**. Important factors include:

1. Soil type, pH, fertility, and moisture levels
2. Weather conditions such as temperature, rainfall, humidity, and solar radiation
3. Crop type, planting methods, and fertilizer use
4. Satellite and drone imagery, vegetation indices (e.g., NDVI, EVI, LAI)

Integrating multiple data sources—called **multimodal data fusion**—improves model accuracy. However, **more data doesn't always mean better predictions**. Models must consider local conditions, regional differences, and environmental factors to be truly effective.

Hybrid Models: Combining Strengths

Many studies show that combining multiple ML and DL techniques—**hybrid models**—can improve accuracy. For example:

1. **CNN-LSTM models** for predicting soybean yield
2. **Random Forest + Gradient Boosting + LASSO regression** for localized crop forecasts
3. **CNN-DNN combinations** for winter wheat yield prediction

These hybrid approaches leverage the strengths of different algorithms, allowing models to handle **complex, nonlinear relationships** between crop yields and environmental factors.

Practical Benefits for Farmers and Policymakers

Crop yield prediction has real-world applications:

1. **Optimizing resource allocation:** Reduce excess fertilizer and water use.

2. Risk management: Prepare for adverse weather or pest outbreaks.

3. Market planning: Predict supply and stabilize commodity prices.

4. Policy formulation: Support food security programs and sustainable agriculture initiatives.

Incorporating AI-driven prediction tools into farm management systems helps **maximize efficiency, reduce losses, and promote sustainable agriculture.**

The Road Ahead

Despite tremendous progress, challenges remain. Accurate crop yield prediction depends on **data quality, feature selection, environmental monitoring, and algorithm choice.** Techniques like **transfer learning** allow models trained in one region to be adapted to others, helping overcome data scarcity. Improving the **interpretability of deep learning models** is also critical for farmer trust and adoption.

By integrating advanced technology with traditional knowledge, agriculture is moving toward a future where farmers can **anticipate yields, optimize resources, and sustainably feed a growing population.** With AI and machine learning, the harvest is no longer a surprise—it's increasingly predictable.

Conclusion

Crop yield prediction is no longer just an academic exercise—it is **essential for modern agriculture.** From improving farmer livelihoods to ensuring national food security, **AI-driven prediction tools are changing the way we grow food.** The combination of machine learning, deep learning, and data from multiple sources promises a future where agriculture is **smarter, more efficient, and better equipped to feed the world.**

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Regenerative Agriculture: Growing Food While Healing the Planet

Article ID: 72248

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Summary of Article

The article explains how regenerative agriculture (RA) offers a transformative approach to farming that not only sustains but restores ecosystems by focusing on soil health, biodiversity, and carbon sequestration. Unlike conventional methods that deplete resources, RA practices—such as cover cropping, no-till farming, composting, agroforestry, and integrated livestock systems—revitalize soil, enhance resilience, and reduce dependence on synthetic inputs. Environmentally, RA mitigates climate change by capturing carbon and improving water retention; economically, it lowers input costs and supports local livelihoods. While challenges like high initial costs and knowledge gaps remain, growing global interest from governments, corporations, and NGOs underscores its potential. Ultimately, regenerative agriculture represents a holistic, climate-positive solution that balances productivity with ecological restoration, ensuring food security and environmental health for future generations.

Introduction

Farming feeds the world, but it comes at a significant cost. Agriculture accounts for roughly one-third of global land use and contributes around 15% of greenhouse gas emissions. If current practices continue—relying on synthetic fertilizers, pesticides, fossil fuels, and producing food waste—the planet's carrying capacity could be surpassed. As populations grow and diets shift, global food demand is expected to rise even further. The question is urgent: **how can we produce more food without destroying the planet?**

What is Regenerative Agriculture?

Regenerative agriculture is a farming approach that goes beyond sustainability. Instead of merely minimizing harm, it **restores and revitalizes ecosystems**, starting with the soil. Soil—the “fragile, living skin of the Earth”—is critical for carbon storage, water retention, crop growth, and erosion prevention. RA practices aim to **build soil health, sequester carbon, enhance biodiversity, and improve water quality**, while maintaining or increasing yields.

The concept emerged in the late 1970s and was popularized in the 1980s by the **Rodale Institute** in the U.S. Robert Rodale described regenerative agriculture as a system that boosts productivity while **enhancing soil and land health**, minimizing reliance on non-renewable resources, and producing food free of synthetic chemicals. Agronomist Richard Harwood emphasized that RA is **a holistic system**: it recognizes the interconnectedness of humans, animals, plants, and soil, and seeks to maximize beneficial biological relationships.

Core Practices of Regenerative Agriculture

Farmers use a variety of methods to regenerate the land:

- 1. Cover cropping and crop rotation:** Protects soil, prevents erosion, and replenishes nutrients.
- 2. Reduced or no-till farming:** Maintains soil structure and microbial life.
- 3. Composting and organic amendments:** Adds nutrients while capturing carbon.
- 4. Agroforestry and perennial plantings:** Enhances biodiversity and stabilizes ecosystems.
- 5. Integrated livestock systems:** Animals naturally fertilize the land and help cycle nutrients.

These practices don't just help the environment—they also **improve farm resilience**, boost yields, and reduce dependency on synthetic fertilizers and pesticides.

Environmental and Climate Benefits

Regenerative agriculture has measurable impacts:

- 1. Carbon sequestration:** Farms can pull significant amounts of CO₂ from the atmosphere into soil. Estimates suggest regenerative cropping alone could sequester **14.5–22 gigatons of CO₂ by 2050**.
- 2. Improved soil health:** Better water retention reduces flood and drought risks.
- 3. Biodiversity enhancement:** Pollinators, birds, and soil microbes thrive under regenerative practices.
- 4. Reduced erosion:** Healthy soil prevents nutrient and topsoil loss.

By improving natural systems, RA contributes to climate change mitigation while supporting long-term food production.

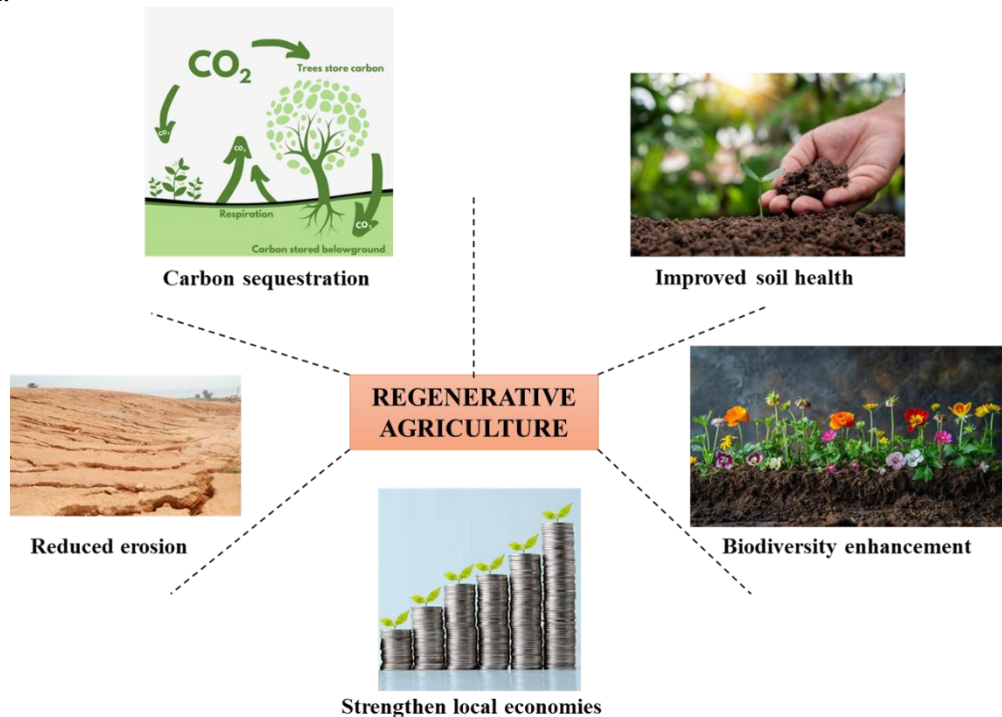


Figure 2: Benefits of Regenerative Agriculture

Economic and Social Advantages

RA can also **strengthen local economies**:

1. Reduced input costs due to less reliance on synthetic fertilizers.
2. Increased employment opportunities on farms through labor-intensive, diversified practices.
3. Stronger community engagement and resilience, particularly in urban and peri-urban farming initiatives.

Challenges and Limitations

Adoption isn't without hurdles:

1. Knowledge and technical expertise are required to implement RA effectively.
2. Initial labour and costs can be higher than conventional farming.
3. Short-term yields may be lower while soils recover.
4. Lack of a universally accepted definition can confuse consumers and complicate policy.

Global Initiatives and Policy Support

Interest in RA spans public, private, and non-profit sectors:

1. Governments are exploring RA as part of climate action plans.
2. Companies like **General Mills** have pledged to adopt regenerative practices on millions of acres.

3. Certification programs, such as the **Regenerative Organic Certification**, are emerging to standardize practices.
4. Non-profits like the **Savory Institute** and **Regeneration International** promote adoption and knowledge-sharing globally.

Regenerative Agriculture in the Bigger Picture

RA fits into a broader vision of sustainable food systems:

1. It aligns with **circular economy principles**—reduce, reuse, recycle, regenerate.
2. Supports **local and urban food systems**, strengthening resilience and reducing transport energy.
3. Complements other sustainable approaches like organic farming, climate-smart agriculture, and sustainable intensification.

Indicators such as **soil organic carbon, crop yields, water retention, and biodiversity metrics** help governments, researchers, and farmers measure success and progress toward sustainable development goals.

Conclusion

Regenerative agriculture is more than a farming method—it's a vision for the future of food. It **nourishes people, restores ecosystems, strengthens communities, and combats climate change**. As the world faces the twin challenges of feeding a growing population and protecting the planet, regenerative agriculture offers a hopeful path forward—**where farming and nature thrive together**.

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Weather Forecasting for Agriculture in the Age of Machine Learning

Article ID: 72249

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Summary of Article

The article discusses how machine learning (ML) is revolutionizing weather forecasting in agriculture, providing farmers with precise, localized, and timely predictions essential for decision-making. Traditional forecasting methods often lack accuracy, but ML analyses vast datasets—including satellite imagery, soil moisture, and historical weather patterns—to deliver smarter insights. These forecasts help farmers manage irrigation, prevent pest and disease outbreaks, optimize planting and harvesting times, and assess risks from extreme weather events. By integrating ML with IoT devices, drones, and sensors, farmers gain real-time, data-driven recommendations that boost productivity, conserve resources, and enhance sustainability. As climate change intensifies weather unpredictability, ML-based forecasting is becoming vital for ensuring food security and resilient farming systems.

Introduction

Farmers have always depended on the weather. A sudden drought, unexpected rainfall, or early frost can drastically affect crop yields and income. Traditionally, farmers relied on experience, seasonal patterns, and government forecasts—but these methods often fall short in accuracy and timeliness. Today, **ML** is transforming weather forecasting for agriculture, helping farmers make smarter, data-driven decisions.

Why Weather Forecasting Matters for Farming?

Weather dictates nearly every aspect of farming. Decisions about when to sow seeds, irrigate fields, apply fertilizers, or harvest crops all depend on accurate forecasts. Even small errors can lead to crop loss, wasted resources, or increased costs. For example:

1. **Over-irrigation** during rainfall wastes water and electricity.
2. **Late frost warnings** can prevent crop damage if farmers act in time.
3. **Optimized harvesting** can reduce spoilage and maximize profits.

With the pressure of climate change, farmers need forecasts that are **more precise, localized, and timely** than ever before.

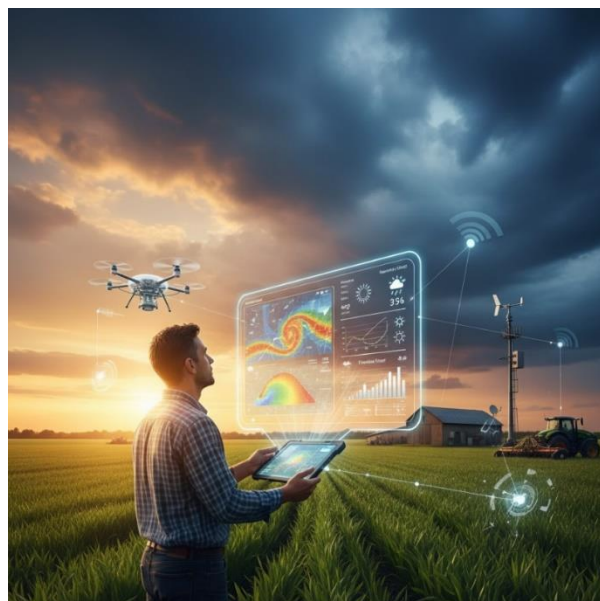


Figure 3: Weather forecasting

Types of Weather Forecasting

Weather forecasting in agriculture can be classified based on the **time horizon**:

- 1. Short-Term Forecasting:** Covers from a few hours up to 7 days. Helps farmers plan daily activities such as irrigation, pesticide application, and harvesting. Provides information on temperature, rainfall, wind, and humidity.
 - 2. Medium-Term Forecasting:** Spans from one week to a few months. Useful for planning crop rotation, fertilizer application, and early preparation for seasonal weather events.
 - 3. Long-Term or Seasonal Forecasting:** Extends over several months to years. Guides decisions on crop selection, planting strategies, and risk management against droughts, floods, or other extreme events.
- Each type of forecasting serves a distinct purpose, and **machine learning** can enhance accuracy across all three-time horizons.

From Numbers to Learning: How Weather Forecasting Works

Traditional forecasting relies on **Numerical Weather Prediction (NWP)** models, which simulate the atmosphere using mathematical equations. While powerful, NWP models require supercomputers, are slow to run, and sometimes struggle to predict local weather accurately.

Machine learning, a branch of artificial intelligence, offers a smarter approach. ML algorithms can analyse vast amounts of historical weather data, satellite imagery, soil moisture readings, and crop data to detect patterns that humans or traditional models might miss.

Unlike traditional models that focus on physics, ML **learns from the data itself**, allowing for faster, localized, and often more accurate predictions tailored to specific farms.

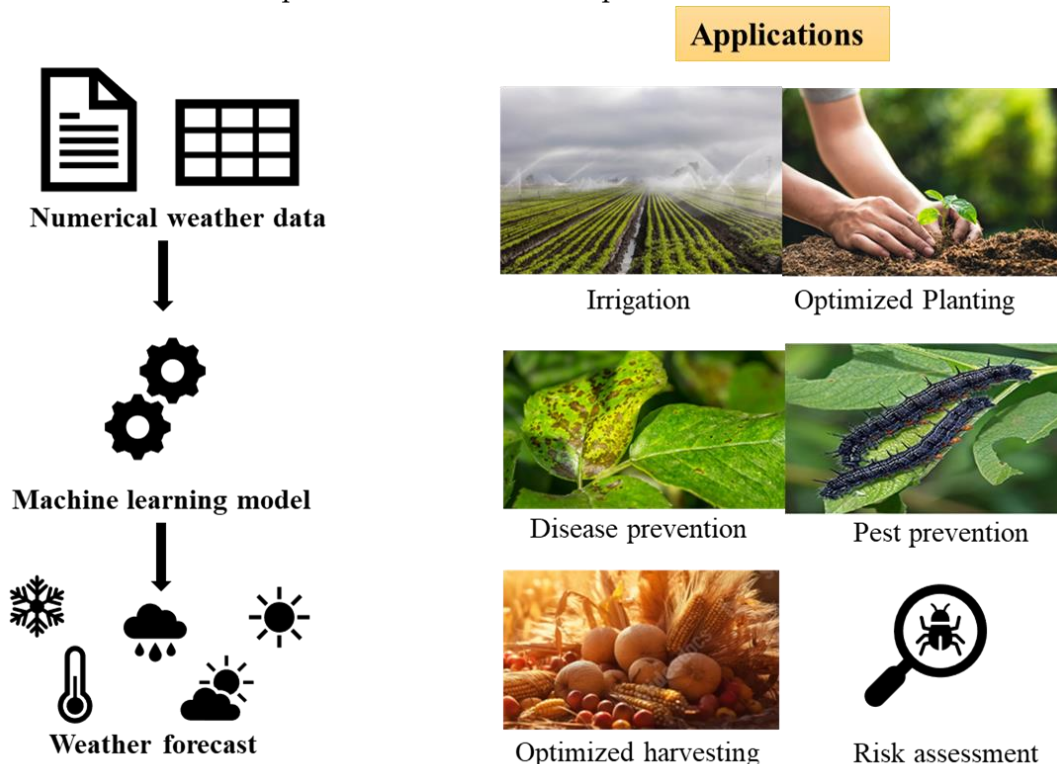


Figure 4: Weather forecasting process and its applications

Applications of ML in Agricultural Weather Forecasting

- 1. Irrigation Management:** ML predicts rainfall and soil moisture, helping farmers decide when and how much to water crops, reducing water waste.
- 2. Pest and Disease Prevention:** Certain pests and diseases thrive under specific weather conditions. ML forecasts can alert farmers to take preventive action.

3. Optimized Planting and Harvesting: ML identifies the best planting and harvesting windows based on predicted weather patterns, ensuring higher yields and better crop quality.

4. Risk Assessment: ML estimates the likelihood of extreme events such as droughts, heatwaves, or hailstorms, allowing farmers to take precautions, protect crops, and plan for insurance needs.

Real-World Impact

In different regions in the world, ML-powered weather forecasting is already helping farmers **increase efficiency and reduce costs**. Farmers can receive mobile alerts with actionable recommendations, such as adjusting irrigation schedules or delaying harvesting. Precision agriculture combined with weather insights ensures **better resource management, higher productivity, and more sustainable farming practices**.

Conclusion

The integration of ML with **IoT devices, drones, and satellite imagery** is taking agricultural weather forecasting to a new level. Sensors in the field can feed real-time data to ML algorithms, which then predict rainfall, soil moisture, and pest risks with high precision. Farmers could make **daily, data-driven decisions**, adapting quickly to changing conditions.

As climate change brings more uncertainty to weather patterns, ML-based forecasting will become essential for **food security, resource optimization, and sustainable agriculture**. By empowering farmers with better weather intelligence, machine learning is not just improving forecasts—it's **shaping the future of farming**.

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Crop Monitoring Using UAVs: The Future of Farming

Article ID: 72250

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Summary of Article

The article explains how Unmanned Aerial Vehicles (UAVs), or drones, are transforming modern agriculture by making farming smarter, more precise, and sustainable. Faced with rising food demand, limited resources, and challenges like climate change and labor shortages, drones equipped with AI, IoT, Machine Learning (ML), and Deep Learning (DL) are helping farmers monitor crops, manage irrigation, predict yields, and apply fertilizers or pesticides with pinpoint accuracy. Different types of drones—fixed-wing, helicopter-style, and multi-copters—serve varied purposes, from large-scale mapping to targeted spraying. By capturing high-resolution data and analyzing it in real time, UAVs enable timely interventions that boost productivity while minimizing waste and environmental impact. Despite challenges related to cost, data analysis, and regulations, agricultural drones hold immense promise for achieving global food security and efficiency in farming.

Introduction

Feeding a growing global population is one of humanity's greatest challenges. Today, over **815 million people** are chronically hungry, and more than **64% of them live in Asia**. By 2050, the world's population is expected to reach nine billion, demanding a **50% increase in food production**. Yet, essential resources like **fertile land and water** are becoming scarcer every year, making traditional farming methods increasingly insufficient. The COVID-19 pandemic has only worsened this problem, disrupted supply chains and limited access to labour, seeds, and fertilizers.

In countries like **India**, where 73% of the population depends on agriculture, farming is still largely conventional. Farmers rely on manual techniques for planting, fertilizing, and pest control. These methods are labour-intensive, less effective, and slow. Enter **drones**, a technological revolution transforming how we grow and protect crops.

What are UAVs?



Crop Monitoring



Pesticide and Fertilizer Spraying



Yield Prediction and Farm Planning



Soil and Irrigation Management

Figure 5: Applications of UAV's in agriculture

UAVs, commonly known as drones, are **pilotless flying vehicles** that can carry cameras, sensors, or sprayers. Originally developed for military use, they are now widely used in agriculture. By flying over fields, drones **capture high-resolution images and data** that help farmers see plant health, water stress, nutrient deficiencies, and pest infestations that are often invisible to the naked eye.

Modern UAVs can operate **autonomously with Artificial Intelligence**, analysing data in real time and taking precise actions such as targeted pesticide spraying or irrigation guidance.

Different Types of Agricultural UAVs

Not all drones are created equal. There are three main types:

- 1. Fixed-Wing UAVs** – Look like miniature airplanes. They cover large areas quickly and efficiently but struggle to hover or operate in small, crowded fields.
- 2. Helicopter-Style UAVs** – Can take off vertically and hover in place, making them ideal for remote or hard-to-reach areas. They carry heavier loads but are expensive and complex to operate.
- 3. Multi-Copters** – The most common type today, with 4–8 rotors. They can hover, land vertically, and perform **spot spraying** with precision. Their low-altitude stability makes them perfect for small- and medium-sized farms.

How UAVs Are Changing Agriculture?

By using UAVs, farmers can:

Applications of UAVs in Agriculture: UAVs have many uses that make modern farming more efficient, safer, and productive:

1. Crop Monitoring:

- Capture images using RGB, multispectral, hyperspectral, or thermal cameras.
- Analyze vegetation indices to identify **healthy vs. stressed plants**, detect diseases, and monitor water and nutrient needs.
- Help farmers take corrective actions early to prevent crop loss.

2. Pesticide and Fertilizer Spraying:

- Replace manual spraying, reducing **chemical exposure and labor costs**.
- AI-enabled drones can perform **spot spraying** based on real-time data.
- Capable of carrying tanks up to 40 liters and covering hard-to-reach areas efficiently.

3. Soil and Irrigation Management:

- Analyze soil health and moisture levels.
- Guide irrigation systems for optimized water usage.

4. Yield Prediction and Farm Planning:

- Use collected data to estimate crop yields accurately.
- Map fields to improve farm planning and resource allocation.

Smart Sensors and AI Make UAVs Even Smarter

Modern UAVs in agriculture are not just flying cameras—they are **smart devices** integrated with IoT sensors, Machine Learning (ML), and Deep Learning (DL):

1. IoT (Internet of Things): Sensors on drones and in fields collect real-time data on soil, water, temperature, and humidity. This data is transmitted to the cloud for analysis, enabling **instant monitoring of crop conditions**.

2. Machine Learning: ML algorithms analyze drone data to detect patterns in crop health, pest infestations, or nutrient deficiencies. For example, ML can classify plants as healthy or stressed based on multispectral images, helping farmers take corrective actions faster.

3. Deep Learning: DL techniques, like **Convolutional Neural Networks (CNNs)**, enable drones to automatically detect diseases, pests, or weeds in real time from images. DL models can segment images, predict yield, and guide AI-based pesticide spraying, making precision agriculture highly efficient.

With **AI** and **ML**, drones can now operate autonomously. They analyse real-time data to make decisions:

- a. Adjust pesticide spraying based on crop needs.
- b. Identify stressed or diseased plants.
- c. Optimize flight paths for maximum efficiency.

This automation not only saves time and labour but also reduces environmental impact and increases crop yields.

Opportunities and Challenges of Agricultural Drones

Opportunities:

- a. **Precision Agriculture:** UAVs provide precise monitoring and data collection, helping farmers **optimize resources**, detect crop diseases early, and improve yields.
- b. **Crop Health and Management:** Advanced imaging sensors give insights into **nutrient deficiencies, water stress, and pests**, allowing timely interventions.
- c. **Mapping and Analysis:** Drones create **accurate field maps, digital elevation models, and orthomosaic images** for irrigation planning, field surveying, and better farm management.

Challenges:

- a. **Data Analysis and Interpretation:** Large volumes of drone data can be overwhelming. Farmers need **user-friendly software and analytical tools** to convert raw data into actionable insights.
- b. **Regulations and Safety:** UAV operations must comply with **aviation rules, privacy concerns, and safety guidelines**, especially near populated areas.
- c. **Cost and Scalability:** Drones can be **expensive to buy and maintain**, and small-scale farmers may find it hard to adopt this technology. Accessibility and training are key challenges.

Overcoming these challenges is essential for unlocking the full potential of agricultural drones and **making precision farming accessible, safe, and effective**.

Conclusion

By integrating UAVs with AI, IoT, ML, and DL, farmers can:

1. Reduce waste of water, fertilizers, and pesticides.
2. Monitor crops frequently without walking the entire field.
3. Make **data-driven decisions** to increase productivity.
4. Minimize environmental impact and improve food security.

UAVs represent a **smarter, safer, and more sustainable future** for agriculture, helping to feed a growing global population with fewer resources.

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Computer vision in Agriculture: Revolutionizing On-Farm Fruit Sorting and Transportation

Article ID: 72251

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Summary of Article

The article explores how Artificial Intelligence (AI) and Computer Vision (CV) are revolutionizing fruit sorting and on-farm transportation by replacing manual, labour-intensive processes with automated, intelligent systems. Through sensors, cameras, and AI algorithms, these technologies can detect defects, assess ripeness, grade quality, and even transport produce efficiently and safely. Equipped with tools like RGB, hyperspectral, and thermal cameras, along with LiDAR and GPS-enabled robots, farms can now achieve faster, more accurate, and consistent sorting while reducing post-harvest losses and worker strain. By integrating AI, machine learning, IoT, and robotics, modern agriculture is evolving into a data-driven, smart system that enhances productivity, sustainability, and profitability from orchard to market.

Introduction

In agriculture, the journey from farm to table is filled with challenges. Sorting and grading fruits and vegetables traditionally rely on **human senses**—colour, texture, size, and odour—to determine quality and ripeness. This manual approach is **time-consuming, labour-intensive, and inconsistent**, often leading to significant post-harvest losses. But thanks to **AI and CV**, a new era of precision agriculture is emerging.

From Manual Sorting to Smart Farms

On-farm sorting involves removing damaged, diseased, or rotten produce and categorizing the rest into bins based on size, colour, maturity, and ripening stage. For small farms, these tasks often occur directly in the field or warehouse, while large fruit producers operate sorting lines in factories. Manual on-farm transportation is repetitive and physically demanding, requiring workers to carry heavy trays and bins from the picking site to collection centres.

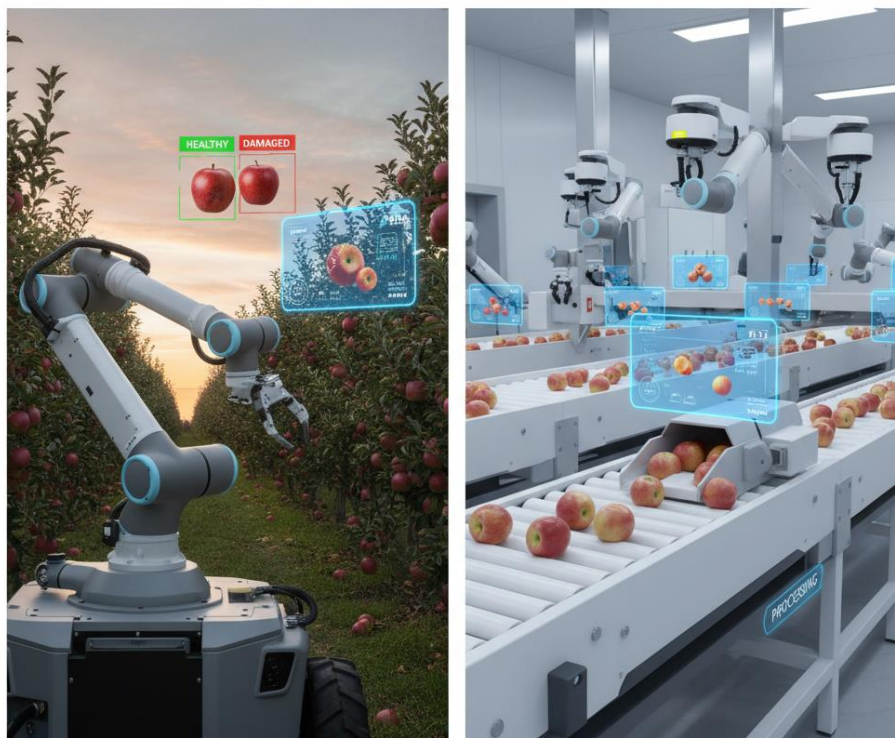


Figure 6: On tree fruit grading and off tree fruit grading

High labour costs, low efficiency, and occupational hazards have motivated the adoption of **AI-based systems** for on-farm sorting and transportation. These systems can **automate defect detection, classify produce, and optimize transportation**, reducing post-harvest losses while enhancing worker safety and efficiency.

How AI and Computer Vision Work?

Computer Vision (CV) is a subset of AI that enables machines to "see" and interpret visual information. In agricultural applications, CV works in tandem with **AI algorithms**, such as machine learning and deep learning, to process images and make intelligent decisions about fruit quality.

1. Artificial Intelligence: AI enables machines to **learn from data**, detect patterns, and make decisions without explicit human programming. Machine learning and deep learning models can analyse images of fruits to detect subtle defects, classify ripeness, or predict internal quality based on visual cues.

2. Computer Vision: CV provides the **image-processing capability**, capturing and analysing features such as **size, shape, colour, and texture**. It allows AI models to quantify visual characteristics objectively and non-destructively.

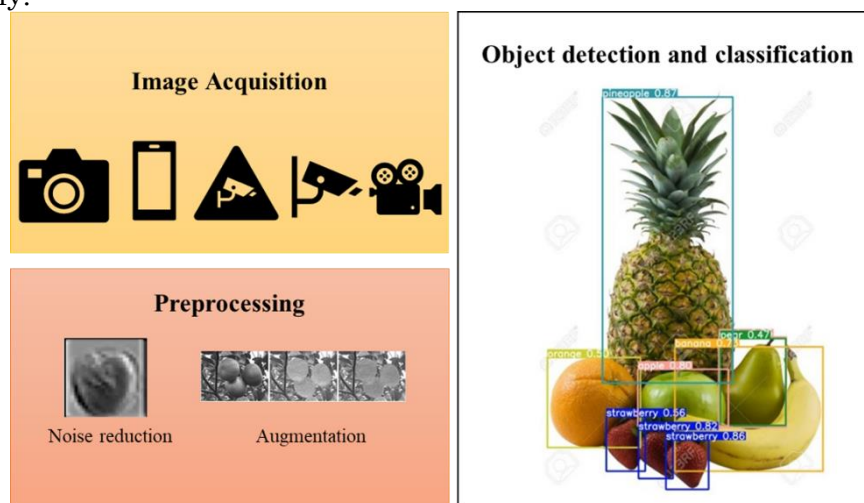


Figure 7: Key processes in computer vision

Applications of AI and CV in fruit sorting include:

- 1. Defect Detection:** Identifying rotting fruits, bruises, or internal defects.
- 2. Content Analysis:** Evaluating chemical or compositional attributes of fruits.
- 3. Maturity and Ripeness:** Assessing firmness and ripeness levels.
- 4. Quality Evaluation:** Measuring size, mass, and colour for precise grading.

Sensors and Technology

AI-powered sorting relies on various sensors:

- 1. RGB Cameras:** Used for surface defect detection, colour grading, and size estimation.
- 2. Hyperspectral and NIR Cameras:** Detect internal defects and chemical composition.
- 3. Thermal Cameras and Microphones:** Analyse ripeness or internal damage.
- 4. LiDAR and Positioning Systems (GPS, GNSS, RTK):** Enable co-robots to navigate orchards.
- 5. Force Sensors and IMUs:** Measure load, vibrations, and orientation to handle produce safely.

A typical system includes illumination devices, image acquisition hardware, frame-grabbers, computers for AI processing, and software programmed in C, C++, or MATLAB for real-time evaluation.

Robotics in On-Farm Transportation

AI doesn't stop at sorting. Co-robots assist with transporting bins and trays, reducing the physical strain on workers and preventing musculoskeletal injuries. These robots are equipped with **GPS, LiDAR, and sensors**, and controlled by AI algorithms that **plan optimal routes, avoid obstacles, and handle produce gently** to minimize mechanical damage.

Advantages of AI in Fruit Sorting

1. **Efficiency:** AI can process and grade thousands of fruits per hour, faster and more consistently than humans.
2. **Accuracy:** Detects internal and external defects invisible to the human eye.
3. **Safety:** Reduces the risk of worker injuries from repetitive tasks.
4. **Profitability:** Minimizes post-harvest losses and improves product quality for the market.

AI systems are particularly valuable for **small commercial farms**, where low-cost, reliable, and miniaturized solutions can directly sort and transport produce to storage or markets.

Conclusion

The integration of **AI, machine learning, deep learning, IoT, and computer vision** is transforming fruit sorting into a fully connected, intelligent process. Sensors collect real-time data, AI models make grading decisions, and robots handle transportation—all seamlessly. This **precision agriculture approach** improves efficiency, reduces waste, and optimizes resource use.

As AI-powered on-farm sorting continues to evolve, the days of slow, labour-intensive, and inconsistent manual grading are numbered. The future of agriculture is **smart, automated, and highly efficient**, ensuring that the journey from orchard to table is faster, safer, and more profitable than ever.

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Data: The New Fertilizer for Indian Farms

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Summary of Article

The article highlights how data-driven technologies are transforming Indian agriculture from traditional, experience-based practices into a precise, efficient, and resilient system. With the integration of ICT tools such as IoT sensors, drones, AI, and big data analytics, farmers can monitor soil health, predict yields, manage resources efficiently, and adapt to climate challenges. This data revolution enables smarter decision-making across every stage—from crop care to market strategy—enhancing productivity, sustainability, and profitability. Ultimately, data has become as essential as fertilizer, fuelling a new era of precision agriculture where the true growth lies not only in fields but also in information.

Introduction

Picture this, a mango farmer in Uttar Pradesh walks through his fields at dawn. Birds chirp, the soil smells fresh, and dew clings to leaves. But instead of relying solely on his eyes and experience, he checks his tablet. Sensors in the soil report moisture levels, drones scan for pests, and a weather forecast predicts a heatwave in two days. Based on this data, he adjusts irrigation, applies nutrients exactly where needed, and gears up for a harvest with minimal losses.

Welcome to modern Indian agriculture—a world where data flows as freely as water and decisions are as precise as the seeds sown. Today, information is as valuable as fertilizer, helping farmers grow smarter, more efficient, and profitable farms.

The Changing Face of Indian Agriculture

Farming in India has never been easy. Erratic rainfall, unpredictable temperatures, soil depletion, and fluctuating market prices make each season a challenge. Traditional methods alone no longer guarantee success. Farmers now need more than experience—they need insight. That's where data comes in. Just as seeds nourish crops, accurate, real-time information is nourishing decisions and transforming agriculture from guesswork into science.

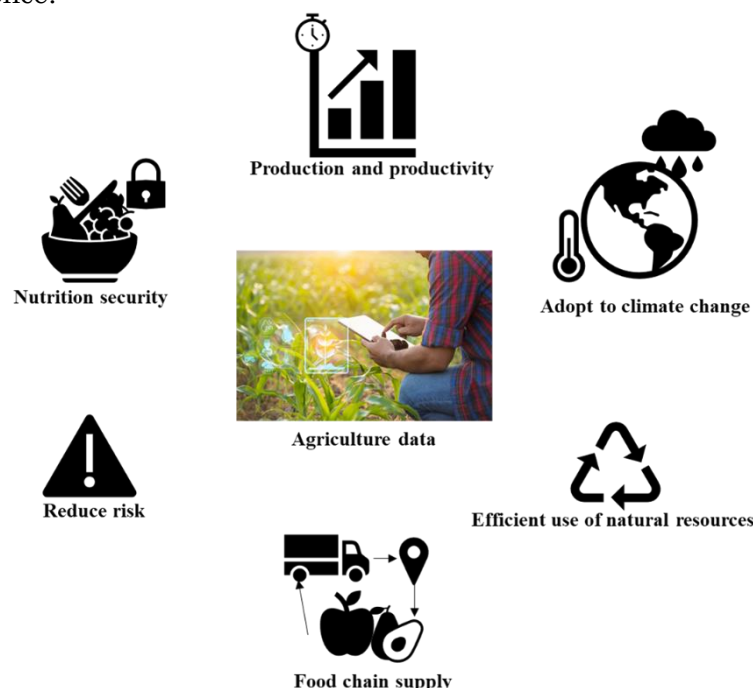


Figure 8: Benefits of data

ICT and the Data Revolution

Information and Communication Technologies (ICT) are being used worldwide to boost efficiency for farmers. This has sparked an explosion of data and led to new applications, tools, business models, and even entire industries dedicated to agriculture. Agri-food systems are transforming before our eyes.

Beyond technology, the collection and use of data for and from farmers has become a major growth area. Investments in big data, blockchain, precision agriculture, farmer profiling, and e-extension services are rising rapidly. Data-driven agriculture promises to:

1. Increase agricultural production and productivity.
2. Help farmers adapt to or mitigate climate change effects.
3. Promote more efficient use of natural resources.
4. Reduce risk and improve resilience in farming.
5. Make agri-food supply chains more efficient.
6. Ultimately contribute to global food and nutrition security.

Farms That Speak

Modern farms are becoming high-tech ecosystems. Sensors monitor soil moisture, humidity, and pest activity. Drones capture aerial images, and connected machinery logs planting, irrigation, and harvesting activity. At first glance, all this data may seem overwhelming—but when analyzed, it reveals patterns and trends that guide better decisions.

Smarter Farming, Step by Step

Data is changing every stage of agriculture:

1. Crop care: Sensors detect water or nutrient shortages before plants show stress.
2. Yield prediction: AI models forecast harvests, helping plan storage, logistics, and sales.
3. Resource efficiency: Precision irrigation and fertilizer application save water and money.
4. Market insights: Analytics help anticipate trends, ensuring fair prices and reducing losses.

As Farmobile CEO Tatge puts it, “Farmers have gotten the short end of the stick for too long. It’s time to understand the value of farm data and leverage it to their advantage.”

Data vs. Fertilizer: Why It Matters

Unlike traditional fertilizer, which nourishes plants directly, data nourishes decisions. Its benefits multiply when combined:

1. The same sensor data can improve irrigation, pest control, and yield forecasts.
2. Weather, soil maps, and market trends integrate to generate actionable insights.
3. Historical and real-time data powers AI-driven crop recommendations and drone monitoring.
4. Even small insights can translate into major gains in efficiency and productivity.

From Fields to the Market

Farm data doesn’t just help individual fields—it reshapes the supply chain. Farmers can negotiate better with suppliers, make informed choices, and reduce dependence on a handful of providers. Companies, too, must rethink strategies as connected devices reveal new competitors and opportunities.

Precision Agriculture in Action

AI, drones, and robotics bring precision farming to life. AI processes massive volumes of data, spotting patterns humans might miss. Drones perform aerial monitoring, robots assist with spraying, and automated systems optimize every input from water to fertilizer. Precision agriculture isn’t a concept anymore—it’s reality, making farming smarter, sustainable, and profitable.

Conclusion

Tomorrow's farms will rely as much on screens and sensors as on soil and sunlight. With IoT, AI, big data, and blockchain:

1. Crop stress and disease can be detected before they spread.
2. Yields can be forecasted, and market demand planned.
3. Resources can be used efficiently, reducing environmental impact.
4. Farmers can make smarter business decisions, leveling the playing field.

Data is no longer a byproduct—it is the fertilizer of the 21st century. By collecting, analyzing, and acting on insights, farmers can boost productivity, increase resilience, and safeguard agriculture's future.

In short, the seeds of tomorrow won't just be sown in soil—they'll be sown in data.

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Swachha Bharat, Swachha Krishi: Managing Liquid Agro Waste for a Cleaner Farm Future

Article ID: 72253

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Introduction

Liquid waste in agriculture and agro-industries refers to wastewater or effluent streams generated during irrigation, livestock management, and the processing of agricultural produce. Unlike solid wastes, liquid wastes can be more mobile and potentially hazardous due to dissolved organic matter, nutrients (N, P), heavy metals, detergents, pesticides, and pathogens, making their management both an environmental and public health imperative.

India's agro-industrial sector, which includes rice mills, sugar factories, oil extraction units, and dairy plants, generates millions of liters of wastewater daily. If untreated, these can lead to eutrophication, groundwater contamination, and soil degradation.

Sources of Liquid Waste in Agriculture

Liquid waste in agriculture arises from on-farm activities and agro-industrial processes. On farms, excess irrigation runoff carries nutrients, fertilizers, and pesticides into water bodies. Livestock operations generate urine, wash water, and slurry rich in organics and pathogens, while aquaculture discharges uneaten feed, excreta, and solids. Leachate from manure piles or silage pits adds nutrient-rich wastewater, posing risks to soil and groundwater.

Agro-industrial sources include rice mills (parboiling and cooling water with starch and husk residues), dairy units (milk washing and cleaning effluents with fats), sugar mills (spent wash and condensate with high BOD/COD), fruit and vegetable processing (washing, peeling, and blanching effluents rich in sugars and acids), and oil/solvent extraction plants (water contaminated with oils and solvents). Collectively, these effluents present significant challenges for sustainable wastewater management.

Characteristics of Liquid Agricultural Waste

The composition of liquid waste varies widely depending on the source and process involved. However, common characteristics include:

Table: Compositional characteristics of liquid waste:

Parameter	Typical Range	Significance
pH	4.5–9.0	Affects microbial activity
BOD (Biochemical Oxygen Demand)	200–6000 mg/L	Indicates organic pollution load
COD (Chemical Oxygen Demand)	400–10000 mg/L	Total oxygen demand for oxidation
TSS (Total Suspended Solids)	100–5000 mg/L	Affects filtration, sludge formation
Nutrients (N, P, K)	Variable	Contributes to eutrophication
Pathogens	High in livestock waste	Public health concern

(Source: CPCB Guidelines, 2017; FAO, 2011)

Environmental and Health Impacts of Poor Liquid Waste Management

- 1. Water pollution:** Entry of pathogens, chemicals, and excess nutrients into rivers and groundwater
- 2. Eutrophication:** Algal blooms due to high nitrogen and phosphorus content

3. Soil degradation: Salinity and heavy metal accumulation from long-term irrigation with untreated effluents

4. Odor and pest problems: Especially near dairy plants or sugar mills

5. Human and animal health issues: Diarrhea, typhoid, skin infections.

Need of Liquid Waste Management

The primary objectives of liquid waste management in agriculture and allied industries are to minimize environmental pollution and safeguard natural resources. Proper treatment and handling of effluents help prevent contamination of surface and groundwater while also avoiding soil salinization and toxicity when wastewater is reused for irrigation. Effective management further enables the recovery of valuable nutrients and water, thereby supporting agricultural reuse and reducing dependency on freshwater inputs. In addition, compliance with the discharge standards prescribed by regulatory agencies ensures that waste disposal does not pose ecological or public health risks. Ultimately, liquid waste management aims to integrate resource recovery with environmental protection, thereby fostering a circular economy approach within agro-industrial systems.

Regulations and Standards

In India, pollution control standards are regulated under:

1. The Environment (Protection) Act, 1986
2. Effluent discharge standards by CPCB and SPCBs
3. The Water (Prevention and Control of Pollution) Act, 1974
4. Agro-industries must install Effluent Treatment Plants (ETPs) and meet $BOD \leq 30 \text{ mg/L}$, $TSS \leq 100 \text{ mg/L}$ (for general discharge into inland surface waters).

Technologies for Liquid Waste Treatment and Management: Liquid waste management typically involves **collection, treatment, reuse, or safe disposal**. The choice of technology depends on the volume, pollutant load, land availability, and intended end use.

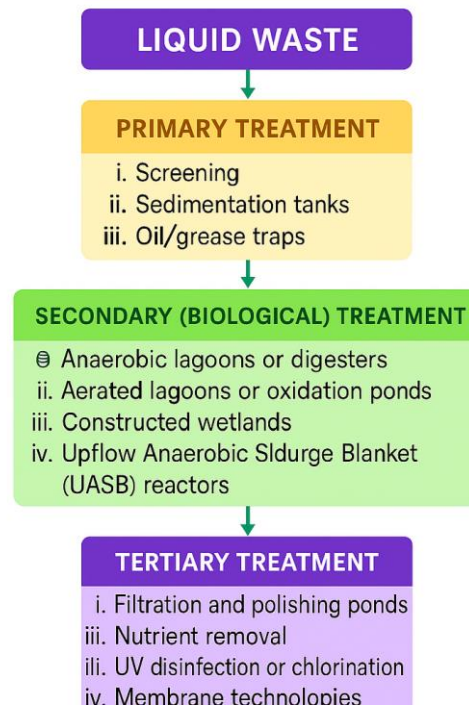
Primary Treatment

Primary treatment focuses on physical separation of coarse solids, settleable particles, and oils/grease from wastewater. Its aim is to reduce the load on secondary and tertiary systems, prolong equipment life, and prevent clogging.

1. Screening: Screening is the first stage of primary treatment used to remove large solids such as leaves, straw, pebbles, and packaging materials from wastewater. Common equipment includes bar screens (10–75 mm spacing) for coarse materials and fine screens (1–10 mm mesh) for smaller particulates. Wastewater passes through the screens, where solids are trapped and periodically removed either manually or mechanically. In agro-industries like sugar mills, screening helps eliminate fibrous matter before anaerobic digestion. It is simple and low-cost but does not remove dissolved organics or fine colloidal particles, which require further treatment.

2. Sedimentation Tanks: Sedimentation tanks separate settleable solids by gravity, reducing pollutant load before secondary treatment. They may be circular clarifiers with central feed and peripheral overflow or rectangular tanks equipped with sludge scrapers. Typically, they operate with a hydraulic retention time of 1.5–3 hours and a surface loading rate of 20–40 $\text{m}^3/\text{m}^2/\text{day}$. As flow slows, heavier particles settle as primary sludge, while clarified water moves to the next stage. In rice parboiling units, sedimentation removes husk and fine bran, reducing suspended solids by 50–60% and BOD by 25–35%, easing the load on later processes.

3. Oil/Grease Traps: Oil and grease traps remove floating fats, oils, and grease that can interfere with biological treatment. Based on the lower specific gravity of oils (0.90–0.95), these systems slow water velocity, allowing oils to rise and be skimmed off while heavier solids settle. They are common in **dairy plants** for milk fat removal and **oil mills** for edible oil residues. By removing these substances early, oil/grease traps prevent aerator clogging, enhance oxygen transfer, and improve the efficiency of downstream treatment systems.



Secondary (Biological) Treatment

Secondary treatment targets dissolved and colloidal organic matter using microbial activity under controlled conditions. **The objective is significant Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) reduction.**

1. Anaerobic Lagoons or Digesters: Anaerobic lagoons or digesters treat wastewater by degrading organic matter without oxygen, producing biogas (mainly methane and CO₂). They are 3–5 m deep, with hydraulic retention times of 20–60 days depending on organic load and temperature. Covered lagoons allow biogas collection for energy use. Anaerobic bacteria convert organic matter to volatile fatty acids, which methanogens transform into methane. Commonly used for dairy and pig farm effluents, these systems offer energy recovery and low operational costs but require temperature control in colder climates.

2. Aerated Lagoons or Oxidation Ponds: Aerated lagoons reduce wastewater BOD through aerobic microbial activity. With depths of 1–3 m and retention times of 5–20 days, aeration via mechanical or diffused air supports aerobic bacteria that convert organic carbon to CO₂ and water. Suitable for fruit-processing wastewater, these lagoons offer simple design, odor control, and high BOD removal (>80%), but high energy demand for aeration increases operational costs.

3. Constructed Wetlands: Constructed wetlands mimic natural wetland purification using plants, substrates, and microbes. Surface flow wetlands allow water to move over soil, while subsurface flow passes through gravel or soil. Sedimentation, filtration, microbial degradation, and plant nutrient uptake (e.g., Phragmites, Typha) remove solids, organics, and nutrients like N and P. Used for aquaculture, dairy, and biodegradable agricultural effluents, they are low-maintenance, energy-efficient, and enhance biodiversity, but require large land areas.

4. Upflow Anaerobic Sludge Blanket (UASB) Reactors: UASB reactors treat wastewater anaerobically by allowing it to flow upward through a dense sludge blanket where microbes degrade organic matter, producing biogas. They are compact, energy-efficient, and suitable for high-strength effluents like dairy and industrial wastewater. Advantages include biogas recovery, low operational costs, and minimal energy use; however, they require careful monitoring of hydraulic and organic loading to maintain performance.

Tertiary Treatment

Tertiary (or advanced) treatment polishes the effluent for high-quality reuse (e.g., irrigation, aquaculture, industrial process water).

1. Filtration and Polishing Ponds: Filtration and polishing ponds provide the final stage of wastewater treatment, removing fine suspended solids, residual organics, and pathogens. Sand or multimedia filters trap particles, reducing turbidity, while polishing ponds—shallow, aerated basins—enhance treatment via aerobic degradation, solar disinfection, and pathogen die-off. This stage stabilizes BOD, COD, and coliform levels, making effluent suitable for reuse in irrigation. The system is low-cost, environmentally friendly, and easy to maintain, though efficiency depends on climate, pond depth, and retention time.

2. Nutrient Removal: Tertiary nutrient removal targets excess nitrogen and phosphorus to prevent eutrophication. Struvite precipitation recovers magnesium ammonium phosphate as a slow-release fertilizer, while biological nutrient removal (BNR) uses aerobic and anaerobic zones for nitrification, denitrification, and microbial phosphorus uptake. These methods mitigate nutrient pollution and support resource recovery, e.g., in poultry processing effluent for fertilizer production.

3. UV Disinfection or Chlorination: UV disinfection and chlorination ensure pathogen removal in treated effluent. UV radiation destroys microbial DNA without chemicals, while chlorination provides residual disinfection but may form by-products like trihalomethanes. Both methods are widely applied in agricultural irrigation and aquaculture water reuse, ensuring microbial safety when combined with earlier treatment stages.

4. Membrane Technologies: Membrane processes—microfiltration, ultrafiltration, nanofiltration, and reverse osmosis—achieve high-quality effluent for industrial and agricultural reuse. They selectively separate contaminants, removing suspended solids, pathogens, salts, nutrients, and micropollutants. While producing near-potable water, these systems have high capital and operational costs and require regular maintenance to prevent fouling. Despite this, they are increasingly used in modern wastewater reclamation for sustainable water management.

Integrated Approach to Liquid Waste Management

An integrated strategy includes:

1. Waste minimization at source (e.g., water-efficient processing)
2. Segregation of clean and contaminated streams
3. Decentralized treatment systems for rural clusters
4. Training and capacity building of farmers and plant operators
5. Use of digital tools for effluent monitoring.

Reuse and Recycling of Treated Liquid Waste

Instead of disposal, treated wastewater can be a valuable resource:

In Agriculture:

- a. **Irrigation:** Nutrient-rich water (after pathogen removal) enhances crop yield
- b. **Fertigation:** Integrating irrigation and fertilization via wastewater
- c. **Aquaculture:** Treated effluent reused in fish ponds under monitored conditions

In Industry:

- a. Cooling water in plants
- b. Cleaning and floor washings
- c. Boiler feed after further treatment

In Energy Systems:

- a. Biogas production from dairy and agro-waste slurry
- b. Algal cultivation using nutrient-rich wastewater for biofuel or feed.

Case Example: Dairy Industry Wastewater Management in India

1. Generation: 2–10 liters of effluent per liter of milk processed
2. Issues: High BOD (~2000–3000 mg/L), fats, detergents
3. Solutions:
 - a. Anaerobic digestion → Biogas
 - b. Reuse of treated water for floor cleaning or gardening
 - c. Sludge used as compost.

Conclusion

Liquid waste management in agriculture and agro-processing sectors is vital for environmental sustainability, public health, and resource recovery. Through appropriate treatment and reuse systems—especially low-cost, decentralized options—liquid waste can be transformed from a liability into a valuable input for farming, energy, and industry.

The Rarity of Blue in Nature: The Hidden Science Behind Blue

Article ID: 72254

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Abstract

Among the broad spectrum of colors found in nature, blue remains one of the rarest and most striking. Unlike green, red, or yellow, blue coloration seldom results from true pigments but rather from complex structural and biochemical mechanisms. This article explores the scientific principles behind the rarity of blue in nature, focusing on plants, pigments, and evolutionary significance. It highlights how anthocyanins, pH balance, metal ions, and light interference contribute to blue hues in flowers and how these traits evolved under specific ecological pressures.

Introduction

Nature displays an incredible diversity of colors that play essential roles in communication, adaptation, and survival. However, among this diversity, blue stands out as a rare and captivating color. The rarity of blue in both flora and fauna has intrigued scientists and artists alike for centuries. While green leaves dominate landscapes and red or yellow flowers attract pollinators, true blue pigmentation is observed in less than 10% of flowering plant species (Lee, 2007). The reason for this scarcity is deeply rooted in chemistry, physics, and evolutionary biology. The scientific explanation for blue's rarity lies in the limited availability of blue pigments, the structural complexity required to reflect blue light, and the evolutionary costs of producing such coloration. This article examines these aspects in detail, focusing on examples from the plant kingdom and their evolutionary implications.

The Science of Color in Nature

Pigments and Light Reflection: Color in biological organisms primarily arises from pigments—chemical compounds that absorb specific wavelengths of visible light and reflect others. The visible color of an object corresponds to the wavelengths of light it reflects.

For instance:

- Chlorophyll absorbs blue and red light, reflecting green, which explains the dominance of green vegetation.
- Carotenoids absorb blue and violet light, producing yellow, orange, or red hues.
- Anthocyanins, a group of flavonoid pigments, produce red, purple, or blue shades depending on cellular conditions (Grotewold, 2006).

However, true blue pigments are extremely rare. Producing a molecule that absorbs red and green light while reflecting blue requires a complex electronic structure—something few natural pigments can achieve. As a result, many “blue” colors in nature are not pigments at all but are produced by structural coloration, which manipulates light physically rather than chemically (Prum & Torres, 2003).

Structural Coloration: Physics Over Chemistry

Principle of Structural Coloration: Structural coloration occurs when micro- or nano-scale structures interfere with incoming light waves, scattering shorter (blue) wavelengths while absorbing or canceling others. This phenomenon can produce brilliant, iridescent blues without pigments.

Examples include:

- Morpho butterfly wings, where microscopic ridges reflect blue light (Vukusic & Sambles, 2003).
- Peacock feathers, whose nanostructures diffract light to create iridescence.

3. Blue fruits, such as *Viburnum tinus* and *Pollia condensata*, whose cell wall structures reflect blue through thin-film interference (Vignolini et al., 2012).

In plants, blue fruits are relatively rare and often result from structural rather than pigment-based coloration, giving them metallic or glossy appearances.

Blue Pigments in Plants: The Chemistry of Rarity

1. Anthocyanins and pH Modulation: The few plants that display blue flowers rely on anthocyanins, particularly the delphinidin class of molecules. Anthocyanins are water-soluble pigments located in vacuoles, and their color depends on the pH of the surrounding environment and the presence of metal ions (Kondo et al., 2009).

- a. In acidic conditions, anthocyanins appear red.
- b. In neutral conditions, they appear purple.
- c. In alkaline environments, they appear blue.

This explains why some flowers change color depending on soil pH or nutrient content. For example, hydrangeas (*Hydrangea macrophylla*) turn blue in acidic soils rich in aluminum ions, which stabilize the blue anthocyanin complex, and pink in alkaline soils (Yoshida et al., 2003).

2. Metal Complex Formation: Blue coloration in flowers often depends on the formation of metal–anthocyanin complexes. Metal ions such as Mg^{2+} , Fe^{3+} , or Al^{3+} interact with anthocyanins and co-pigments to shift the absorption spectrum toward blue wavelengths.

For example:

- a. In cornflowers (*Centaurea cyanus*), the blue pigment results from a supramolecular complex of anthocyanin (cyanidin), flavone, and Fe^{3+} ions (Kondo et al., 2009).
- b. Bluebells (*Hyacinthoides non-scripta*) produce delphinidin-based pigments that yield vivid blue tones under specific pH and ion conditions.
- c. The Himalayan blue poppy (*Meconopsis betonicifolia*), native to high-altitude regions, synthesizes unique anthocyanins that remain stable in blue form due to its cooler, alkaline environment.

Thus, true blue pigmentation in plants requires a perfect chemical balance, one that few species can achieve or sustain.

Examples of Blue Coloration in Plants

1. Hydrangea (*Hydrangea macrophylla*): The color transition in hydrangeas exemplifies how soil chemistry determines pigment expression. Blue hydrangeas form in acidic soils (pH < 5.5) where aluminum ions are bioavailable, forming stable complexes with anthocyanins (Yoshida et al., 2003).

2. Cornflower (*Centaurea cyanus*): Cornflower blue results from metal–anthocyanin–flavone complexes, which stabilize cyanidin molecules in a blue state. This structure has been elucidated using X-ray crystallography, confirming the role of Fe^{3+} and Mg^{2+} ions (Kondo et al., 2009).

3. Himalayan Blue Poppy (*Meconopsis betonicifolia*): Native to the Himalayas, this species thrives in cool, slightly alkaline conditions where anthocyanins remain stable in their blue form. The unique pigment combination and cellular pH create one of nature's truest blues (Tanaka et al., 2008).

4. Blueberries and Viburnum Fruits: While blueberries appear blue, their pigment, anthocyanin, is actually purple. The apparent blue color arises from light scattering through waxy cuticles on fruit skin (Jacobs et al., 2019). Similarly, *Viburnum tinus* produces a structural blue sheen from lipid layer arrangements.

Evolutionary Perspectives: Why Blue is Rare?

1. Evolutionary Costs and Limitations: Producing blue pigments requires complex biosynthetic pathways, precise pH control, and often the presence of specific metal ions. These demands are metabolically costly and offer limited adaptive advantage in most environments (Lee, 2007). In contrast, pigments like chlorophyll and carotenoids are simpler to synthesize and serve essential physiological functions—photosynthesis and photoprotection, respectively. Evolution thus favors efficiency over aesthetics unless coloration offers a clear reproductive or ecological advantage.

2. Blue as a Signal in Evolution: When blue does evolve, it often serves as a signal for pollinators. Bees, for example, have trichromatic vision sensitive to ultraviolet, blue, and green light (Chittka & Menzel, 1992). Blue flowers thus effectively attract bee pollinators, enhancing reproductive success.

Some notable examples include:

- a. Lobelia, Salvia, and Gentiana species that evolved blue petals specifically to attract bees.
- b. Blue irises that rely on visual contrast in their habitats.

Thus, while blue is rare, its emergence often reflects co-evolution between plants and pollinators, particularly in temperate ecosystems.

3. Structural Color Evolution in Animals: In animals, blue frequently arises through evolutionary adaptation for signaling or camouflage. The blue morpho butterfly uses structural color for mate attraction, while blue jays display blue feathers that result from nanoscale keratin-air structures rather than pigment (Prum & Torres, 2003). These structures evolved independently in multiple lineages, indicating convergent evolution driven by visual communication and environmental factors.

The Intersection of Physics, Chemistry and Biology

The rarity of blue in nature beautifully illustrates the interdisciplinary nature of color production.

1. Physics explains how light interacts with surfaces to create structural blues.
2. Chemistry describes how molecular bonds and ions shift pigment hues.
3. Biology and evolution determine when and why these mechanisms are advantageous.

Nature's blue is therefore not a simple pigment, but a symphony of molecular design, optical precision, and ecological purpose.

Cultural and Scientific Significance

The scarcity of blue has also made it symbolically precious in human culture. Historically, natural blue dyes such as lapis lazuli and indigo were rare and expensive, mirroring their biological rarity. Modern scientists study natural blue coloration to develop bio-inspired materials, such as colorfast fabrics, nanoscale coatings, and eco-friendly dyes that mimic structural colors without harmful chemicals (Vukusic & Sambles, 2003).

Conclusion

The rarity of blue in nature is not due to aesthetic bias but to scientific constraints in pigment chemistry and light manipulation. Only a few plants and animals have evolved the structural and chemical sophistication required to produce blue hues. From the delicate Himalayan blue poppy to the iridescent morpho butterfly, every natural instance of blue represents a remarkable evolutionary and biochemical achievement. In essence, blue is rare because it is complex to create, costly to maintain, and only sometimes advantageous — making it one of nature's most exquisite exceptions.

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Post-Harvest Diseases of Fruits and Vegetables

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Abstract

Postharvest diseases of fruits and vegetables are a major cause of quantitative and qualitative losses along the food chain, driven primarily by necrotrophic fungi and a smaller set of bacteria and physiological disorders. These losses reduce food availability, farmer income and marketability, and pose food-safety risks through mycotoxins. Effective control of postharvest diseases requires an integrated approach: good pre- and postharvest practices to minimize inoculum and wounds; temperature, humidity and atmosphere management (cold chain and controlled atmosphere); sanitation and hygiene; targeted physical treatments; safe chemical interventions where regulated and necessary; and increasing deployment of non-chemical tools such as biological control agents (BCAs), edible coatings, and novel physical and nanotechnology-based methods. Despite progress, major gaps remain in low-cost cold chain access for smallholders, scalable biological products, rapid in-field diagnostics, and policies and infrastructure to reduce losses at scale.

Introduction

Fruits and vegetables are highly perishable commodities. Postharvest losses—losses occurring between harvest and consumption—are substantial for horticultural produce and, according to FAO estimates, represent a large fraction of global food losses for perishable crops. These losses are caused by biological agents (primarily fungi and bacteria), physical damage and physiological disorders, and are exacerbated by inadequate handling, transport and storage (especially lack of cold chain). Reducing postharvest disease is therefore critical for food security, farmer livelihoods, waste reduction and food-safety (mycotoxins) objectives.

Table 1: Major Postharvest Diseases of Fruits and Vegetables, Their Causal Organisms, and Management Strategies:

Crop	Postharvest Disease	Causal Organism(s)	Management / Control Measures
Apple	Blue mold, Gray mold, Bitter rot	<i>Penicillium expansum</i> , <i>Botrytis cinerea</i> , <i>Colletotrichum gloeosporioides</i>	Rapid cooling after harvest; sanitation of bins; fungicidal dips (imazalil, thiabendazole where allowed); biological antagonists (e.g., <i>Candida sake</i>); storage at 0–1°C, 90–95% RH
Banana	Crown rot, Anthracnose	<i>Colletotrichum musae</i> , <i>Fusarium semitectum</i>	Hot water treatment (50–55°C for 5 min); fungicide dips; careful handling to prevent crown injury; maintain temperature 13–14°C
Citrus (Orange, Lemon)	Green mold, Blue mold	<i>Penicillium digitatum</i> , <i>P. italicum</i>	Sanitation of packinghouse; fungicide dips (imazalil, sodium o-phenylphenate); waxing; maintain 4–7°C cold storage; use of biological control (<i>Pseudomonas putida</i>)
Mango	Anthracnose, Stem-end rot	<i>Colletotrichum gloeosporioides</i> , <i>Lasiodiplodia theobromae</i>	Hot water treatment (52°C, 5 min); fungicide dip (thiabendazole); CA storage; field sanitation and preharvest fungicide sprays
Papaya	Anthracnose, Stem-end rot	<i>Colletotrichum gloeosporioides</i> , <i>Phomopsis caricae-papayae</i>	Hot water treatment; calcium chloride dips; postharvest fungicide spray; proper ventilation during storage

Grape	Gray mold, Rhizopus rot	<i>Botrytis cinerea</i> , <i>Rhizopus stolonifer</i>	Preharvest fungicide sprays; sulfur dioxide fumigation; maintain 0°C, 90–95% RH; biological control (<i>Aureobasidium pullulans</i>)
Guava	Anthracnose, Alternaria rot	<i>Colletotrichum psidii</i> , <i>Alternaria alternata</i>	Harvest at optimal maturity; postharvest hot water (50°C); fungicidal dip; maintain cold storage at 5–8°C
Pomegranate	Fruit rot, Aspergillus rot	<i>Alternaria alternata</i> , <i>Aspergillus niger</i>	Avoid mechanical injury; proper drying before storage; application of fungicides; storage at 5°C, low humidity
Tomato	Alternaria rot, Rhizopus soft rot	<i>Alternaria alternata</i> , <i>Rhizopus stolonifer</i>	Handle gently to avoid wounds; chlorine (100 ppm) wash; storage at 12–15°C; use of edible coatings (chitosan + essential oils)
Potato	Soft rot, Dry rot	<i>Pectobacterium carotovorum</i> , <i>Fusarium solani</i>	Avoid injury during harvest; cure tubers at 18°C, 90% RH for 10 days; maintain dry storage (4–5°C); proper ventilation
Onion	Neck rot, Black mold	<i>Botrytis allii</i> , <i>Aspergillus niger</i>	Cure bulbs before storage; avoid bruising; dry storage at <30% RH, 0–2°C; fungicidal dusting with approved chemicals
Carrot	Bacterial soft rot, Sclerotinia rot	<i>Erwinia carotovora</i> , <i>Sclerotinia sclerotiorum</i>	Avoid washing before storage; sanitize wash water; cold storage at 0°C, 95% RH; chlorine dips
Cabbage	Bacterial soft rot	<i>Pectobacterium carotovorum</i>	Pre-cooling; avoid over-trimming; sanitize containers; cold storage at 0°C; maintain low free water on surfaces
Chili / Capsicum	Anthracnose, Alternaria rot	<i>Colletotrichum capsici</i> , <i>Alternaria alternata</i>	Field sanitation; avoid overripe fruits; hot air drying; postharvest fungicidal dip; modified atmosphere packaging
Brinjal (Eggplant)	Alternaria rot, Rhizopus rot	<i>Alternaria solani</i> , <i>Rhizopus stolonifer</i>	Handle gently; surface disinfection with sodium hypochlorite (0.1%); cold storage at 10–12°C; edible coating treatment
Cucumber	Watery rot, Soft rot	<i>Pythium spp.</i> , <i>Erwinia spp.</i>	Proper drainage and clean handling; avoid condensation in storage; chlorine sanitation; cold storage 7–10°C
Strawberry	Gray mold, Rhizopus rot	<i>Botrytis cinerea</i> , <i>Rhizopus stolonifer</i>	Rapid cooling to 0°C; high CO ₂ MAP packaging; biological control (<i>Trichoderma harzianum</i>); avoid washing before sale
Pineapple	Black rot, Fruitlet core rot	<i>Ceratocystis paradoxa</i> , <i>Penicillium funiculosum</i>	Hot water treatment (52°C, 5 min); controlled atmosphere (5% O ₂ + 10% CO ₂); waxing; avoid overripe harvest
Okra	Alternaria rot, Rhizopus rot	<i>Alternaria alternata</i> , <i>Rhizopus stolonifer</i>	Avoid bruising during picking; use perforated crates; store at 8–10°C; chitosan coating to reduce decay
Lettuce / Leafy greens	Soft rot, Gray mold	<i>Pectobacterium carotovorum</i> , <i>Botrytis cinerea</i>	Sanitize wash water (100 ppm chlorine); hydrocooling; storage at 0°C; modified atmosphere packaging (MAP)
Pumpkin / Squash	Black rot, Fusarium rot	<i>Didymella bryoniae</i> , <i>Fusarium spp.</i>	Cure fruits before storage; avoid chilling (<10°C); storage at 12–14°C, 60% RH; sanitize storage bins

Disease Cycle and Epidemiology

Postharvest disease development is triggered by primary inoculum sources such as orchard residues, latent infections, and contaminated equipment. Pathogens enter through wounds during harvest or exploit latent infections established preharvest. Environmental factors like temperature, relative humidity, and atmospheric composition significantly influence disease progression. While cold temperatures can delay pathogen growth and host senescence, some pathogens thrive in specific temperature ranges. Understanding these factors is crucial for developing effective postharvest disease management strategies that combine good agricultural practices, proper handling, and optimal storage conditions to minimize disease risk and maintain produce quality.

Factors Influencing Postharvest Disease Development

Postharvest disease development is influenced by a combination of preharvest, harvest, handling, and storage factors. Preharvest factors such as cultivar susceptibility, irrigation management, nutrient status, and disease control in the field can impact produce quality. Harvest practices like timing, picking methods, and sanitation of harvest containers also play a crucial role. During handling and transport, mechanical injuries, temperature shocks, and prolonged exposure to high relative humidity can increase disease risk. Furthermore, storage environment factors like inadequate refrigeration, poor ventilation, high ethylene levels, and unregulated atmospheres can exacerbate disease development. Effective temperature management and rapid cooling are critical in slowing down disease development and maintaining produce quality.

Detection and Monitoring

Detection and monitoring of produce quality involve various methods, including visual inspection and sorting, rapid diagnostics like molecular tests and biosensors, VOC profiling, and microbial monitoring. While visual inspection is limited for latent infections, rapid diagnostics and VOC profiling show promise for early spoilage detection. Microbial monitoring assesses sanitation efficacy in packinghouses. Recent research highlights the potential of VOC signatures and biosensor platforms for early detection of spoilage organisms, enabling rapid and accurate monitoring to improve product quality, reduce waste and enhance food safety.



Blue mold
Penicillium expnsum



Gray mold
Botrytis cinerea



Green mold
Penicillium digitatum



Green mol
Brown rot

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Anthracnose
Colletotrichum



Gray mold
Botrytis cinerea



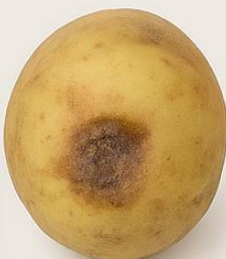
Anthracnose
Colletotrichum psi



Pomegranate
Fruit rot



Alternaria rot
Aiternaria



Soft rot
Pectobacterium



Neck rot
Botrytis allii



Bacchial
Erwinia carotovora



Bacterial soft rot
Pectobacterium carotovorum



Anthracnose
Colletotrichum capsici



Alternaria rot
Alternaria solani



Watery rot
Pythium spp.

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Management Strategies — Integrated Approaches

An integrated pest management (IPM) style approach for postharvest disease combines preventive measures, sanitary practices and targeted interventions. Below we summarize major approaches.

1. Prevention and hygiene (first line): Preharvest disease management: reduce field inoculum via pruning, removal of mummified fruits, fungicide programs timed to reduce latent infections.

Good harvesting practices: harvest at recommended maturity, minimize handling injuries, use clean bins and sanitized tools, exclude obviously diseased fruits.

Facility hygiene: regular cleaning and disinfection of packing lines, crates and cold rooms to reduce cross-contamination.

2. Temperature and atmosphere management: Rapid cooling (hydrocooling, forced-air, vacuum cooling) immediately after harvest reduces respiration and pathogen growth.

Cold storage — many pathogens are slowed at low temperatures; however, chilling-sensitive commodities require careful temperature management.

Controlled Atmosphere (CA) and Modified Atmosphere Packaging (MAP) — reduced O₂ and elevated CO₂ can extend shelf life and suppress certain pathogens when matched to commodity tolerance.

(Kader's textbook and UC Davis postharvest resources provide standardized temperature/atmosphere targets for many commodities.)

3. Chemical control: Postharvest fungicides and sanitizers — synthetic fungicides have been widely used (e.g., thiabendazole, imazalil for citrus), as have sanitizers such as chlorine, peracetic acid, and hydrogen peroxide—subject to regulatory limits and residue concerns.

Limitations: fungicide resistance, regulatory restrictions, residue and consumer acceptance make routine use increasingly constrained.

4. Physical and non-thermal methods: Hot water and heat treatments — effective surface disinfection and induction of host defences but can affect sensory quality if not optimized.

Irradiation, high-pressure processing, pulsed electric fields, ultrasound and cold plasma — non-thermal approaches under experimentation and some commercial use; cold plasma shows rapid reduction of surface inoculum with minimal heat damage.

Modified handling (gentle sorting, cushioning, shock-reduction) to reduce wound-related entry points.

5. Biological control and antagonists: Yeasts, bacteria and fungal antagonists (commercial BCAs) are used to outcompete or antagonize rot pathogens on fruit surfaces; mechanisms include competition, antibiosis, lytic enzymes and induction of host resistance. Yeast antagonists have been commercialized for some crops. Biological control is especially attractive where chemical use is restricted.

6. Edible coatings and films: Chitosan, alginate, starch, and composite coatings provide barrier properties to water loss and gas exchange, sometimes combined with antimicrobial agents (essential oils, nanoparticles) to reduce decay and extend shelf life. Meta-analyses and reviews indicate consistent quality improvements, though efficacy varies by commodity and formulation.

7. Nanotechnology and novel formulations: Nanoparticles (e.g., ZnO, TiO₂) and nano-emulsions loaded with essential oils or antimicrobials can enhance delivery and stability; while promising in lab studies, regulatory, safety and scale-up issues remain active research areas.

8. Packaging technologies: Active packaging: antimicrobial films, oxygen scavengers and moisture controllers help maintain quality and reduce rot.

Cold chain integration: appropriate packaging that supports rapid cooling and CA conditions reduces disease.

Mycotoxins and Food Safety

Certain postharvest fungi (*Aspergillus*, *Penicillium*, *Fusarium*) produce mycotoxins contaminating fruit and vegetables or their processed products. Mycotoxins are heat-stable and represent public-health hazards; therefore, prevention of fungal growth (prevention of contamination and rapid cold-chain) is more effective than attempts at remediation.

Socio-Economic and Supply-Chain Considerations

1. Magnitude of losses: older FAO estimates indicated that roughly one-third of food produced for human consumption is lost or wasted globally; fruits and vegetables are disproportionately affected due to

perishability, weak cold chain, and market standards that exclude imperfect produce. Losses have direct economic consequences for growers and raise consumer prices.

2. Smallholder constraints: lack of affordable refrigeration, poor transport infrastructure and limited access to postharvest technologies are principal barriers in low- and middle-income countries. Low-cost interventions (improved sorting, evaporative cooling, sanitation, solar cold rooms) can yield high returns.

3. Policy and market levers: investments in rural infrastructure, aggregation centres, postharvest training, grading/market access and incentives for cold-chain development reduce losses.

Research Advances and Future Directions

Research advances in early detection technologies, such as biosensors, VOC profiling, and machine-vision sorting, enable earlier detection of latent infections, reducing the distribution of infected produce. Scalable biological solutions, including robust and shelf-stable biological control agents (BCAs), are being developed with predictable field performance and registration pathways. Optimized edible coatings and safe nano-delivery systems are transitioning from lab-scale success to standardized commercial products. Additionally, data-driven logistics, such as IoT temperature sensors and blockchain traceability, minimize temperature abuse during distribution. There's also a growing emphasis on sustainability and residue-free approaches, including non-chemical methods, combined treatments, and minimizing environmental footprint. Novel physical treatments like cold plasma and high-pressure, as well as integrated biological and coating approaches, are promising areas for future research.

Practical Recommendations

To maintain produce quality and extend shelf life, minimize preharvest inoculum through sanitation, disease control, and field hygiene. Harvest at recommended maturity and handle gently to avoid wounds. Rapidly cool produce and maintain cold storage conditions, ensuring temperature control, the most cost-effective factor for shelf-life extension. Implement good sanitation practices at packinghouses, including cleaning and disinfecting surfaces, crates, and water. For smallholders and markets, adopt low-cost cooling methods like evaporative or forced-air cooling, use improved crates, and provide training on proper handling practices.

Conclusion

Postharvest diseases of fruits and vegetables represent a multifaceted challenge—biological, environmental and socio-economic. Traditional approaches (cold chain, sanitation, fungicides) remain central, but sustainable reduction of losses increasingly depends on integrated systems that include biological control, edible coatings, advanced diagnostics and affordable cold-chain solutions for smallholders. Continued interdisciplinary research and targeted investments in infrastructure and regulatory pathways for novel technologies will be essential to reduce losses, improve food safety and strengthen value chains.

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A Brief Insight on Off Season Cole Crop Cultivation

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Summary

Off-season cultivation of cole crops (*Brassica* spp.) like cabbage, cauliflower, broccoli, knolkhol, kale, Chinese cabbage) enables year-round supply, higher market prices, and improved farm incomes by exploiting temporal market windows and diverse agroclimatic niches. Successful off-season production combines site and season selection, appropriate cultivar choice, protected/modified environments (polyhouses, low tunnels, mulches), precise nursery management, altered sowing/planting schedules, irrigation and nutrient adjustments, and proactive pest-disease management. While technology (protected structures, season-stretching agronomy) offers strong yield and quality advantages, adoption faces constraints (capital costs, pest/disease pressure, labor and input costs, market timing). This review synthesizes agronomic principles, production practices, biotic/abiotic constraints, and socioeconomic considerations for off-season cole crops with practical recommendations for researchers, extensionists and growers.

Introduction

Cole crops (*Brassica oleracea* and related species) are high-value vegetables with wide nutritional and commercial importance. Off-season cultivation — growing outside the traditional or peak harvest season — aims to (a) capture premium market prices, (b) supply urban/peri-urban demand year-round, (c) reduce glut in main seasons, and (d) utilize otherwise underused agroclimatic windows (riverbeds/diara lands, hills, protected structures). In many regions of India and globally, off-season production is increasingly pursued using both open-field agroclimatic advantages and protected cultivation technologies.

Table 1: Common cole crops (*Brassicaceae* family) grown in India:

Crop	Botanical Name
Cabbage	<i>Brassica oleracea</i> var. <i>capitata</i>
Cauliflower	<i>Brassica oleracea</i> var. <i>botrytis</i>
Broccoli	<i>Brassica oleracea</i> var. <i>italica</i>
Kohlrabi / Knol Khol	<i>Brassica oleracea</i> var. <i>gongylodes</i>
Kale / Leafy Brassicas	<i>B. oleracea</i> var. <i>acephala</i> (kale), mustard greens etc.
Chinese cabbage / Pak-choi / Bok choy	<i>Brassica rapa</i> / <i>B. chinensis</i> group (some are less common in many regions)

Agro-climatic Strategies for Off-Season Production

1. Exploiting Agroclimatic Diversity: Regions with contrasting temperature and day-length (hills, highlands, riverine diara lands, northern plains in cool months) allow growers to schedule cole crops outside normal season windows. For example, hilly areas provide summer off-season opportunities for cauliflower and cabbage that would otherwise be cool-season crops in plains.

2. Protected and Microclimate Modification: Polyhouses, naturally ventilated greenhouses, low tunnels, shade nets, and mulches allow growers to control temperature, relative humidity and radiation to suit the crop's phenology, enabling winter or summer off-season production depending on method. Protected cultivation reduces exposure to extreme cold/heat, can lower pest incidence for some pests, and improves uniformity and quality. However, different protected structures have crop- and location-specific cost-benefit profiles.

Varietal Selection and Breeding Considerations

1. Maturity class and heat tolerance: Early and heat-tolerant cultivars help avoid curd/heading problems (e.g., fuzziness in cauliflower) when grown in warmer off-seasons. Varietal trials and hybrids developed for year-round production have been standardized in certain zones (e.g., Kullu valley studies for cabbage and cauliflower).

2. Hybrid vs open-pollinated: Hybrids often give uniform heads/curds, better marketable yield and stress tolerance, making them preferable for high-value off-season production despite higher seed cost.

Table 2: Heat tolerant Cole crops varieties and hybrids:

Crop	Variety / Hybrid (heat-tolerant / tropical type)	Source	Notes (season / traits)
Cauliflower	Pusa Deepali	ICAR / IARI (Pusa series) — public.	Early, tropical/warmer-season type; used for extended/early planting.
	Pusa Snowball K-1 (and Snowball series; Pusa Hybrid-1)	ICAR / IARI — public.	Snowball types (some are late-maturing temperate) but several Pusa hybrids and early types were bred/tropicized for Indian conditions; Pusa Hybrid-1 used for wider adaptation.
	Arka Kanti	ICAR-IIHR (IIHR Bangalore) — public.	IIHR release; compact heads, adapted to warmer/rainy windows (popular in plains).
	Ooty-1	State (TCV/Ooty/UPAS) / ICAR lists — public.	Developed/adapted for hill/tropical high-altitude plantings (regional release).
	(Commercial hybrids e.g., 'Rajkumar F1', 'Seminis SV4051AC', C-6099)	Private seed houses (company hybrids) — not govt.	Widely marketed as tropical/summer hybrids; check local trials before large scale use.
	Rajkumar F1 (Cauliflower)	Private Sector	Bred for summer / hot-season cultivation; performs in high temperatures.
	<i>Summer King F1</i> , <i>Summer Beauty F1</i> , <i>BN-40 F1</i> , <i>Chakra-1000 F1</i> , <i>BN-50 F1</i> etc.	Private Sector	Varieties/hybrids tolerant of heat and rain, early maturity (≈40-50 days for some) for summer off-season cauliflower.
	Syngenta C-6099	Private Sector	Tropical season hybrid, semi-dome compact curds; marketed as heat tolerant.
Cabbage	Pusa Ageti / Pusa Drum Head / Pusa Mukta (Pusa series)	ICAR / IARI — public.	Pusa lines include some varieties adapted to warmer seasons or early plantings.
	Palam Samridhi (and other Palam series)	ICAR / IARI / Palampur (HPU) — public.	Released for good adaptability; used in diverse planting windows.
	PAU / Punjab varieties (e.g., Punjab Maghri / PAU-recommended varieties)	Punjab Agricultural University (PAU) — public.	PAU bulletins list varieties adapted to local warm/short-season windows.
	Gannesha (Seminis)	Private Sector	Very solid, uniform round cabbage; described as heat tolerant; suitable for warm / tropical / subtropical areas.

	NS 43 (Namdhari Seeds)	Private Sector	Hybrid with strong resistance to black rot; also claimed to have heat resistance.
Broccoli	Pusa Broccoli Kt-1 / 'Palam Samridhi' (used as improved broccoli lines)	ICAR / IARI / SAU releases — public.	Broccoli in India often uses improved lines/hybrids suited to subtropical planting windows; check IIHR/IARI lists.
	(Commercial heat-tolerant hybrids like 'Gypsy', 'Sun King')	Private suppliers / seed companies	Marketed for warmer months / protected cultivation; verify with trials.
Knol-khol (Kohlrabi)	White Vienna / Purple Vienna (improved lines)	Govt. varietal lists / SAU releases — public.	Generally adaptable; early types perform better in warmer seasons.
Chinese cabbage / Pak-choi	IIHR / State released early/tropical lines (e.g., IIHR selections)	IIHR / SAUs — public.	Improved lines targeted for off-season/short-duration plantings in plains.
Kale / Leaf Brassicas	Local improved/tropical cultivars (e.g., Lacinato types adapted trials)	ICAR/SAUs / public trials — public.	Leaf brassicas often show greater heat tolerance; use regionally recommended cultivars.

Nursery Management and Crop Scheduling

1. Nursery timing: Off-season success depends on precisely timed nurseries so that transplanting coincides with the desired microclimate window. Seedlings should be of uniform size and age to avoid asynchronous heading/curding.

2. Seedling raising practices: Use sterilized media, raised beds/float trays, and hardened seedlings (gradual exposure to field temperatures) to reduce transplant shock. For protected systems, seedlings may be raised inside the same structure to avoid acclimation stress.

3. Schedule examples: Localized standardization trials (e.g., recommended planting dates and spacings for summer off-season planting in hilly regions) are valuable — e.g., March planting dates recommended in some Himalayan valley experiments for summer cauliflower/cabbage.

Soil, Nutrition and Water Management

1. Soil Requirements and Preparation: Cole crops prefer well-drained, fertile loams with good organic matter (pH ~5.5–6.8). For off-season production on heavier or marginal soils, raised beds and improved drainage are recommended. Pre-plant incorporation of well-decomposed farmyard manure or compost improves structure and nutrient buffering.

2. Fertility Management:

a. Baseline: Balanced NPK based on soil test; typical starter recommendations can be 100–150 kg N, 50–75 kg P₂O₅ and 50–100 kg K₂O per hectare for many Brassica crops, adjusted by local recommendations.

b. Split applications: Split N into basal and multiple top dressings to avoid luxuriant vegetative growth that delays heading/curd formation. Foliar micronutrient sprays (B, Zn, Mn) in deficient soils improve curd/head formation and quality.

c. Organic options: Compost, vermicompost and green manures can support off-season cropping especially in protected/organic systems.

3. Irrigation: Off-season windows often bring atypical moisture regimes. Drip irrigation or frequent light surface irrigation ensures steady moisture for cole crops; protected structures paired with fertigation improve water and nutrient use efficiency. Mulching reduces evaporation and moderates rootzone temperature.

Crop Geometry, Planting and Cultural Practices

- 1. Spacing:** Optimum spacing varies with cultivar and season; trials have recommended different spacings (e.g., 45×30 cm for some hybrids in off-season hilly trials), balancing head size and plant population.
- 2. Transplanting depth & timing:** Avoid deep planting; transplant in evening or cloudy weather to minimize transplant shock. Harden seedlings 7–10 days before transplant.
- 3. Intercultural:** Timely weeding, earthing up (where relevant), and side-dressing increase yield and quality. For cauliflower, practices to prevent unprotected curd exposure (tying or blanching) may be needed when hot sun or strong winds occur.

Protected Cultivation Practices (Key to Off-Season Success)

1. Structure Selection and Microclimate Control:

- a. Low tunnels and row covers** are low-cost options for frost protection and early season warming.
- b. Polyhouses and naturally ventilated greenhouses** provide better year-round control (temperature, humidity, pest barriers) and allow fertigation and integrated climate control. Choice depends on capital, scale, and market value.

2. Environmental Management:

- a. Ventilation & shading:** Vital to avoid overheating in summer off-season setups; shade nets or retractable screens can prevent heat stress and curd abortion.
- b. Humidity control:** High humidity favours diseases hence proper ventilation and disease-resistant varieties help.
- c. Soil solarization / disinfecting:** For repeated protected structure use, soil hygiene reduces soilborne pathogen build-up.

Pest and Disease Management in Off-Season Contexts

Off-season conditions and protected structures can alter pest/disease complexes: some pests diminish while others (thrips, aphids, whiteflies, flea beetles) may flourish; humidity-related fungal diseases (downy mildew, *Alternaria*, *Sclerotinia*) can increase under poor ventilation. Key principles:

- 1. Integrated Pest Management (IPM):** Use cultural controls (crop rotation, sanitation), biologicals (parasitoids, entomopathogens), and selective pesticides when needed. Monitor pest thresholds to time interventions.
- 2. Disease management:** Use disease-free transplants, resistant varieties, proper plant spacing, and fungicide rotations as per recommendations. Protected structures require strict sanitation to limit inoculum.

Harvesting, Quality and Postharvest Handling

- 1. Harvest timing:** Harvest heads/curds at marketable maturity for desired size and compactness. Off-season markets often prefer uniform, blemish-free produce.
- 2. Postharvest:** Rapid cooling (hydrocooling or shade), clean packing, and cold chain utilization retain quality and extend shelf life. Proper grading and packaging allow premium prices in off-season markets.

Economics, Market and Value Chain Considerations

- 1. Economic Benefits and Challenges:** Off-season produce can command higher prices due to limited supply, potentially leading to increased profits for farmers. However, the economic viability of off-season cultivation depends on various factors, including the costs of protected structures, higher seed costs, energy, and labor. Feasibility studies and pilot trials have shown that smallholder farmers can achieve positive returns when they market their produce to higher-value consumers or institutional buyers.
- 2. Risk Management Strategies:** Off-season cultivation comes with risks such as price volatility, market gluts, input cost fluctuations, and perishability. To mitigate these risks, farmers can establish linkages with buyers through contract farming or partnerships with retail chains. Additionally, staggering plantings can help avoid single-time gluts, ensuring a more stable supply and reducing the risk of price crashes. By

adopting these strategies, farmers can better manage risks and ensure a more sustainable and profitable off-season cultivation operation.

Constraints to Adoption and Scaling of Off-Season Cole Crop Cultivation

The adoption and scaling of off-season cole crop cultivation face significant constraints, primarily the high capital and operational costs associated with protected structures and energy requirements for cooling and ventilation. Additionally, the risk of increased pest and disease pressure poses a major challenge, necessitating robust management strategies. Furthermore, knowledge and extension gaps hinder farmers' ability to effectively implement off-season cultivation, highlighting the need for localized guidance on package-of-practices, including optimal cultivation calendars, cultivar selection, and protected cultivation management. Addressing these constraints is crucial for successful adoption and scaling of off-season cole crop cultivation.

Research Gaps and Future Directions

To enhance off-season production, research and development should focus on location-specific agronomy through adaptive trials to optimize planting dates, spacing, and cultivar choice. Developing low-cost, energy-efficient protected systems suitable for smallholders is crucial. Breeding programs should prioritize varieties with heat tolerance, uniform heading, and disease resistance tailored to protected environments. Additionally, socioeconomic studies can inform integrated packages, including market linkages, contract models, and financing mechanisms, to support farmers adopting off-season production methods.

Practical Recommendations

To optimize off-season production, consider the following practical recommendations: conduct local trials to determine the best planting window for your region, use hybrids or varieties suitable for off-season and protected cultivation, employ low tunnels or row covers for small-scale frost protection and polyhouses for larger, high-value operations. Additionally, implement strict Integrated Pest Management (IPM) and sanitation practices in protected systems, and secure forward marketing arrangements before scaling up production to mitigate price and volume risks.

Conclusion

Off-season cole crop cultivation is a potent strategy to increase farm incomes, balance market supplies, and meet year-round consumer demand. Success depends on harmonizing variety choice, precise scheduling, microclimate control (often via protected cultivation), resource-efficient water and nutrient management, and robust pest/disease control — all tailored to local agroclimatic conditions and market structures. With targeted research, low-cost protected solutions, and strengthened extension and value-chain linkages, off-season Brassica production can be both agronomically and economically sustainable.

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Participatory Approaches to Agricultural Extension: A Review of Benefits and Challenges

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Summary

Participatory approaches to agricultural extension—ranging from Participatory Rural Appraisal (PRA) and Farmer Field Schools (FFS) to Participatory Technology Development (PTD) and farmer-led on-farm trials—seek to shift extension from top-down delivery of technologies toward co-learning, farmer empowerment, and locally adapted innovation. These approaches emphasize farmer knowledge, joint problem-diagnosis, experimentation, and iterative feedback between researchers, extension agents, and farming communities. Evidence indicates participatory methods can increase relevance and adoption of innovations, build local capacity, strengthen social capital, and improve sustainability of interventions; however, they also face important challenges: power asymmetries, uneven participation, scaling difficulties, high transaction costs, weak monitoring/evaluation, and institutional constraints. This review synthesizes conceptual foundations, principal participatory modalities, documented benefits, key challenges, and practical recommendations for policy and implementation.

Introduction

Agricultural extension traditionally focused on transferring research-derived technologies to farmers through public agents. Over recent decades, critiques of top-down models prompted the emergence of participatory approaches that treat farmers as active agents in knowledge creation rather than passive recipients. Participatory approaches draw on social learning, local knowledge systems, and iterative experimentation to ensure technologies and practices are relevant, acceptable, and sustainable in local socio-ecological contexts. These approaches are rooted in broader participatory development debates and were popularized in the 1980s–1990s with tools such as Rapid Rural Appraisal (RRA) and Participatory Rural Appraisal (PRA).

Key Participatory Modalities in Agricultural Extension

Below are the principal participatory modalities commonly used in extension programs:

- 1. Participatory Rural Appraisal (PRA) and Rapid Rural Appraisal (RRA):** PRA/RRA are sets of tools (mapping, seasonal calendars, wealth ranking, focus groups) for rapid, community-led assessment and prioritization of problems and resources. PRA is explicitly oriented to participation, local analysis, and empowerment.
- 2. Farmer Field Schools (FFS):** FFS use season-long, experiential learning cycles where groups of farmers meet regularly in a field to observe crop ecology, compare practices, and experiment. Learning is collective and experiential, emphasizing agro-ecological understanding and farmer experimentation.
- 3. Participatory Technology Development (PTD) / Farmer Participatory Research (FPR):** PTD/FPR involve farmers directly in designing, testing, and adapting technologies through on-farm trials and joint evaluation, so that technologies are tailored to diverse local conditions.
- 4. Farmer-to-Farmer extension / Farmer Promoters:** These models use lead farmers, farmer trainers, or farmer networks to disseminate innovations horizontally, often enhancing credibility and cultural fit.
- 5. Participatory Market and Value-chain Approaches:** Participation extends beyond production to include assessments of market constraints, value-chain coordination, and collective action for market access.

6. Community-based organizations, cooperatives, and pluralistic advisory systems: Participatory extension often links with farmer organizations and private service providers to create pluralistic, demand-responsive advisory systems.

Theoretical Rationales and Mechanisms of Impact

Participatory approaches rest on several theoretical mechanisms:

- 1. Relevance and fit:** Local farmer input ensures that technologies respond to real constraints, resource endowments, and preferences, increasing likelihood of adoption.
- 2. Learning and capacity building:** Co-learning and adult education principles (experiential learning) build farmer skills for ongoing innovation.
- 3. Empowerment and agency:** Participation can strengthen farmers' voice, bargaining power, and capacity to organize.
- 4. Social capital and collective action:** Group-based approaches can create networks and institutions needed for collective problem solving and market engagement.
- 5. Systems thinking:** Farmer observations and iterative trials integrate ecological variability into decision making, improving resilience.

Benefits of Participatory Approaches to Agricultural Extension

Empirical and evaluative literature highlights multiple benefits of participatory extension:

- 1. Improved relevance and higher adoption rates** — When farmers participate in design and testing, the innovations are better adapted to heterogeneous local conditions, which correlates with higher uptake compared with purely top-down recommendations.
- 2. Capacity building and enhanced problem-solving** — Approaches like FFS improve farmer diagnostic skills and adaptive management of pests, soils, and water. Farmers learn to observe, record, and experiment.
- 3. Empowerment and gender outcomes** — Participatory methods that intentionally include marginalized groups can increase women's technical knowledge and decision-making influence, though outcomes vary with design and context.
- 4. Sustainability of practices** — Locally adapted innovations and farmer ownership of trials increase the probability that practices are maintained after external project support ends.
- 5. Better feedback to research and faster local innovation** — PTD and FPR create channels for farmer observations to inform research agendas and breeding/technology priorities.

Main Challenges and Limitations

Despite potential, participatory extension faces substantial practical and conceptual challenges:

- 1. Power dynamics and representativeness:** Participation is not automatically inclusive. Local elites may dominate processes; women, tenant farmers, landless laborers, and other marginalized groups may be excluded unless explicitly targeted. Tokenistic participation (invited attendance without real influence) undermines empowerment aims.
- 2. Transaction costs and resource intensity:** Participatory methods require sustained facilitation, training, and time for group facilitation and iterative trials—raising per-farmer costs relative to broadcast models. Financial and human resource constraints in public extension reduce capacity for long-term facilitation.
- 3. Scaling and institutionalization:** Scaling participatory successes from pilot communities to regional or national programs is difficult. Institutional incentives, bureaucratic cultures, and staff skillsets often favor linear technology transfer over facilitation. Designing scaled models that retain participatory quality remains an open challenge.
- 4. Monitoring, evaluation and attribution:** Evaluating impact is methodologically challenging: participatory interventions are context-specific, multi-dimensional, and produce diffuse outcomes (social capital, empowerment) that are hard to quantify. Weak M&E reduces ability to learn what works and why.

5. Risk of co-option and depoliticization: Some participatory projects have been critiqued for depoliticizing structural issues (land tenure, market power) by focusing on technical fixes without addressing underlying institutional constraints, or for being co-opted by development actors to legitimize pre-set agendas.

6. Heterogeneity of evidence quality: While many case studies report positive outcomes, rigorous impact evaluations are fewer and results are heterogeneous; context, facilitation quality, and program design hugely influence outcomes. The literature urges caution about generalizing from success stories without attention to counterfactuals.

Design Principles and Best Practices

To realize benefits and mitigate challenges, programs should follow evidence-informed design principles:

1. Clear Objectives and Participation Depth: Define the level of participation (consultative, collaborative, or farmer-led) and match methods and resources accordingly. This ensures that all stakeholders understand their roles and responsibilities, and that the program is designed to achieve its objectives effectively.

2. Inclusive Targeting and Facilitation: Use gender-sensitive facilitation, schedule meetings to enable women's participation, and monitor representation to reduce elite capture. This principle emphasizes the importance of inclusivity and equity in participatory programs, ensuring that all stakeholders, including marginalized groups, have a voice and are able to participate.

3. Build Facilitator Capacity: Invest in training extension staff in facilitation, participatory methods, conflict sensitivity, and adult learning techniques. Well-trained facilitators can effectively manage group dynamics, build trust, and ensure that participatory processes are inclusive and productive.

4. Hybrid and Pluralistic Delivery: Combine participatory group approaches with individual advisory services, private providers, and ICT tools to expand reach while preserving quality. This principle recognizes that different approaches may be more effective in different contexts, and that a pluralistic approach can leverage the strengths of various actors, including NGOs, farmer organizations, private advisors, and public extension.

5. Adaptive M&E and Learning Agendas: Use mixed-methods M&E combining participatory monitoring with quasi-experimental designs where feasible; document process indicators (participation quality) as well as outcomes. This principle emphasizes the importance of adaptive monitoring and evaluation, which allows programs to learn and adjust as they implement, and to capture both the quality of participation and the outcomes achieved.

6. Institutional Incentives and Policy Support: Align staff performance metrics, budgeting, and career incentives to value facilitation, learning, and local innovation rather than only coverage metrics. This principle recognizes that institutional incentives and policies can either support or hinder participatory approaches, and that aligning incentives with program goals is crucial for success.

7. Pathways for Scaling: Use farmer-to-farmer diffusion, trainer-of-trainer models, and embedding participatory modules into formal curricula; however, carefully preserve core participatory elements when scaling. This principle emphasizes the importance of scaling participatory approaches in a way that preserves their core elements, while also adapting to new contexts and stakeholders. By doing so, programs can achieve greater impact and sustainability.

Illustrated Examples

1. PRA-based planning: Participatory Rural Appraisal (PRA) techniques have been used in various Asian and African countries to conduct community diagnosis and set priorities. This approach empowers local communities to identify their needs and develop plans tailored to their specific contexts.

2. Farmer Field Schools (FFS): FFS has been widely implemented to promote integrated pest management (IPM). By educating farmers on ecological principles and management practices, FFS has led to improved pest control, reduced pesticide use, and enhanced environmental sustainability. However, concerns about costs and scalability remain.

3. Participatory Technology Development (PTD): PTD involves farmers in the development and evaluation of new agricultural technologies, such as crop varieties. By incorporating farmer preferences and local knowledge, PTD has resulted in the development of varieties better suited to specific micro-environments, ultimately improving crop performance and farmer adoption rates

Policy Implications and Recommendations

1. Prioritize capacity development for extension staff in participatory facilitation and adult education; include participatory competencies in recruitment and training curricula.

2. Ensure inclusive design—explicitly plan to include women and marginalized groups, monitor representation, and adapt methods to local social norms.

3. Adopt pluralistic and demand-driven systems—public extension should create space for NGOs, farmer organizations, and private advisors to complement participatory approaches and expand coverage.

4. Invest in rigorous M&E and documentation—fund mixed-method evaluations that capture adoption, livelihoods, and social outcomes to build an evidence base for cost-effectiveness.

5. Design realistic scaling pathways—use cascade training carefully, protect FFS/PR A quality elements, and pilot scaling mechanisms with active monitoring.

Conclusion

Participatory approaches in agricultural extension hold considerable promise for making advisory services more relevant, equitable, and sustainable by centering farmer knowledge and co-creating solutions. The empirical literature and practitioner experience (as synthesized in foundational reviews and World Bank guidance) show meaningful benefits in capacity building, local innovation, and ownership. Yet realizing these benefits at scale requires confronting real constraints—resource intensity, institutional incentives, inclusion, and rigorous evaluation. Thoughtful program design that invests in facilitation capacity, inclusiveness, adaptive M&E, and pluralistic delivery systems offers the best pathway to harness participatory approaches for resilient, farmer-led agricultural development.

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Pivotal Role of Entomophily in Pollination & Yield Enhancement - A Brief Discussion

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Summary

Entomophily is the system of pollination mediated by insects which is a foundational ecological process that underpins reproduction for the majority of angiosperms and is critically important for many agricultural crops. Insect pollinators (bees, flies, beetles, butterflies, moths, wasps, and others) influence not only fruit/seed set but also yield quality, uniformity, and genetic diversity. Managed pollinators (e.g., honeybees) and wild pollinator assemblages often act complementarily; wild insects in particular frequently provide equal or greater pollination effectiveness for many crops. Growing evidence links declines or alterations in pollinator communities to reduced crop productivity, lower quality produce, and risks to food security. Maintaining and enhancing entomophilous services relies on integrated conservation and farm-management strategies that sustain pollinator diversity and abundance across landscapes.

Introduction

Entomophily refers to pollination by insects — a mutualistic interaction in which animals transfer pollen while foraging for nectar or pollen, thereby enabling sexual reproduction in plants. This mechanism contrasts with abiotic pollination (wind, water). Overwhelming evidence indicates that a large fraction of flowering plants, and many crops of economic importance, depend on animal (largely insect) pollination to varying degrees. In agricultural systems, insect pollination often translates directly into increased fruit set, yield quantity, and improvements in product quality (size, shape, seed set, marketability). Understanding entomophily is therefore vital for agronomy, ecology, conservation, and food security planning. (Klein et al., 2007; Garibaldi et al., 2013.)

Table 1. Major crops pollinated by entomophilous insects and their yield benefits:

Crop/Plant Species	Crop Group	Primary Insect Pollinators	Nature of Dependence on Entomophily	Yield/Quality Impact Due to Insect Pollination
Apple (<i>Malus domestica</i>)	Fruit crop	Honeybees (<i>Apis mellifera</i> , <i>A. cerana</i>), bumblebees	Highly dependent; self-incompatible	60–90% increase in fruit set, improved size and uniformity
Mango (<i>Mangifera indica</i>)	Fruit crop	Flies (<i>Diptera</i>), bees (<i>Apis dorsata</i> , <i>A. cerana</i>), beetles	Partial dependence	Increased fruit set and yield stability
Citrus spp. (Orange, Lemon)	Fruit crop	Bees (<i>A. mellifera</i> , <i>A. cerana</i>), hoverflies	Moderate dependence	Higher seed set and uniform fruits
Litchi (<i>Litchi chinensis</i>)	Fruit crop	Honeybees, solitary bees, flies	High dependence	Improved fruit retention and yield
Guava (<i>Psidium guajava</i>)	Fruit crop	Bees (<i>A. cerana</i> , <i>Trigona</i> spp.)	Partial dependence	Enhanced fruit size and pulp quality
Watermelon (<i>Citrullus lanatus</i>)	Vegetable/fruit	Honeybees, stingless bees, bumblebees	Fully dependent on insect pollination (monoecious flowers)	Higher fruit set, uniform shape, better sweetness

Cucumber (<i>Cucumis sativus</i>)	Vegetable	Honeybees, leaf-cutter bees, stingless bees	Highly dependent	Fruit shape uniformity and marketable yield improved
Pumpkin (<i>Cucurbita moschata</i> , C. pepo)	Vegetable	Honeybees, squash bees (<i>Peponapis</i> , <i>Xenoglossa</i>)	High dependence	60–80% increase in fruit set and quality
Brinjal (<i>Solanum melongena</i>)	Vegetable	Carpenter bees (<i>Xylocopa</i> spp.), bumblebees	Moderately dependent; aided by buzz-pollination	Improved fruit size, shape, and seed content
Tomato (<i>Solanum lycopersicum</i>)	Vegetable	Bumblebees (<i>Bombus</i> spp.), <i>Xylocopa</i> spp.	Requires buzz pollination	Fruit set up to 80% higher with bee activity
Mustard (<i>Brassica juncea</i>)	Oilseed	Honeybees, solitary bees	Partially cross-pollinated	Seed set and oil content improved by 15–25%
Sunflower (<i>Helianthus annuus</i>)	Oilseed	Honeybees, solitary bees, flies	Partially cross-pollinated	Enhanced seed fill, weight, and oil quality
Coconut (<i>Cocos nucifera</i>)	Plantation crop	Honeybees, wasps, flies	Moderate dependence	Increased nut set per inflorescence
Coffee (<i>Coffea arabica</i> , C. <i>canephora</i>)	Plantation crop	Honeybees, stingless bees	Partial dependence	15–20% higher fruit set with insect pollination
Cardamom (<i>Elettaria cardamomum</i>)	Spice crop	Honeybees, solitary bees, flies	High dependence	Increased capsule set and yield
Black pepper (<i>Piper nigrum</i>)	Spice crop	Flies, small bees	Moderate dependence	Enhanced berry development
Alfalfa (<i>Medicago sativa</i>)	Forage/seed	Leaf-cutter bees (<i>Megachile rotundata</i>)	Strong dependence	Essential for seed production
Cotton (<i>Gossypium</i> spp.)	Fibre crop	Honeybees, bumblebees	Partially cross-pollinated	Improved boll number and lint quality
Papaya (<i>Carica papaya</i>)	Fruit crop	Moths, honeybees, flies	Cross-pollinated (dioecious)	Essential for fruit set in female plants
Strawberry (<i>Fragaria × ananassa</i>)	Fruit crop	Honeybees, bumblebees	High dependence	Improved shape, weight, and shelf-life
Okra (<i>Abelmoschus esculentus</i>)	Vegetable	Honeybees (<i>A. dorsata</i> , <i>A. cerana</i>)	Highly dependent	25–35% yield increase due to bee activity
Pomegranate (<i>Punica granatum</i>)	Fruit crop	Honeybees, carpenter bees	Partial dependence	Improved aril number and fruit set
Rapeseed (<i>Brassica napus</i>)	Oilseed	Honeybees, hoverflies	Moderate dependence	Seed yield and oil content increased
Onion (<i>Allium cepa</i>)	Seed crop	Honeybees, flies	Fully dependent for seed set	High-quality seed yield depends on pollinators

Carrot (<i>Daucus carota</i>)	Seed crop	Honeybees, flies	Fully dependent	Essential for hybrid seed production
Chilli (<i>Capsicum annuum</i>)	Vegetable	Honeybees, stingless bees	Moderate dependence	Improved fruit set and weight
Tea (<i>Camellia sinensis</i>)	Plantation crop	Bees, flies	Partially cross-pollinated	Enhanced seed production and genetic diversity

Biological Basis and Mechanisms of Entomophily

1. Plant traits that promote insect visitation: showy petals, floral scent, nectar guides, rewards (nectar/pollen), timing of anthesis, and specialized floral morphologies that match insect anatomy (e.g., long nectar spurs for hawkmoths).

2. Pollinator behaviors and pollen transfer: insects differ in foraging patterns, flower-handling behavior, body size, hairiness, and fidelity (constancy) — all traits that determine pollen deposition efficiency. For example, bumblebees' size and buzz-pollination behavior are effective for crops like tomato and blueberry, while small solitary bees can be most effective on small flowers and for pollen transfer between closely spaced flowers.

3. Mode of pollen adherence and transfer: pollen can adhere to insect body parts (hairs, legs), or be intentionally packaged (pollen baskets in some bees), affecting how much pollen moves between flowers and conspecifics.

Diversity of Insect Pollinators and Functional Complementarity

1. Taxonomic diversity: major pollinator groups include Apidae (honeybees, bumblebees, stingless bees), Halictidae, Megachilidae (leafcutter and mason bees), Syrphidae (hoverflies), Lepidoptera (butterflies, moths), Coleoptera (beetles), and many solitary wasps and ants (though ants often poor pollinators).

2. Functional complementarity: different pollinators complement each other in activity time (diurnal/nocturnal), flower-handling techniques, and environmental tolerance. Empirical studies show that systems with higher pollinator diversity often achieve more stable and higher pollination services than those reliant on a single species. Garibaldi et al. (2013) demonstrated that wild pollinators enhanced crop fruit set across diverse crops and regions even where honeybees were abundant, highlighting complementarity rather than redundancy.

Entomophily and Crop Dependency — Magnitude of the Effect

1. Extent of dependence: Reviews and meta-analyses indicate that a substantial proportion of food crops benefit from insect pollination. Klein et al. (2007) quantified crop dependence and reported that many globally important crops show moderate to high pollinator dependence for yield and/or quality. Estimates of the proportion of angiosperms that are animal-pollinated vary by study, but most recent syntheses place the figure at roughly 80–90% of flowering species being animal-pollinated (see Ollerton et al. as a background reference).

2. Yield and quality response: Insect pollination can increase crop yield from modest to very large margins depending on species: documented yield increases range widely (for some crops mean increases of 20–70% or more in experimental exclusion studies). Beyond quantity, pollination often improves fruit size, shape, seed number, uniformity, shelf-life and market value. (Bartomeus et al., 2014; Klein et al., 2007.)

Examples and Crop-Specific Notes

1. Apple, pear, and tree fruits: many are self-incompatible or have reduced fruit set without cross-pollination; insect visitation ensures cross-pollination and uniform fruit set.

2. Brassicas and oilseeds (canola/rapeseed): insect pollination can increase seed set and oil yield depending on cultivar and environmental context.

3. Cucurbits (pumpkin, cucumber, squash): rely heavily on bees (often bumblebees/solitary bees) for pollen transfer between separate male and female flowers.

4. Solanaceae (tomato, eggplant): tomatoes often require buzz-pollination (sonication) performed by bumblebees or certain solitary bees to release pollen; managed honeybees cannot buzz-pollinate.

5. Berries (blueberry, strawberry): benefit from diverse bee assemblages for larger, marketable fruits. The magnitude of benefit varies with cultivar, management, weather, and landscape factors.

Economic and Ecosystem-Service Valuation

Pollination is an ecosystem service with large economic value. Multiple regional and global assessments have monetized insect pollination contributions to crop production (estimates differ by methodology and year), consistently showing that pollinator-mediated services contribute billions of dollars per annum to global agriculture. Beyond direct economic valuation, pollination supports genetic diversity, wild plant reproduction, and overall ecosystem resilience.

Threats to Entomophily

1. Habitat Loss and Fragmentation: Habitat loss and fragmentation are significant threats to pollinators. As natural habitats are converted to agricultural land, urban areas, or other human-dominated landscapes, pollinators are left with limited access to food, shelter, and nesting sites. This can lead to population declines, reduced genetic diversity, and even local extinctions. Fragmented habitats can also make it difficult for pollinators to move between patches, further exacerbating population declines.

2. Agrochemical Exposure: Agrochemical exposure is a major threat to pollinators. Pesticides, particularly systemic insecticides like neonicotinoids, can have devastating effects on pollinator health. These chemicals can be absorbed by plants and contaminate nectar and pollen, which are then ingested by pollinators. Exposure to these chemicals can impair pollinator navigation, communication, and reproduction, ultimately leading to population declines. The widespread use of these chemicals has been linked to pollinator declines and has significant implications for ecosystem health.

3. Pathogens and Parasites: Pathogens and parasites are another significant threat to pollinators. Varroa mite infestations, for example, have had a devastating impact on honeybee colonies worldwide. Similarly, emerging diseases in wild bees can have significant impacts on populations. These pathogens and parasites can spread quickly through pollinator populations, exploiting weaknesses in their immune systems. The impact of these pathogens and parasites can be exacerbated by other stressors, such as habitat loss and pesticide exposure.

4. Monoculture and Intensive Cropping: Monoculture and intensive cropping practices can have significant impacts on pollinators. By growing a single crop, farmers can create resource-poor landscapes that lack diversity and complexity. This can leave pollinators without access to a balanced diet, making them more susceptible to disease and other stressors. Additionally, intensive cropping practices often rely heavily on pesticides and fertilizers, which can further exacerbate pollinator declines. By promoting more diverse and sustainable agricultural practices, farmers can help support pollinator populations.

5. Climate Change: Climate change is a significant threat to pollinators, impacting their distribution, behavior, and interactions with plants. Changes in temperature and precipitation patterns can disrupt the delicate timing of plant-pollinator interactions, making it difficult for pollinators to find the resources they need. Climate change can also lead to range shifts, as pollinators and plants move to new areas in response to changing environmental conditions. This can create new challenges for pollinators, such as adapting to new habitats and interacting with new species. By understanding the impacts of climate change on pollinators, we can develop strategies to mitigate these effects and promote pollinator resilience.

Management and Conservation Strategies to Sustain Entomophily

1. On-Farm Habitat Enhancement: On-farm habitat enhancement is a crucial strategy for supporting pollinators. This can be achieved by creating wildflower strips, hedgerows, cover crops, fallow patches, and maintaining permanent semi-natural habitats. These habitats provide continuous forage and nesting sites for pollinators, helping to sustain their populations and promote pollination services. By incorporating these features into farm landscapes, farmers can create pollinator-friendly environments that support biodiversity and ecosystem health.

2. Agri-Environmental Schemes and Landscape Planning: Agri-environmental schemes and landscape planning are essential for supporting pollinators at a larger scale. By designing mosaics that include natural and semi-natural areas, farmers and land-use planners can create habitats that support pollinator metapopulations and facilitate spillover into crops. This approach recognizes the importance of landscape-level connectivity and habitat diversity in maintaining healthy pollinator populations. By working together, farmers, conservationists, and policymakers can create landscape-scale habitats that benefit both pollinators and agriculture.

3. Integrated Pest Management (IPM): Integrated Pest Management (IPM) is a critical strategy for reducing the impact of pesticides on pollinators. By adopting IPM practices, farmers can minimize the use of prophylactic pesticides, use targeted applications, and avoid applications during bloom times when pollinators are most active. This approach not only helps protect pollinators but also reduces the development of pesticide resistance and promotes more sustainable agricultural practices.

4. Managed Pollinator Use: Managed pollinators, such as honeybees and native bees, can play an important role in pollination services. However, it is essential to use these pollinators carefully, recognizing that they can supplement but not replace wild pollinators. Management practices should prioritize disease screening to prevent pathogen spillover to wild bees. By adopting responsible management practices, farmers can help maintain the health and diversity of pollinator populations.

5. Policy, Education, and Market Instruments: Policy, education, and market instruments can all play a role in promoting pollinator-friendly practices. Incentives for pollinator-friendly practices, pollinator monitoring programs, and public awareness campaigns can help raise awareness and drive behavior change. By working together, policymakers, farmers, and consumers can create a supportive environment for pollinators and promote sustainable agriculture practices.

6. Research and Monitoring: Long-term monitoring of pollinator populations and pollination outcomes is essential for understanding the effectiveness of conservation efforts and identifying areas for improvement. Adaptive management approaches can help respond to observed declines and promote pollinator health. By investing in research and monitoring, we can better understand the complex relationships between pollinators, agriculture, and ecosystems, and develop effective strategies for promoting pollinator health and sustainable agriculture.

Evidence Synthesis and Key Studies

1. Klein et al. (2007) provided a foundational global synthesis of crop dependence on animal pollinators and emphasized that many crops show substantial yield and quality reductions in the absence of animal pollination. Their work highlighted the potential for landscape and local management to sustain pollination services. (Klein et al., 2007).

2. Garibaldi et al. (2013) analyzed >40 crop systems worldwide and found that wild pollinators increased fruit set more strongly than did honeybees, and that wild pollinator visitation and honeybee visitation contributed additively to crop pollination — demonstrating the critical role of wild insect diversity for agriculture. (Garibaldi et al., 2013).

3. Meta-analytic and region-specific syntheses (e.g., Bartomeus et al., 2014) quantify how insect pollination improves yield and quality across a range of crops, showing substantial heterogeneity between crops but a consistent positive effect on agriculture.

Research Gaps and Future Directions

1. Functional Trait Approaches: Research on linking pollinator traits (e.g., body size, foraging range, phenology) to pollination outcomes across crops can enable predictive management. This approach can help identify key pollinator species and traits that are most beneficial for specific crops, allowing for more targeted conservation and management efforts.

2. Landscape-Scale Experiments: Conducting landscape-scale experiments can help quantify the impact of habitat configuration and connectivity on pollinator populations and crop pollination at farm and regional scales. This research can inform landscape-level conservation and planning efforts to support pollinators and pollination services.

3. Socioeconomic Integration: Valuing pollination services within farm decision-making, supply chains, and policy frameworks is crucial for creating effective incentives for pollinator conservation. Research in this area can help identify economic benefits and costs of pollination services and develop mechanisms to reward farmers for pollinator-friendly practices.

4. Climate Adaptation: Studying phenological shifts and designing planting and management strategies can help reduce pollination mismatches under climate change. This research can inform adaptation strategies for farmers and conservation practitioners to maintain pollination services in the face of climate change.

5. Interactions between Managed and Wild Pollinators: Assessing the risk-benefit trade-offs, disease dynamics, and competition between managed and wild pollinators can guide best practices for pollinator management. This research can help develop management strategies that balance the needs of both managed and wild pollinators.

Conclusion

Entomophily is central to both natural ecosystems and agricultural productivity. Insect pollinators contribute to crop yield, quality, and production stability; in many systems, wild pollinator diversity is particularly important and cannot simply be substituted by managed honeybees. Protecting and enhancing entomophilous services requires integrated actions spanning habitat conservation, pesticide stewardship, landscape planning, and research-informed farm management. Given the strong links between pollinator health and food security, entomophily must be a core concern for sustainable agriculture and biodiversity conservation.

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Scientific Cultivation Practice of Off-Season Onion: *Kharif Onion*

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Summary

Kharif (monsoon or off-season) onion is an important supplementary cropping system in India that produces bulbs for marketing in October–December and helps spread harvest risk and income across the year. Kharif onion differs from the main rabi crop in sowing/transplanting dates, climatic requirements (higher humidity, different day-length/temperature interactions), water management (drainage during heavy rains), and cultivar choice (short-day / intermediate-day types adapted to monsoon conditions). Adoption of improved nursery techniques, timely transplanting, balanced nutrient and water management, integrated pest and disease control, and careful post-harvest handling are essential to obtain competitive yields and bulb quality. This review synthesises agronomy, cultivar selection, nursery and transplant techniques, soil and nutrient management, water management, pest/disease and weed control, harvest and postharvest practices, economics and constraints, and future research directions for kharif (off-season) onion production in the Indian context.

Introduction

Onion (*Allium cepa* L.) is a major vegetable and commercial spice crop in India grown in multiple seasons: rabi (winter), kharif (monsoon/autumn) and late-kharif (post-monsoon/late autumn). While the rabi crop contributes the largest share of production, kharif and late-kharif crops supply the market in other months and are crucial for price stabilization, local income, and export possibilities. Kharif onion provides marketable bulbs during October–December and is of particular importance in states such as Maharashtra, Gujarat, Karnataka, Rajasthan and parts of Uttar Pradesh and West Bengal. The kharif crop plays a key role in cropping intensification and farmer cash flow because it can be taken between major cropping cycles or as an additional crop in irrigation-enabled systems.

Agro-Ecology and Seasonality

1. Climate and photoperiod: Kharif onion is raised to mature during or soon after the monsoon so seedlings experience high humidity, moderate to high temperatures during establishment, and gradually decreasing temperatures toward bulb maturation. Day length and temperature affect bulb initiation and size: kharif cultivars are usually short-to-intermediate day types adapted to the photoperiod and thermal regime of the monsoon and post-monsoon period. Excess rainfall and waterlogging during monsoon pose key establishment and disease challenges.

2. Soil and land preparation: Well-drained, deep loamy soils with good organic matter are preferred. Because monsoon rains can waterlog fields, farmers use raised beds or broad-bed and furrow (BBF) systems to improve drainage and aeration in kharif plantings. Land is prepared to a fine tilth for uniform sowing and nursery establishment. Soil pH of 6.0–7.5 is desirable; saline/alkaline soils reduce bulb size and storability.

Variety Selection and Seed Material

Variety selection and seed material are crucial for successful kharif onion cultivation. To thrive in India's monsoon season, kharif onions require varieties that can tolerate higher humidity and variable solar radiation during bulb formation, have shorter growing cycles suited to monsoon-timed plantings, and produce firm bulbs with acceptable skin drying and storage life. Region-specific varieties, such as NHRDF lines like Agrifound Dark Red and other short-duration hybrids/varieties recommended by state centers and ICAR stations, are often promoted for kharif and late-kharif seasons. It's essential to use certified seeds

from reliable sources, as seed health directly impacts nursery success and seedling vigor, setting the stage for a healthy and productive crop.



Nursery Management and Seedling Production

1. Timing and method: Kharif onion is generally raised as a transplanted crop. Nursery sowing is timed so seedlings attain the recommended age and vigour at transplanting (commonly 40–50 days old depending on seed rate, variety, and season). Nursery bed preparation (raised seedbeds, well-decomposed FYM/compost incorporation) and use of polytunnels or low tunnels for protection from heavy rains can improve seedling survival. Harden seedlings by withholding excess water 3–4 days before transplanting to reduce post-transplant shock.

2. Seed rate and spacing in the nursery: Seed rate for nursery broadcast/line sowing is typically between 1.0–2.5 kg/ha (varies by variety and seed germination). In line sowing, seedlings are spaced to allow easy uprooting and reduce root/tip damage. Proper seedbed hygiene and seed treatment against seed-borne pathogens (where recommended) reduce early damping-off and other nursery diseases.

Transplanting: Timing, Spacing, and Establishment

1. Timing: Transplanting is done at an age and season to avoid peak rain periods if possible; for kharif crops this is typically during early to mid-monsoon window depending on local agro-climate so that bulb formation coincides with receding rains. Early transplanting into well-prepared, drained beds reduces seedling mortality.

2. Spacing: Common spacings are 15–20 cm between rows and 7–10 cm within rows (depends on target bulb size and cultivar). Wider spacing produces larger bulbs but lowers plant population; spacing must balance yield per hectare and desired bulb size.

3. Transplant method: Transplant seedlings carefully to avoid root damage; transplanting during late afternoon or on overcast days reduces stress. Apply light irrigation after transplanting (if field conditions are not waterlogged) to help establishment.

Nutrient Management

Balanced nutrition and organic matter incorporation are central to profitable kharif onion production.

1. Basal and top-dressing recommendations: General recommendations (example package of practices; adapt to soil test results):

- Apply well-rotted FYM/compost (10–20 t/ha) at land preparation to improve soil structure and drainage.
- NPK rates commonly recommended for kharif onion range in trials (e.g., 100–150 kg N, 40–80 kg P₂O₅ and 40–80 kg K₂O per hectare) — specific recommendations should be adjusted by ICAR/state package of practices and soil test. Split nitrogen application: half at basal or after first weeding, rest in 2–3 splits during active growth. Micronutrients (Zn, B) may improve bulb set where deficient.

2. Organic amendments and bio-inputs: Organic manures and green manures enhance soil water holding, microbial activity, and bulb quality. Biofertilizers (e.g., Azospirillum) and nutrient-efficient formulations may supplement inorganic fertilizers to enhance nutrient use efficiency. Field demonstrations have shown improved yields and economics when recommendations tailored to kharif situations are followed.

Irrigation and Water Management

Onion is shallow-rooted and sensitive to both drought and waterlogging. Kharif growers must carefully manage irrigation during monsoon and post-monsoon months:

1. Use raised beds, BBF or furrow systems to prevent waterlogging during heavy rains.
2. When rain is insufficient, provide frequent light irrigations to meet crop evapotranspiration because shallow roots cannot access deep moisture. Irrigation frequency is usually higher in rabi; kharif crop irrigation needs vary regionally but aim to maintain moisture for active growth and bulb expansion without causing saturation. Drip irrigation and micro-sprinklers can save water and reduce disease incidence by minimizing foliage wetting.

Weed Management

Weeds reduce yield and bulb size. Integrated practices include:

1. Pre-plant land preparation to reduce weed seed bank.
2. Shallow intercultural hoeing, hand weeding at early stages (2–3 weeding depending on weed pressure).
3. Mulching (organic or black polyethylene) in some regions reduces weeds and conserves moisture but must be adapted to monsoon conditions to avoid trapping excess water.
4. Herbicide use is regionally recommended with caution and following label directions; manual removal remains common where labour is available.

Pest and Disease Management

Kharif crops face pest/disease pressures exacerbated by high humidity and rains.

1. Major pests:

a. Onion thrips (*Thrips tabaci*): causes silvering, tip necrosis and reduces bulb size; integrated control includes timely monitoring, use of resistant/tolerant genotypes when available, optimized nitrogen management (excess N can increase thrips), biopesticides, and targeted insecticides when economic thresholds reached.

b. Stem and bulb nematodes and other sucking pests may be locally important.

2. Major diseases: Downy mildew (*Peronospora destructor*), purple blotch (*Alternaria porri*), bacterial soft rot (*Erwinia* spp.), and basal rot (*Fusarium oxysporum*) are common, especially under high humidity. Good drainage, field sanitation, seed health, crop rotation, and fungicide/bactericide applications per local recommendations reduce incidence. Use certified seed and treat bulbs/seeds as recommended to prevent seed-borne diseases.

Harvesting and Postharvest Handling

1. Maturity indices: Bulbs are harvested when foliage tops fall over and begin to dry. In kharif crop timing must balance market window and avoiding rainy period that damages skin drying.

2. Cure and dry: Rapid curing (neck drying and skin formation) is essential for storage life. In humid conditions, mechanical or covered curing yards and forced-air drying reduce fungal rots. Avoid harvesting immediately after heavy rains; provide field drainage and allow time for foliage to dry.

3. Grading and storage: Bulbs are cured, graded by diameter and skin quality, and stored in well-ventilated, dry conditions. Kharif bulbs often have shorter storage life than rabi bulbs; improved curing and low-temperature storage (if available) extend shelf life. Proper postharvest handling reduces losses and improves returns.

Yield, Economics and Front-Line Demonstrations

Field demonstrations and trials have shown that adoption of improved kharif production packages (improved varieties, balanced fertilizers, timely transplanting, proper irrigation and pest/disease management) increases yields substantially over farmer practice in many zones; yield responses and economics vary by state, cultivar and season. Reports from frontline demonstrations indicate yield improvements in the range of ~15–25% for improved packages in some trials and improved net returns

when market timing is favorable. However, extreme weather events (excessive monsoon rains, unseasonal downpours) can severely damage kharif plantings, affecting area and yields in a given year.

Constraints and Challenges

Kharif onion production faces several constraints and challenges that impact its yield, quality, and profitability. High rainfall and waterlogging during the establishment and curing stages can lead to seedling mortality and increased disease pressure, ultimately affecting crop productivity. Additionally, kharif onions have a shorter storage life and lower bulb firmness compared to rabi onions, which affects their market prices. The humid conditions during the kharif season also favor the growth of pests and diseases, further compromising crop health. Furthermore, the availability of suitable short-duration, high-yielding, and storage-worthy cultivars adapted to local zones remains a significant challenge. Market price volatility and infrastructure gaps for storage and cold chain also pose significant risks to farmers, potentially leading to substantial losses. Recent severe rain events have exacerbated these challenges, resulting in substantial declines in planted area in major kharif production hubs, highlighting the need for region-specific solutions and improved agricultural practices to mitigate these risks.

Opportunities and Future Research Directions

Future research directions for kharif onion production include several key areas: breeding short-duration, kharif-adapted varieties with thrips and disease tolerance, and improved skin drying and storability; developing and promoting water management technologies such as raised beds, broad-bed and furrow systems, and water-saving irrigation methods like drip irrigation; innovating postharvest handling and storage, including low-cost curing technologies and affordable cold storage; and creating integrated pest management packages tailored to kharif conditions. Additionally, climate resilience can be enhanced through forecast-based planting windows, weather-smart advisories, and insurance mechanisms to mitigate monsoon risks. Implementing these research priorities in partnership with ICAR, state KVKs, and private sector seed companies can improve kharif onion productivity and profitability, ultimately benefiting farmers and the onion industry.

Conclusion

Kharif (off-season) onion is a valuable component of India's onion production system, providing marketable bulbs outside the main rabi harvest window and contributing to farm incomes and market supply management. Scientific cultivation tailored to the monsoon environment — including careful nursery and transplanting, drainage and raised bed systems, balanced nutrient and water management, IPM, and improved postharvest curing — can substantially raise productivity and profitability. Continued emphasis on breeding for kharif adaptation, affordable postharvest technologies and climate-resilient agronomy will be essential to expand and stabilize kharif onion production under increasingly variable monsoon regimes.

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The Relationship Between Agricultural Extension and Rural Livelihoods: A Review

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Summary

Agricultural extension and advisory services (EAS) play a vital role in transferring knowledge, technologies, and market information to farmers, influencing productivity, income, food security, resilience, and rural livelihoods. Over time, extension systems have evolved from top-down, public-sector models to more pluralistic approaches, incorporating public, private, NGO, and farmer-led advisory arrangements. The focus has shifted to finding "best fit" solutions that align with local context, farmer demand, and market conditions. Research shows that extension services can be effective in raising productivity and incomes when they are relevant to farmer needs, delivered in a timely and sustained manner, linked to markets and inputs, and intentionally target gender and marginalized groups. However, challenges persist, including underfunding, weak monitoring, poor incentives, limited capacity to address non-technical constraints, and equity gaps. Addressing these challenges is crucial to improving the impact of extension services on livelihoods.

Introduction

Rural livelihoods are multi-dimensional, encompassing household income, food and nutrition security, asset accumulation, labour opportunities, health, social capital, and resilience to shocks. Agricultural extension — broadly defined to include all advisory, information, training and facilitation supplied by public agencies, private firms, NGOs, cooperatives, and farmer organizations — aims to strengthen the capacities of farming households to increase productivity, adopt innovations, diversify income sources, and manage risks. This review examines how different extension models affect rural livelihoods, what evidence exists of impact, what constraints limit effectiveness, and what design principles can improve contribution to livelihood outcomes. The body of evidence reviewed spans conceptual syntheses, program evaluations, and global reviews.

Conceptual Links: How Extension Affects Livelihoods

Extension influences rural livelihoods through several pathways:

- 1. Technical productivity:** by transferring improved agronomic practices, seed/variety choices, integrated pest and nutrient management, and post-harvest techniques — leading to yield increases and lower production costs.
- 2. Income diversification and value chains:** by advising on high-value crops, livestock, agro-processing, and farm-level value-addition or by linking farmers to buyers and contract arrangements.
- 3. Risk management and resilience:** by disseminating climate-smart practices, water management, early-warning information, and integrated pest management to reduce vulnerability.
- 4. Human and social capital:** by building farmer knowledge, managerial skills, and social networks (farmer groups, cooperatives) that support collective action and market access.
- 5. Gender and inclusion effects:** by targeting women, youth, and marginalized groups with tailored messages, training, and services that can alter intrahousehold outcomes and control of resources.

These pathways are influenced by demand-side factors (farmer preferences, ability to pay), supply-side institutions (public/private capacity, incentives), and enabling conditions (markets, infrastructure, policy). The "public goods" dimension of some advisory services (e.g., pest surveillance) motivates public sector involvement, while many advisory functions can be privatized or delivered via partnerships when commercial incentives exist.

Historical Evolution and Delivery Models

1. Classical public models: Historically, many countries relied on state-run extension systems (e.g., Training & Visit — T&V) characterized by hierarchical training, top-down messages, and government extension agents. T&V showed important short-term dissemination gains in some contexts but often struggled with sustainability, narrow technology focus, and lack of farmer feedback.

2. Pluralistic and market-oriented models: Since the 1990s and 2000s there has been a policy shift toward pluralism: combining public advisory roles (policy, public goods, outreach to poor and remote farmers) with private sector actors (input suppliers, agribusiness), NGOs (community mobilisation), and farmer organizations. Birner and colleagues propose a “best fit” framework: rather than transplanting a single model, systems should be designed according to local objectives, institutional capacities, and farmer diversity. This pluralistic approach acknowledges heterogeneity in demand and willingness to pay for services.

3. Innovations in delivery: Recent innovations include ICT-enabled advisory (mobile extension, SMS alerts, apps), farmer field schools (participatory experiential learning), value-chain oriented advisory (linking advice to market actors), voucher-based extension to stimulate private providers, and hybrid public–private partnerships. These aim to increase timeliness, tailor messages, and scale services while trying to retain equity goals. FAO and other agencies have documented many country cases and “good practices” illustrating these models.

Empirical Evidence: Impacts On Livelihoods

1. Productivity and income: Meta-analyses and program evaluations show that advisory services can increase adoption of improved technologies and practices, often translating into higher yields and incomes — but effect sizes vary widely by context, commodity, and service design. Key determinants of positive impacts include continuity of contact, relevance of recommendations, integration with input supply and markets, and attention to complementarities (credit, infrastructure). The World Bank synthesis emphasizes that extension is necessary but not sufficient; without markets, affordable inputs, or land tenure security, productivity gains may be limited or unsustainable.

2. Food security and nutrition: Extension that promotes diverse cropping systems, nutrition-sensitive agriculture, and home gardening can improve household dietary diversity, but evidence is mixed and depends on whether nutrition objectives are explicitly integrated into program design (e.g., behaviour change communication, women’s empowerment). Programs that link technical advice to nutrition education and women’s involvement show stronger nutritional outcomes.

3. Social and institutional outcomes: Extension that fosters farmer groups, participatory learning, and collective marketing can strengthen social capital and market power, supporting livelihood diversification. Farmer field schools and group-based approaches often show benefits in knowledge diffusion and risk sharing, though scaling such participatory models remains challenging.

4. Equity and gender: Standard public provision often reaches larger, better-off farms; without pro-poor targeting, the poorest and women can be excluded. Deliberate design features (female extension workers, timing/venue of meetings, content relevant to women’s crops and roles) improve outreach to women. The literature stresses that extension must be designed to overcome social barriers and ensure equitable access.

Constraints Limiting Extension’s Contribution to Livelihoods

1. Underfunding and staffing: public extension agencies are frequently under-resourced, with low coverage and limited training for staff.

2. Poor incentive structures: extension agents often lack performance incentives or face weak accountability for outcomes.

3. Mismatch between supply and demand: centrally designed messages may not match diverse farmer needs; weak feedback loops reduce relevance.

4. Limited integration with markets and inputs: advising on technologies without enabling access to inputs/markets reduces adoption potential.

5. Equity and accessibility gaps: remote, small, or female-headed households may be systematically underserved.

6. Monitoring and evidence gaps: weak M&E systems and limited rigorous impact evaluations make it hard to learn what works at scale.

Design Principles and Promising Practices

Drawing on the syntheses and global reviews, the following design principles strengthen the linkage between extension and improved livelihoods:

1. Contextualisation (best-fit): adopt models fitted to local agro-ecological, market, and institutional realities rather than transplanting a single approach.

2. Demand-responsiveness and farmer participation: use participatory diagnostics and farmer groups to ensure relevance and foster ownership.

3. Pluralistic delivery and partnerships: combine public functions (public goods, reaching marginalised farmers) with private and NGO roles where commercial incentives support sustainability.

4. Integration with value chains and finance: link advisory messages to input supply, credit, and market access to convert knowledge into income.

5. Targeted inclusion strategies: design gender-sensitive approaches, youth-oriented services, and mechanisms to reach landless or marginal households.

6. Use of digital tools with caution: ICT can increase reach and timeliness but should complement, not replace, interpersonal and group learning; attention to digital divides is necessary.

7. Robust M&E and learning: embed monitoring systems and rigorous evaluations (including randomized or quasi-experimental designs where feasible) to build an evidence base and adapt programs.

Policy Implications

Policymakers aiming to maximise extension's contribution to rural livelihoods should:

1. Reorient public extension toward public-good functions (e.g., pest surveillance, R&D linkages, pro-poor outreach) while enabling private actors where markets permit.

2. Provide stable financing and invest in human capacity, including extension staff training in facilitation, gender, and market linkages.

3. Institutionalize mechanisms for stakeholder coordination (ministries, research institutions, private sector, NGOs, farmer organizations) to prevent fragmentation and duplication.

4. Incentivize performance and accountability, using outcome-oriented indicators (adoption, income change, nutritional outcomes) rather than input measures alone.

Research Gaps and Future Directions

1. Causal evidence on livelihoods outcomes: more rigorous impact evaluations linking extension to long-term livelihood indicators (income dynamics, resilience) are needed.

2. Cost-effectiveness across delivery modes: comparative studies that account for both fiscal costs and equity effects would inform resource allocation.

3. Designs for inclusivity: tested models that successfully reach women, the landless, and the most marginal households at scale are still limited.

4. Hybrid ICT + interpersonal learning: research on how digital tools can best complement participatory methods in different contexts.

Conclusion

Agricultural extension remains a foundational policy lever for improving rural livelihoods but is neither a panacea nor a one-size-fits-all solution. Evidence indicates substantial potential to raise productivity, income, and resilience — particularly when extension is responsive to farmer demand, integrated with markets and inputs, and intentionally inclusive. The shift from “best practice” to “best fit” underscores the

need for flexible, pluralistic systems tailored to local constraints and opportunities. Strengthening public-good functions, fostering partnerships, investing in human capacity, and improving monitoring and evaluation will increase the likelihood that extension translates knowledge into sustained livelihood gains.

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Advances in Omics Technologies for Quality Improvement in Fruits

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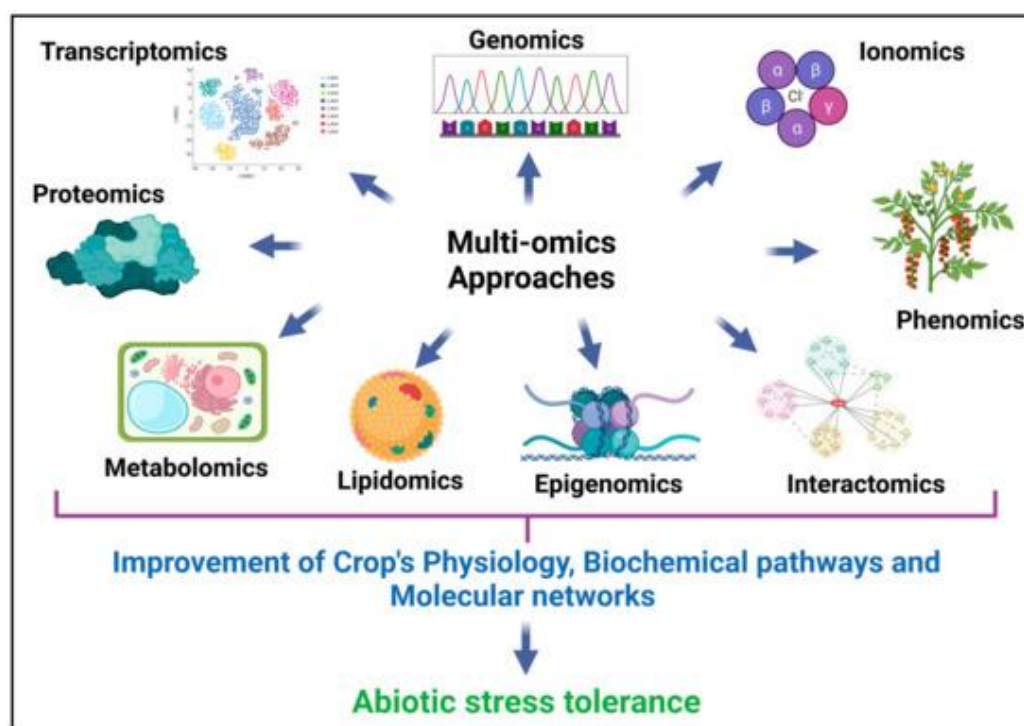
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Summary

The application of multi-omics technologies—genomics, transcriptomics, proteomics, metabolomics, and phenomics—has ushered in a new era of precision biology in horticultural science, fundamentally advancing our understanding of the complex traits that constitute fruit quality. These high-throughput technologies facilitate the systematic identification of key genetic markers, elucidate intricate regulatory pathways, and map the comprehensive biochemical networks that underpin desirable consumer attributes such as flavor complexity, textural properties, nutritional density, and postharvest longevity. This review synthesizes recent groundbreaking developments in these omics-based approaches, highlighting their powerful integration into modern, data-driven breeding programs and innovative postharvest management strategies to enhance the value chain of fruit production.

Introduction

Fruit quality is a multifaceted concept encompassing a broad spectrum of consumer- and market-driven attributes. These include sensory characteristics (sweetness, acidity, aroma volatiles, and firmness), nutritional content (vitamins, antioxidants, dietary fibers), and postharvest performance (shelf life, resistance to physiological disorders and pathogens). For decades, traditional breeding methods, relying on phenotypic selection and hybridization, have made substantial, albeit slow, contributions to enhancing these traits. However, the polygenic and environmentally influenced nature of most quality traits has posed significant challenges. The advent of omics technologies has revolutionized this field by providing unprecedented, comprehensive insights into the genetic, molecular, and metabolic landscapes of fruit species. By decoding the fundamental blueprint of life and its functional outputs, omics approaches enable a more precise, predictive, and accelerated pathway for the genetic improvement and quality preservation of fruits.



Genomics: Decoding the Genetic Blueprint

Genomics serves as the foundational bedrock for understanding the hereditary architecture of fruit quality. The dramatic reduction in the cost of high-throughput sequencing has led to a proliferation of high-quality, chromosome-level genome assemblies for a wide range of fruit species, from staples like apple and tomato to more exotic fruits. This genomic resource is pivotal for identifying genes and allelic variations directly associated with key quality attributes. For instance, genome-wide association studies (GWAS) have been successfully deployed in tomato and grape populations to pinpoint precise genomic loci and single nucleotide polymorphisms (SNPs) linked to variations in soluble solid content (sweetness), organic acid composition (acidity), and the synthesis of key aroma compounds. Beyond discovery, genomics empowers practical applications. The development of dense molecular marker arrays and high-resolution genetic maps has significantly enhanced the efficiency of Marker-Assisted Selection (MAS), allowing breeders to introgress desirable quality alleles from wild relatives into elite cultivars with greater speed and accuracy, bypassing the need for lengthy phenotypic evaluations (Mathiazhagan et al. 2021).

Transcriptomics: Profiling Gene Expression

While genomics provides the parts list, transcriptomics reveals which parts are active, when, and under what conditions. This technology involves the global analysis of RNA transcripts (the transcriptome) to understand spatiotemporal gene expression patterns throughout fruit development, ripening, and in response to postharvest stresses. Techniques like RNA-Seq have been instrumental in dissecting the complex regulatory networks that govern critical processes. For example, transcriptomic time-course studies have meticulously charted the expression waves of genes involved in hormone biosynthesis (e.g., ethylene in climacteric fruits, abscisic acid in non-climacteric fruits), cell wall modification, pigment accumulation, and stress signaling. These studies not only identify master regulatory transcription factors but also reveal entire co-expression networks, providing a systems-level view of ripening control. The insights gained enable the identification of high-priority candidate genes for genetic engineering or gene editing and facilitate the development of molecular biomarkers for non-destructive quality assessment and predicting shelf-life potential.

Proteomics: Understanding Protein Dynamics

Proteomics bridges the gap between gene expression and cellular function by providing a direct readout of the proteome—the complete set of proteins, including their post-translational modifications, interactions, and abundances. In the context of fruit quality, proteomic analyses (using 2D-GE, iTRAQ, or TMT technologies) have been crucial for identifying effector proteins that directly determine trait outcomes. For instance, studies have pinpointed specific isoforms of enzymes involved in pectin degradation (e.g., polygalacturonase, pectin methylesterase) that are directly responsible for textural changes and softening during ripening. Similarly, proteomics has identified key proteins in pathways synthesizing flavor and aroma volatiles, as well as antioxidant enzymes and stress-related proteins that confer tolerance to chilling injury or fungal attacks during storage (Romero, 2024). This functional information is invaluable for designing targeted postharvest treatments (e.g., controlled atmospheres, heat treatments) that modulate the activity of these specific proteins to maintain quality.

Metabolomics: Profiling Metabolic Networks

Metabolomics offers the closest molecular representation of the phenotype by comprehensively profiling the entire complement of small-molecule metabolites (sugars, acids, amino acids, lipids, volatiles, and secondary metabolites). This provides a direct, real-time snapshot of the fruit's physiological and nutritional state. Metabolic profiling has been revolutionary in deconstructing the complex chemistries of flavor, aroma, and health-promoting compounds. For example, by correlating metabolite abundance with sensory panel data, studies have identified not just the primary sugars and acids, but specific ratios and minor metabolites that contribute to the unique flavor profiles of mango, strawberry, and blueberry. Furthermore, the power of metabolomics is magnified when integrated with other omics data. Constructing detailed metabolic networks by combining genomic loci (QTLs), transcript levels of biosynthetic genes, and metabolite abundances allows researchers to identify rate-limiting steps and key regulatory nodes in pathways. This systems biology approach is essential for targeted metabolic engineering to enhance nutritional value or flavor intensity.

Phenomics: Linking Genotype to Phenotype

Phenomics addresses a critical bottleneck in plant breeding: the accurate, rapid, and large-scale measurement of complex phenotypes. Utilizing advanced non-destructive imaging technologies (e.g., hyperspectral imaging, MRI, X-ray CT), robotics, and sensor systems, phenomics enables the precise quantification of fruit attributes at a scale impossible for human evaluators. These systems can measure internal and external qualities—including fruit size, shape, color uniformity, internal browning, sugar content (Brix), and even firmness—on thousands of individual fruits. The true power of phenomics is realized through its integration with omics data. By creating massive, high-resolution datasets that link genomic information to digitally captured phenotypes, breeders can develop highly accurate predictive models for Genomic Selection. This allows them to select superior genotypes based on genetic data alone, drastically shortening breeding cycles and enhancing the efficiency of selecting for complex, multi-genic quality traits.

Integrated Omics Approaches

The integration of multiple omics layers—genomics, transcriptomics, proteomics, metabolomics, and phenomics—provides a holistic, systems-level view of the biological processes governing fruit quality. This multi-omics integration is transformative, as it allows researchers to move from correlative observations to causal inference by connecting genetic variation to molecular changes and ultimately to the phenotypic outcome. For instance, combining transcriptomic and metabolomic data from a population of peaches has enabled the reconstruction of gene-metabolite networks, revealing how the expression of specific transcription factors regulates the flux through pathways leading to the production of key aroma volatiles and anthocyanin pigments (Wang et al., 2025). Similarly, integrating proteomic and phenomic data can explain how different protein expression profiles in the cell wall directly lead to measurable differences in fruit firmness and juiciness. This synergistic approach is key to understanding trade-offs and pleiotropic effects, enabling the development of strategies to enhance multiple quality traits simultaneously without unintended negative consequences.

Applications in Breeding and Postharvest Management

The practical applications of omics technologies span the entire fruit production chain. In breeding, they are the engine of modern precision agriculture. Genomic Selection, powered by genome-wide markers and phenomic data, is accelerating the development of new cultivars with superior flavor, enhanced nutritional profiles, and improved texture. Marker-Assisted Selection continues to be refined for introgressing traits like high lycopene content or specific disease resistances that are linked to postharvest quality. In postharvest management, omics provides a deep molecular understanding of the processes of ripening, senescence, and stress response. For example, transcriptomic studies have identified early warning gene expression signatures for chilling injury, allowing for the development of pre-conditioning treatments. Proteomic analyses of fruits treated with ethylene inhibitors or 1-MCP have revealed how these treatments alter the expression of cell wall-modifying proteins, providing a scientific basis for optimizing application protocols to extend shelf life while preserving eating quality.

Future Directions

The future of fruit quality improvement is intrinsically linked to the continued evolution of omics technologies. Emerging fields such as epigenomics will uncover how DNA methylation and histone modifications influence heritable traits like ripening behavior without altering the DNA sequence itself. Single-cell omics promises to resolve the cellular heterogeneity within fruit tissues, revealing, for example, how different cell layers in the pericarp contribute uniquely to flavor and texture. Synthetic biology approaches could use omics-derived parts lists to design and engineer entirely new metabolic pathways into fruits to boost the production of valuable nutraceuticals. A major frontier lies in the application of artificial intelligence (AI) and machine learning to integrate and interpret the vast, multi-dimensional datasets generated by omics studies. These AI models will be crucial for predicting complex genotype-phenotype relationships, identifying novel gene functions, and ultimately, for the *in silico* design of ideal fruit cultivars tailored to specific environments and consumer preferences.

Conclusion

In conclusion, omics technologies have fundamentally transformed the study and enhancement of fruit quality. By providing deep, multi-layered insights into the genetic, molecular, and biochemical machinery, they have shifted the paradigm from descriptive observation to predictive and precise intervention. The synergistic integration of genomics, transcriptomics, proteomics, metabolomics, and phenomics into a cohesive systems biology framework is unlocking a new level of understanding. The continued application and integration of these powerful tools into breeding programs and postharvest practices hold immense potential for developing the next generation of fruit cultivars—those that not only meet consumer demands for taste and health but also contribute to sustainable agriculture and global food security through reduced waste and enhanced resilience.

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An Insight on the Role of Omics Technologies in Soybean Breeding

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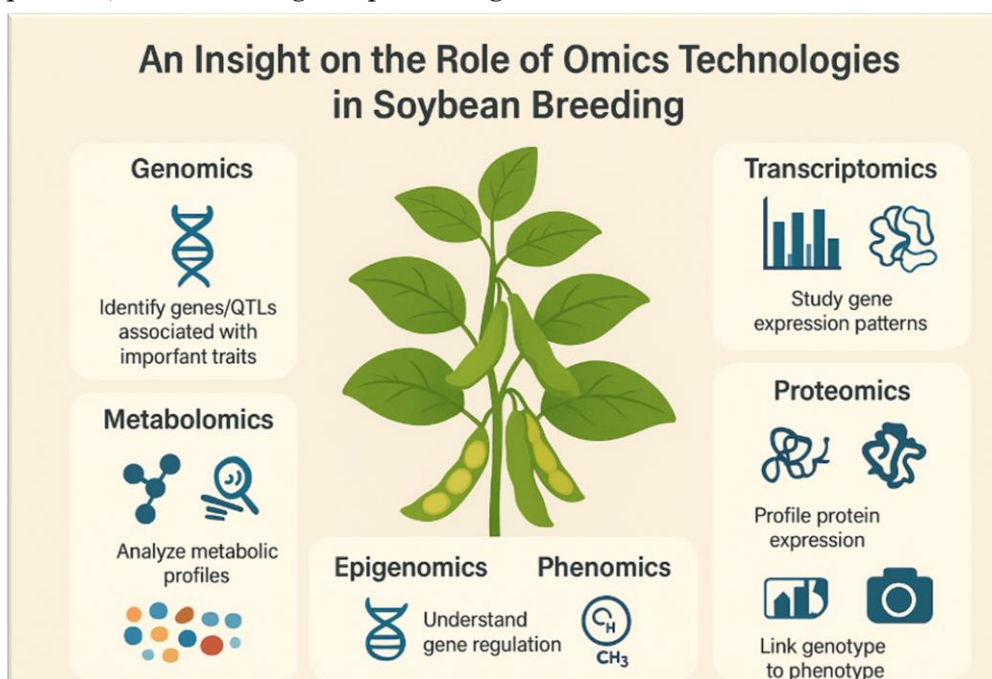
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Summary

Soybean (*Glycine max*) stands as a pillar of global agriculture, serving as an indispensable source of plant-based protein for human consumption and animal feed, as well as a primary source of vegetable oil. Its economic and nutritional importance has driven the need for continuous improvement. The advent of omics technologies—a suite of disciplines including genomics, transcriptomics, proteomics, metabolomics, epigenomics, and phenomics—has fundamentally transformed soybean breeding. This paradigm shift moves beyond reliance on observable traits to a data-driven, molecular-level understanding. These technologies collectively empower breeders to pinpoint precise genetic markers, decipher gene functions, and unravel the complex interplay between genes, proteins, and metabolites that underpin critical agronomic traits. Consequently, the path to developing high-yielding, nutrient-dense, disease-resistant, and climate-resilient soybean varieties has been significantly accelerated.

Introduction

For decades, traditional soybean breeding, reliant on phenotypic selection and hybridization, has been the backbone of cultivar development. While successful, this process is inherently slow, often taking a decade or more to release a new variety (Haidar et al., 2024). It is also constrained by the influence of environmental conditions on phenotypic expression, making it difficult to select for complex traits like abiotic stress tolerance or specific nutritional qualities. The integration of omics technologies offers a revolutionary, holistic approach. By dissecting the biological blueprint of the soybean plant at every level from its DNA to its physical form—these tools provide unprecedented insights (Cao et al., 2022). This review comprehensively examines the individual and collective contributions of the various omics disciplines to modern soybean breeding, detailing their specific applications, discussing the practical challenges they present, and outlining the promising future directions for this field.



Genomics: The Foundation of Heredity

Genomics, the study of an organism's complete set of DNA, provides the foundational map for all breeding efforts. The completion of a high-quality soybean reference genome was a landmark achievement, providing a standardized sequence against which variations can be compared. Modern genomic tools extend far beyond sequencing to include high-throughput genotyping techniques like SNP (Single Nucleotide Polymorphism) arrays and Genotyping-by-Sequencing (GBS). These tools are leveraged in Genome-Wide Association Studies (GWAS) and QTL (Quantitative Trait Loci) mapping to statistically link specific genomic regions to traits of interest. For example, genomics has been pivotal in identifying genes controlling crucial aspects such as seed oil and protein composition, the determinacy of growth habit, and resistance to specific races of soybean cyst nematode. This allows breeders to use Marker-Assisted Selection (MAS) to pyramid favorable alleles into elite breeding lines with high precision (Haidar et al., 2024).

Transcriptomics: The Dynamic Blueprint of Gene Activity

While genomics reveals what genes are present, transcriptomics reveals which of those genes are actively being transcribed into RNA molecules at any given time or under specific conditions. Techniques like RNA sequencing (RNA-Seq) allow for the comprehensive profiling of the transcriptome. In soybean, this has been instrumental in understanding how gene expression networks are rewired in response to drought, flooding, pathogen attack, or during critical developmental stages like nodulation (the symbiotic relationship with nitrogen-fixing bacteria) and seed filling (Cao et al., 2022). By comparing transcriptomes of resistant and susceptible lines, breeders can identify key defense-related genes that are switched on upon pathogen challenge. Similarly, understanding the transcriptomic shifts during seed development helps identify master regulators of oil and protein biosynthesis, providing targets for genetic improvement.

Proteomics: From Gene Message to Functional Machinery

Proteomics bridges the gap between gene expression and cellular function by studying the entire complement of proteins—the primary functional actors in the cell. The presence of an mRNA transcript does not always guarantee the production of a corresponding protein, and proteins often undergo post-translational modifications that regulate their activity. Proteomic techniques, such as mass spectrometry, are used to profile protein abundance, modifications, and interactions. In soybean, proteomic studies have revealed how the protein profile of a leaf changes during water deficit, identifying key stress-responsive proteins like chaperones and antioxidant enzymes. In seeds, proteomics helps characterize the different storage protein families (glycinin and β -conglycinin) and their ratios, which directly impact nutritional quality and functional properties for food processing (Yang et al., 2024).

Metabolomics: The Biochemical Phenotype

Metabolomics focuses on the comprehensive analysis of all small-molecule metabolites (e.g., amino acids, sugars, lipids, secondary metabolites) within a tissue or organism. The metabolome represents the ultimate downstream product of genomic, transcriptomic, and proteomic activity and is most closely linked to the observable phenotype. Metabolomic profiling using technologies like mass spectrometry and NMR spectroscopy provides a deep biochemical snapshot. In soybean, this approach has been used to identify metabolites associated with flavour profiles, anti-nutritional factors, and the synthesis of beneficial compounds like isoflavones. Under stress, metabolomics can reveal the accumulation of compatible solutes (e.g., proline, sugars) for osmotic adjustment or the production of antimicrobial phytoalexins, offering tangible biomarkers for selection (Yang et al., 2024).

Epigenomics: The Layer of Heritable Regulation Beyond DNA Sequence

Epigenomics is the study of reversible, heritable changes in gene expression that occur without altering the underlying DNA sequence. These changes include DNA methylation and modifications to histone proteins, which act as a regulatory layer controlling chromatin structure and gene accessibility. Research has shown that environmental stresses, such as drought or heat, can induce specific epigenetic marks in soybean. These marks can fine-tune the expression of stress-responsive genes, potentially providing a mechanism for short-term adaptation (Cao et al., 2022). Furthermore, there is evidence that some of these epigenetic states can be transmitted to subsequent generations, a phenomenon known as transgenerational

epigenetic inheritance. Understanding this layer of regulation opens avenues for developing varieties with enhanced phenotypic plasticity and stability across variable environments.

Phenomics: High-Throughput Phenotypic Profiling

Phenomics addresses the bottleneck of detailed phenotypic data collection by using automated, high-throughput technologies to precisely measure plant traits. This involves field-based platforms equipped with advanced sensors, including RGB, multispectral, hyperspectral, and thermal cameras, as well as LiDAR. These systems can rapidly and non-destructively capture data on hundreds of plants for traits like canopy cover, chlorophyll content, plant architecture, and water stress status. The power of phenomics is fully realized when this rich phenotypic data is correlated with genomic information—a practice known as genomic selection. This allows breeders to predict the performance of new lines based on their genotype and historical phenotype-genotype models, drastically speeding up the selection cycle (Haidar et al., 2024).

Integration of Multi-Omics Approaches: A Systems Biology Perspective

The true power of omics lies not in their individual application, but in their integration. A multi-omics approach seeks to build a comprehensive, systems-level model of the soybean plant. For instance, a QTL identified through genomics (e.g., for drought tolerance) can be validated by examining differential gene expression (transcriptomics) in that region, followed by identifying the corresponding protein (proteomics) and the resulting changes in key metabolites like proline (metabolomics), all while monitoring the plant's water status and biomass with drones (phenomics). Sophisticated bioinformatics and computational biology tools are essential to integrate these massive, heterogeneous datasets (Yang et al., 2024). This holistic view enables the identification of robust biomarker panels and the elucidation of complete gene regulatory networks controlling complex traits.

Applications in Soybean Breeding

1. Disease Resistance: Soybean is affected by numerous pathogens, including *Phytophthora sojae* (root and stem rot), *Fusarium virguliforme* (causing sudden death syndrome, SDS), *Pseudomonas syringae*, and various viral pathogens. Omics technologies have revolutionized the identification and functional characterization of resistance (R) genes and quantitative resistance loci (QRLs).

a. Genomics and GWAS: Whole-genome sequencing and genome-wide association studies (GWAS) have enabled the mapping of both major R-genes and minor QRLs that contribute to partial resistance. For instance, *Rps* genes conferring complete resistance against *P. sojae* have been cloned and characterized, allowing breeders to use marker-assisted selection (MAS) to introgress these genes into elite cultivars. QRLs for complex diseases like SDS are now being elucidated through high-density SNP arrays and haplotype mapping (Yang et al., 2024).

b. Transcriptomics and Proteomics: Transcriptomic studies under pathogen challenge reveal the upregulation of defense-related pathways such as pathogenesis-related (PR) proteins, phenylpropanoid biosynthesis, and reactive oxygen species (ROS) signaling. Proteomic studies complement this by identifying proteins involved in pathogen recognition, signal transduction, and cell-wall reinforcement (Cao et al., 2022).

c. Stacked Resistance: Modern breeding strategies integrate multi-omics data to stack multiple R-genes and QRLs, creating cultivars with durable and broad-spectrum resistance. This approach reduces the likelihood of resistance breakdown, especially against pathogens with high genetic variability.

3. Abiotic Stress Tolerance: Abiotic stresses such as drought, salinity, extreme temperatures, and flooding significantly constrain soybean productivity. Multi-omics approaches allow the dissection of stress response networks at multiple biological levels:

a. Transcriptomics: RNA-seq and microarray analyses have identified numerous stress-responsive genes, including transcription factors (e.g., DREB, NAC, MYB families), heat-shock proteins, aquaporins, and enzymes involved in osmolyte synthesis (proline, trehalose).

b. Proteomics and Metabolomics: Proteomic studies reveal key proteins involved in ROS detoxification, osmotic adjustment, and membrane stabilization, while metabolomic profiling identifies compounds such as compatible solutes and secondary metabolites that enhance stress tolerance (Yang et al., 2024).

c. Epigenomics: DNA methylation and histone modification studies have uncovered epigenetic regulatory mechanisms that modulate stress-responsive gene expression, enabling the development of stress-adapted cultivars without altering the genome sequence.

d. Breeding Applications: Integrating these omics insights allows breeders to identify candidate genes for MAS or gene editing (e.g., CRISPR-Cas9) to develop varieties that maintain yield stability and seed quality under suboptimal environmental conditions. Stress-tolerant varieties are particularly important for regions experiencing climate variability and soil salinity (Cao et al., 2022).

3. Nutritional Quality: Soybean's value as a protein and oil source makes nutritional quality a major breeding target. Omics technologies enable precise manipulation of biochemical and genetic pathways:

a. Protein Content and Composition: Genomics and transcriptomics have been used to identify alleles and regulatory networks controlling storage protein accumulation (glycinin, β -conglycinin). Proteomic profiling allows the quantification and characterization of seed proteins, guiding breeding for enhanced amino acid profiles.

b. Oil Content and Fatty Acid Composition: Metabolomic analyses help understand lipid biosynthesis pathways, facilitating the selection for desirable fatty acid profiles such as low linolenic acid (for oil stability) or increased oleic acid content.

c. Reduction of Anti-Nutritional Factors: Anti-nutritional compounds like trypsin inhibitors, lectins, and raffinose family oligosaccharides limit soybean utilization. Omics tools have identified the genetic loci and enzymatic pathways responsible for these compounds, enabling breeders to reduce their levels without compromising yield.

d. Integration with Multi-Omics: By integrating transcriptomic, metabolomic, and proteomic data, breeders can pinpoint regulatory nodes in protein and oil biosynthesis, allowing the simultaneous improvement of multiple nutritional traits (Cao et al., 2022).

4. Yield Improvement: Yield is the most complex agronomic trait in soybean, being influenced by multiple component traits and environmental interactions. Omics approaches allow the dissection of yield into measurable, heritable sub-traits:

a. Genomics and GWAS: High-density SNP arrays and sequencing data have enabled the identification of QTLs and alleles associated with pods per plant, seeds per pod, seed weight, and harvest index. Genomic selection (GS) models now utilize thousands of markers to predict yield potential in early-generation plants, drastically reducing breeding cycle time.

b. Phenomic Integration: High-throughput phenotyping platforms provide precise measurements of canopy architecture, leaf area, flowering time, and pod set under field or controlled conditions. These phenotypic datasets are combined with genomic data to improve predictive accuracy for yield-related traits.

c. Molecular Mechanisms: Omics studies reveal that genes involved in photosynthetic efficiency, hormone regulation (e.g., gibberellins, cytokinins), nutrient uptake, and source-sink relationships are critical determinants of yield. Modifying these pathways through MAS, gene editing, or transgenic approaches enables targeted improvement (Cao et al., 2022).

d. Acceleration of Genetic Gain: By combining genomic prediction, phenomics, and omics-informed trait dissection, breeders can increase the rate of genetic gain per year. Multi-trait selection strategies guided by omics data allow simultaneous improvement of yield, quality, and stress resilience.

Challenges and Future Directions

The widespread implementation of omics-led breeding holds tremendous promise, but it faces significant challenges that need to be addressed. One major hurdle is the integration and management of large volumes of multi-omics data, which requires the development of user-friendly bioinformatics platforms, standardized data formats, and robust statistical models. Additionally, the high cost of high-throughput omics platforms, advanced phenotyping equipment, and computational infrastructure can be prohibitive for public institutions and programs in developing countries. Furthermore, the polygenic nature of complex traits and strong genotype-by-environment interactions pose biological challenges, necessitating validation across multiple locations and seasons. To overcome these challenges, future efforts will focus on developing

more cost-effective and accessible technologies, leveraging artificial intelligence and machine learning to extract meaningful patterns from complex datasets, and deepening our functional understanding of genes and networks through techniques like gene editing (CRISPR-Cas9) to validate omics-derived discoveries.

Conclusion

Omics technologies have irrevocably shifted the paradigm of soybean breeding from an art grounded in observation to a science driven by deep molecular data. Each omics layer—genomics, transcriptomics, proteomics, metabolomics, epigenomics, and phenomics—provides a unique and invaluable perspective on the plant's biology. Their integration into a multi-omics framework offers the most powerful approach yet to decipher the intricate mechanisms governing yield, stress resilience, and quality. While challenges in data handling, cost, and biological complexity persist, the ongoing refinement of these technologies and analytical methods promises to unlock further gains. By systematically addressing these challenges, the global soybean research community can continue to harness the full potential of omics to breed the next generation of superior soybean cultivars, ensuring food and nutritional security for a growing global population in the face of climate change.

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Advances in Proteomics Technologies for Crop Quality Improvement - A Review

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Summary

Proteomics — the large-scale study of proteins, their abundance, modifications, interactions and spatial/temporal dynamics — has emerged as a central layer of functional biology for understanding phenotypes that matter to crop quality: nutritional composition (protein, amino-acid profiles, vitamins), processing traits (dough strength, oil composition), flavor and aroma, allergenicity, and storage/processing stability. Technological advances in sample preparation, mass spectrometry (MS), data-independent acquisition (DIA), targeted proteomics, post-translational modification (PTM) mapping, spatial and single-cell proteomics, and bioinformatic integration with genomics and metabolomics now allow deep, quantitative, and high-throughput profiling of crop proteomes. These innovations enable discovery of biomarkers and molecular mechanisms that can be translated into breeding, precision phenotyping, and post-harvest or processing interventions to improve crop quality. This review summarizes the major technological advances, highlights applications to crop-quality traits, discusses bottlenecks and validation strategies, and outlines future directions for proteomics-driven improvement of crop quality. Key recent overviews and method papers that shaped this field are noted.

Introduction

Genetic sequence and transcriptome information are essential but incomplete predictors of phenotype: proteins execute biochemical functions, determine processing behaviour, and are the direct determinants of nutritional and allergenic properties of foods. For quality traits — e.g., seed storage protein composition (affecting nutritional value and processing), enzymes controlling aroma volatile formation, or PTMs that influence protein solubility and digestibility — proteomics provides necessary, often unique, insights. Modern MS-based proteomics can quantify thousands of proteins across tissues and developmental stages, enabling mechanistic links between genotype, environment and final product quality.

Key Technological Advances

This section summarizes the major technological building blocks that have recently expanded proteomics' power for crop-quality research.

1. Sample preparation optimized for plants: Plant tissues are chemically complex (phenolics, pigments, polysaccharides) and often low in protein percent — obstacles that historically limited proteomics in crops. Universal and automated extraction workflows (e.g., SP3 single-pot approaches, optimized precipitation and cleanup) now allow reproducible processing across diverse crop tissues (leaf, seed, fruit, tuber) and enable downstream high-throughput LC-MS workflows. Automating extraction reduces bias and improves inter-sample comparability — essential for breeding/phenotyping experiments.

2. Mass spectrometry hardware — depth and speed: Modern high-resolution Orbitrap and time-of-flight instruments, improved ion sources, and faster scan cycles dramatically increase proteome coverage. Combined with improved chromatographic separations and offline fractionation, studies now identify and quantify 5k–10k proteins from single crop tissues in realistic time frames — enabling population or multi-tissue studies relevant to quality traits.

3. Acquisition strategies: DDA, DIA, and targeted proteomics:

a. Data-dependent acquisition (DDA): classical shotgun approach — still useful for discovery but can miss low-abundance proteins due to stochastic sampling.

b. Data-independent acquisition (DIA; e.g., SWATH): increasingly preferred for reproducible, deep, and quantitative proteome coverage across many samples, improving biomarker validation and cross-study comparability.

c. Targeted proteomics (SRM/MRM, PRM): gold standard for validating candidate quality biomarkers (e.g., storage proteins, allergen peptides) with high sensitivity and absolute quantification when coupled to stable isotope standards. DIA + targeted validation forms a robust pipeline from discovery to breeding/phenotyping assays.

4. Quantitation approaches: label-free, isobaric labels, and absolute quantification: Label-free quantitation scales well for many samples and populations. Isobaric tagging (TMT/iTRAQ) enables multiplexed comparisons and deeper coverage when combined with offline fractionation. For trait translation (breeding or food processing), absolute quantification using isotope-labeled peptide standards or QconCAT constructs is essential to create thresholds or decision rules (e.g., allergen content limits, minimum essential amino-acid concentrations).

5. Post-translational modification (PTM) analysis: PTMs (phosphorylation, glycosylation, acetylation, ubiquitination) modulate enzyme activity, stability and interactions that determine metabolic fluxes and, ultimately, quality attributes (e.g., starch biosynthetic enzyme regulation affecting grain texture). Enrichment techniques (TiO₂/IMAC for phosphopeptides, lectin or HILIC for glycopeptides) and specialized MS workflows enable PTM mapping, adding mechanistic depth beyond abundance changes.

6. Spatial and single-cell proteomics: Spatial proteomics (subcellular fractionation, laser capture microdissection, imaging mass spectrometry) and early single-cell/single-cell-type proteomics offer the capacity to link cell-type specific protein profiles to tissue-level quality traits (e.g., aleurone vs endosperm storage protein distribution affecting milling and processing). Although still technically challenging in many crop tissues, methodological advances and higher instrument sensitivity are closing the gap.

7. Proteogenomics and multi-omics integration: Proteogenomics uses proteomic evidence to refine gene models and detect translated novel ORFs; integrated proteome + transcriptome + metabolome analyses unravel pathways that determine flavor, nutritional profiles, and processing traits. Machine-learning tools are now used to integrate omics layers for trait prediction and candidate prioritization.

Applications to Crop Quality Improvement

Below are concrete application areas where proteomics has been used or shows strong promise for improving crop quality.

1. Seed and grain nutritional quality:

a. Storage protein profiling (glutenins/gliadins in wheat; storage globulins in legumes) ties directly to nutritional value, allergenicity and processing quality (e.g., dough rheology). Proteomics has dissected subunit composition, allelic variants and PTMs that affect functionality.

b. Amino-acid completeness: proteomics quantifies relative representation of essential amino-acid-rich proteins and supports breeding for better protein quality.

c. Biofortification validation: after genetic or agronomic biofortification (e.g., higher methionine, lysine), proteomics confirms target protein increases and assesses unintended proteome shifts.

2. Flavor, aroma and secondary metabolites: Proteins (enzymes in volatile biosynthesis pathways) determine flavor/aroma compounds (terpenoids, esters, phenolics). Quantitative proteomics has identified differentially abundant biosynthetic enzymes between cultivars and ripening stages — informing breeding or post-harvest handling to retain desirable aromas (e.g., in tomato, strawberry, fruit crops). Integration with metabolomics directly ties enzyme levels to volatile abundance.

3. Oil and lipid composition (oilseed quality): Proteomic profiling of seed development reveals enzymes in fatty-acid and lipid assembly pathways; abundance and phosphorylation status of key enzymes can predict shifts in oil composition (saturated/unsaturated ratios), guiding selection or editing strategies for healthier oil profiles.

4. Allergen and anti-nutritional factor monitoring: Proteomics enables peptide-level detection of known allergenic proteins and discovery of novel allergenic peptides. Targeted MS assays provide sensitive,

quantitative tests for regulatory monitoring and breeding programs aiming to reduce allergen content (e.g., selective down-regulation of specific seed proteins).

5. Processing and functional quality (e.g., baking, malting): Proteins determining viscoelastic properties (wheat gluten network), enzyme activities (amylases in malting barley) or gelation (soy proteins in tofu) are measurable by proteomics. Profiling multiple genotypes under processing-relevant conditions allows breeders and processors to choose varieties optimized for end-use.

6. Post-harvest quality and shelf life: Proteomic changes during storage reveal proteases, oxidative enzymes and stress-related proteins that control textural degradation, browning, and nutrient loss. Identification of such markers supports storage interventions (temperature, atmosphere) and selection of varieties with slower proteome drift.

Table 1. Crop-Specific Proteomics Technologies for Crop Quality Improvement:

Crop	Targeted Quality Traits	Proteomic Technologies/Approaches	Major Findings and Applications
Rice (<i>Oryza sativa</i> L.)	Grain texture, aroma, cooking quality, nutritional composition	2D-DIGE, iTRAQ, LC-MS/MS, phosphoproteomics	Identified key starch biosynthetic enzymes (GBSS, SSIIa) linked to amylose content and cooking quality; discovered aroma-associated BADH2 protein variants; mapped phosphorylation sites affecting carbon allocation during grain filling.
Wheat (<i>Triticum aestivum</i> L.)	Dough elasticity, gluten strength, bread-making quality	Label-free LC-MS/MS, MALDI-TOF/TOF, SWATH-DIA, 2D-GE	Quantified glutenin/gliadin subunits influencing dough rheology; profiled heat-stress effects on storage proteins; developed MRM assays for quality prediction in breeding programs.
Maize (<i>Zea mays</i> L.)	Kernel protein composition, starch content, nutritional value	iTRAQ-based quantitative proteomics, phosphoproteomics, SRM	Identified storage proteins (zeins) and metabolic enzymes affecting kernel hardness and lysine content; mapped phosphorylation controlling starch biosynthesis and nutrient accumulation.
Barley (<i>Hordeum vulgare</i> L.)	Malting quality, enzyme activity, flavor	Label-free shotgun proteomics, SRM/PRM assays	Characterized differential abundance of β -amylase, protein Z, and lipid transfer proteins critical for beer flavor and foam stability; enabled marker-assisted selection for improved malting quality.
Soybean (<i>Glycine max</i> L.)	Seed storage protein composition, allergenicity, oil quality	TMT-based quantitative proteomics, targeted MRM, glycoproteomics	Identified allergen proteins (Gly m 4, Gly m 6); discovered PTM-driven changes affecting allergenicity; profiled lipid metabolism enzymes influencing oil composition and oxidative stability.
Chickpea (<i>Cicer arietinum</i> L.)	Protein digestibility, cooking quality	iTRAQ, LC-MS/MS, gel-free label-free proteomics	Revealed up-regulation of storage globulins linked to digestibility; identified stress proteins affecting seed hardening and cooking time.
Groundnut (<i>Arachis hypogaea</i> L.)	Oil composition, allergenicity	2D-GE, MALDI-TOF/TOF, targeted proteomics	Characterized allergenic proteins (Ara h 1, Ara h 2); mapped proteome shifts during seed

			development affecting fatty acid profiles and oil stability.
Tomato (<i>Solanum lycopersicum</i> L.)	Fruit ripening, flavor, color, shelf life	LC–MS/MS, SWATH-DIA, phosphoproteomics	Identified enzymes in carotenoid and volatile biosynthesis (PSY1, LOX, ADH) associated with flavor and color; revealed protein networks regulating ripening and postharvest softening.
Potato (<i>Solanum tuberosum</i> L.)	Starch quality, processing suitability (frying color, texture)	2D-GE, label-free proteomics, PTM analysis	Detected changes in tuber proteome influencing starch branching and sugar accumulation; guided selection for reduced browning during frying.
Banana (<i>Musa spp.</i>)	Postharvest firmness, flavor, ripening control	Label-free LC–MS/MS, phosphoproteomics	Identified cell wall-modifying enzymes (PGs, PME) and ethylene-signaling proteins influencing ripening rate and textural quality; suggested biomarkers for shelf-life extension.
Grapes (<i>Vitis vinifera</i> L.)	Aroma, wine quality, phenolic content	iTRAQ proteomics, shotgun LC–MS/MS	Profiling of aroma-related enzymes (terpene synthases, glycosidases); identified stress-related proteins influencing phenolic composition in berries.
Tea (<i>Camellia sinensis</i> L.)	Aroma, flavor compounds, leaf quality	2D-GE, MALDI-TOF/TOF, label-free proteomics	Characterized aroma and catechin biosynthetic enzymes (PAL, CHI, DFR); correlated protein expression with flavor intensity and antioxidant potential.
Apple (<i>Malus domestica</i> Borkh.)	Texture, browning resistance, storage quality	Label-free quantitative proteomics, PRM assays	Identified cell-wall degrading enzymes influencing firmness; studied oxidative enzymes (PPOs, peroxidases) related to enzymatic browning during storage.
Peanut (<i>Arachis hypogaea</i> L.)	Allergen reduction, oil quality	LC–MS/MS, targeted SRM, glycoproteomics	Quantified allergen proteins (Ara h family); mapped glycosylation affecting allergenicity; characterized lipid metabolism enzymes improving oil profile.
Rapeseed (<i>Brassica napus</i> L.)	Oil content, fatty acid composition	iTRAQ and label-free quantitative proteomics	Identified enzymes in fatty acid biosynthesis and storage oil assembly; linked phosphorylation changes to improved oleic/linolenic acid balance.
Pea (<i>Pisum sativum</i> L.)	Nutritional protein quality, flavor	Label-free proteomics, SRM assays	Quantified vicilin/legumin subunits affecting digestibility; linked sulfur-rich proteins to improved amino acid profile and flavor neutrality.

From Discovery to Application: Pipelines and Validation

A recommended pipeline for proteomics-driven quality improvement:

- 1. Discovery phase (DIA/DDA):** comparative proteomics across contrasting genotypes or treatments to identify candidate proteins/pathways.
- 2. Prioritization via integrative analysis:** cross-reference with transcriptomics, metabolomics and trait measurements to select robust candidates.
- 3. Targeted quantitative validation:** develop SRM/PRM or immunoassays for candidate peptides/proteins; include isotope-labeled standards for absolute quantification when thresholds matter (food safety or nutrition labeling).
- 4. Population screening:** apply validated targeted assays across breeding populations or germplasm panels for marker-assisted selection or genomic prediction models incorporating proteomic features.
- 5. Functional follow-up:** genetic validation (mutants, transgenics, or gene editing) to ascertain causality and enable direct trait manipulation.

Challenges and Limitations

Crop proteomics faces several challenges and limitations that impact its application in breeding programs. One major challenge is the complexity of sample matrices, where residual interference from secondary metabolites can complicate protein extraction for certain tissues. However, protocol standardization, such as the SP3 method, and automation can help mitigate this issue. Another challenge is the trade-off between proteome depth and throughput, where achieving maximal proteome depth often requires extensive fractionation and instrument time, conflicting with the need for high-throughput and reproducibility in breeding programs. Incomplete proteome databases for non-model crops also hinder peptide identification, necessitating proteogenomics approaches to refine annotations. Furthermore, interpreting protein abundance changes can be complex, as they do not always reflect protein activity, and post-translational modifications (PTMs), localization, and interaction context are crucial for understanding protein function. Lastly, the cost and infrastructure required for comprehensive proteomics, including capital equipment and bioinformatics capacity, can be a significant barrier for many breeding programs, limiting the widespread adoption of proteomics in crop improvement.

Future Directions and Opportunities

Future directions in crop proteomics hold significant promise for advancing our understanding and improvement of crop quality traits. Large-scale crop proteome atlases will systematically map major crop tissues, developmental stages, and varieties, creating comprehensive reference atlases that support trait mapping and proteogenomics. The development of high-throughput targeted panels for phenotyping will enable routine screening in breeding and seed certification through multiplexed targeted assays for core quality proteins. Advancements in single-cell and spatial proteomics will allow for the linking of cell-type proteomes to textural or compositional heterogeneity within organs, offering new trait targets. Furthermore, integrating proteomic features into genomic selection models may improve the prediction of complex quality traits. Standardization of sample preparation, metadata, and public deposition of raw files and spectral libraries will facilitate cross-study comparisons and meta-analyses, accelerating the discovery and application of proteomic insights in crop improvement.

Practical Recommendations for Researchers and Breeders

- 1. Adopt Robust, Reproducible Extraction Protocols:** Adopt extraction protocols that are robust and reproducible, and validated for the specific crop or tissue of interest. SP3-based workflows are a strong option for many crops due to their ability to efficiently extract proteins and remove contaminants. Standardized extraction protocols help ensure consistency across samples and experiments, which is crucial for reliable proteomic analysis.
- 2. Use DIA for Large Panels:** For large-scale proteomic studies, consider using Data-Independent Acquisition (DIA) methods. DIA allows for comprehensive and reproducible quantification of proteins across large sample sets. Following DIA with targeted assays for validation and routine screening can help identify and quantify specific proteins of interest with high accuracy and sensitivity.
- 3. Invest in Building Spectral Libraries:** Investing in building comprehensive spectral libraries is essential for proteomic analysis. Spectral libraries contain information on the fragmentation patterns of

peptides, which can be used to identify and quantify proteins. Improving reference proteomes, especially for non-model crops through proteogenomics, can enhance the accuracy of protein identification and quantification.

4. Combine Proteomics with Metabolomics and Phenotyping: Combining proteomics with metabolomics and high-quality phenotyping can provide a more comprehensive understanding of the biological processes underlying important traits. This integrated approach can help identify key proteins and metabolites associated with desirable traits, strengthening candidate selection for breeding programs.

5. Plan for Bioinformatics: Effective bioinformatics planning is crucial for translating proteomic data into actionable breeding decisions. This involves developing and using standardized bioinformatics pipelines for consistent and reproducible data analysis, maintaining versioned spectral libraries to track updates and ensure reproducibility over time, implementing robust statistical workflows to identify significant changes in protein abundance, and properly managing and storing proteomic data, including raw data and analysis results, to facilitate future analyses and meta-analyses, ultimately enabling informed breeding decisions.

By following these practical recommendations, researchers and breeders can harness the power of proteomics to improve crop breeding and develop crops with desirable traits.

Conclusion

Proteomics technologies have matured to a point where they can meaningfully contribute to crop quality improvement. Continued advances in sample preparation, MS acquisition strategies, PTM analysis, spatial and single-cell workflows, and multi-omics integration are making it feasible to discover, validate and deploy protein-level markers and mechanisms for nutritional quality, flavor, processing performance, allergenicity and shelf life. To fully realize this potential, the community must continue to standardize methods, expand reference proteomes for crops, and build cost-effective targeted assays that integrate with breeding and post-harvest programs.

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Customized Fertilizer for Sustainable Crop Nutrition

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The anticipated food grain demand in India is projected to reach 355 million tonnes by 2030, surpassing the current production of 315.7 million tonnes recorded in 2021-22 (PIB, 2023). With no foreseeable possibility of expanding the cultivation area beyond the existing 142 million hectares, the imperative for achieving the desired upsurge in food grain production rests on enhancing productivity per unit area. Moreover, the imprudent utilization of inorganic fertilizers poses a persistent threat to soil health, counteracting sustainability principles and ecofriendly agricultural practices. Excessive production and indiscriminate application of fertilizers contribute significantly to the disruption of environmental equilibrium. Therefore, it is imperative to focus on fulfilling the crop's complete nutrient demand as well as optimizing fertilizer application in the current context to mitigate the adverse impacts on both soil ecosystems and broader environmental stability and also to continue grain production in sufficient amounts. Customized fertilizers are formulated by considering the fertility status of the soil, climate, and cropping pattern in a given region. So, there is no or less chance of excessive application. Some salient features of customized fertilizers include their uniqueness and ready-to-use nature. These kinds of fertilizers are formulated on comprehensive scientific plant nutrient principles unified with soil information. They are evaluated through both laboratory and field research. Central Fertilizer Committee has recognized customized fertilizer as a new category of area/soil/crop-specific fertilizer and included it in the Fertilizer Control Order (FCO), 1985. According to FCO customized fertilizer is a multi-nutrient carrier intended to comprise macro, secondary, and/or micronutrients both from inorganic sources and/or organic sources, manufactured by an organized process of granulation, satisfying the crop's nutritional needs, specific to its site, soil and stage validated by a scientific crop model, capability developed by an accredited fertilizer manufacturing/marketing company.

Conventional vs. Customized Fertilizer

Conventional and customized fertilizers differ in their composition, production methods, and application strategies, etc. The key distinctions between the above two are listed in Table1.

Table1. Differences between conventional and customized fertilizer:

Aspects	Conventional	Customized
Composition	Pre formulated, uniform mix; fixed nutrient ratio	Tailored to specific needs; adjustable nutrient ratio
Application strategy	Applied uniformly across fields, often based on general recommendations for the target crop	Location and crop-specific. Applied based on the specific nutrient needs of the soil and crop. Precision agriculture techniques, such as variable rate application, may be used to tailor the fertilizer application to different zones within a field
Production methodology	Produced in large quantities using standard manufacturing processes. Readily available and costeffective due to economies of scale	Produced on demand or in smaller batches to meet specific requirements. The production process may involve blending different nutrient sources to achieve the desired nutrient profile.
Distribution near the root zone	Irregular distribution	Uniform distribution

Results of application	Low response, reduced yield, soil degradation	Efficient response and good soil health

Production Techniques of Customized Fertilizers

There are three main production techniques namely Bulk Blending, Compound Granulation/Steam Granulation, and Complex/Chemical Granulation. Amongst them bulk blending is the cheapest method which consists of pure mixing of solid fertilizers in a ratio needed to get the desired nutrient ratio. The shape and size of all fertilizers, raw materials, which are being used in bulk blends should have similar physical standards. Otherwise using different-sized and shaped fertilizers will result in the settlement of heavier particles at the bottom. Because of the strict specification on raw material size and shape, the cost of raw material become very high, and results in high cost. In India, such fertilizers are not accessible and due to cost factor, importing such fertilizers in bulk with the above physical specification will be unfeasible. Thus, bulk blends route seems to be a remote option for making customized fertilizers in India.

Compound granulation or stem granulation is formed purely by agglomeration process using solid raw materials and formed by the use of water, steam, and heat in the dryer. These types of fertilizers are also called as 'steam granulation' or 'physical granulation'. Its investment costs are much higher than that required for bulk blends but are much cheaper than chemical granulation plants. The main reason is that no cost is involved in forming infrastructure for the storage and handling of chemicals. Change of grade can be done easily within 3-4 hours. As control over quality is assured, this option is the ideal option for manufacturing customized fertilizers of different grades and more so in our country where large sector players are coming in this field. Chemical granulation also known as slurry or complex granulation is a process in which NPK production takes place by chemical reaction between ammonia and acid and results in ammonium sulfate or ammonium nitrate salt formation. Then granulation is done with the addition of discrete K₂O either in solid or liquid form. Granule formation process occurs through accretion plus agglomeration methods.

Precision Farming and Customized Fertilizers

In this era of non-judicious application of inorganic chemical fertilizers, precision farming strategies by tailoring the application of agricultural inputs as per the variability of field conditions are emerging as very crucial for prevention of the ecological degradation. Blanket application of fertilizers at a predetermined rate has affected the fertilizer use efficiency and enhanced nutritional deficiencies owing to variability within soils. As a result of extensive farming practices, the mining of nutrients has hiked resulting in a huge nutrient gap. Deficiencies of macronutrients like nitrogen and sulphur, and micronutrients like zinc, copper, manganese, iron, and boron are widespread leaving Site Specific Nutrient Management (SSNM) as the only option to mitigate it (Majumdar and Prakash, 2018). Customized fertilizers have the potential to serve as an effective precision farming tool, enhancing fertilizer utilization efficiency and meeting the nutritional requirements of crops (Singh et al., 2019). Customized fertilizers will supply the plant nutrients including the multi-micronutrients as per the specific requirement of the crop at a given growth stage and agroclimatic zone meeting the mentioned micronutrient deficiencies in the given pie charts (Rakshit et al., 2012). Hence, by adopting customized fertilizers, precision farming aims to maximize fertilizer use efficiency, minimize environmental impact, and enhance overall crop productivity.

Contribution of Customized Fertilizers Towards Sustainability

Customized fertilizers promote the sustainability of the cropping system. Application of the right plant nutrient in the right quantity using customized or designer fertilizer fulfills the nutrient demand of the crop and also reduces the overuse of inorganic chemical fertilizers. Hence, various environmental pollution can be prevented. Conventional farming practices rely upon the addition of only specific macronutrients mainly nitrogen, phosphorus, and potassium, however, the other secondary nutrients like sulphur and trace elements like zinc, manganese, copper, boron and molybdenum are ignored resulting in widespread deficiencies in the soil. By adopting customized fertilizers these deficiencies can be corrected leading to more yield of crops and subsequently more economic income for the farmers. Due to the slow release of the plant nutrients, it coincides well with the growth phases of the crop and prevents runoff of excess chemicals

to the nearby water bodies thereby protecting the aquatic life. Even the environmental footprint can be reduced to some extent due to customized fertilizers.

Advantages of using customized fertilizer:

1. Higher nutrient use efficiency: Customized fertilizer provides the complete range of fertilizer sources in the right concentration; thus, the plant gets all its requirements according to its needs and responses. This form of fertilizer promotes a slow-release ability to meet the crop demand as and when it is required by the plants. Precision fertilization helps minimize nutrient wastage and reduce the risk of over fertilization.

2. Easy application: Customized fertilizers are available in granular formulations and have wide adaptability among the farmer's community, making it easy to handle and satisfy the farmer's requirement for effective crop cultivation and ultimate crop yield.

3. Nutrient combination: It can be formulated as a multi-source fertilizer combination. Customized fertilizer ensures the existence of major nutrients including all forms of macro as well as micronutrients. This may help to provide for the actual needs of plants and prevent them from causing nutrient deficiencies.

4. Crop-specific: Customized fertilizers are crop and location-specific products, allowing the farmers to adapt their fertilizer application to specific conditions. It can be made based on crop type, soil type, location, and regional climatic conditions. This ensures that the plants receive the right balance of essential nutrients, promoting healthier growth and maximizing yield.

5. Cost-effective: Customized fertilizers are the source of all essential crop nutrients; farmers need not purchase micronutrients separately by spending extra costs. By optimizing nutrient use and minimizing waste, they can achieve a better B: C ratio on their fertilizer investments.

6. Environmental sustainability: Customized fertilizers can be made from inorganic as well as organic sources. Thus, it can minimize the adverse impact on the environment. A granular form of fertilizers decreases the risk of leaching loss and surface runoff, preventing the contamination of the nearby water bodies and ecosystems.

7. Inputs in precision farming: Precision farming enables the farmers to cultivate crops based on soil test-based data, satellite imagery, and other technologies and provides nutrients as per crop demand. Customized fertilizers suitably fit with the concept of precision farming as an effective fertilizer input and improve overall farm management efficiency.

Challenges for Customized Fertilizer

1. Complex manufacturing process: Customized fertilizer production requires sound knowledge for understanding the specific nutrient requirements of crops, soil conditions, and plants' various growth stages. Formulating fertilizer blends can be a complex process, as it requires a complete setup of laboratories and manufacturing units.

2. High-cost input: The cost of customized fertilizers may be more expensive to produce compared to generic fertilizers. The cost of formulation, testing, and production of customized blends can be a challenge for farmers, particularly smallholders with small budgets.

3. Variable Soil Conditions: Soils can vary not only between fields but also within a single field. Customized fertilization requires accurate soil testing and mapping to account for these variations. Inaccurate or insufficient data may lead to suboptimal nutrient prescriptions.

4. Limited Accessibility: The availability of customized fertilizers may be limited in certain regions. Farmers in remote areas or developing countries may face challenges accessing the necessary resources and technologies for precision fertilization. This can hamper the widespread adoption of customized fertilizer practices.

5. Regulatory Compliance: Customized fertilizers may face regulatory challenges, especially if there are strict regulations governing the formulation and sale of fertilizers. Ensuring compliance with regional and national standards can be a barrier for manufacturers and farmers alike.

Conclusion

Tailoring fertilizers to crop-specific nutrient requirements via customized or designer fertilizers enables precise application of the complete spectrum of essential plant nutrients in optimal proportions throughout various stages of crop development. Customized fertilizers represent a pivotal advancement within the fertilizer paradigm, serving as a milestone in fostering the adoption of Site Specific Nutrient Management and Precision Agriculture. It is imperative to disseminate knowledge among farmers regarding the utility and advantages associated with the application of customized fertilizers. Furthermore, governmental initiatives are warranted to formulate and implement policies that incentivize and promote the widespread use of customized fertilizers, thereby augmenting the overall efficiency of agricultural ecosystems.

Advances in Metabolomics in Quality Improvement of Crops - A Review

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Summary

Metabolomics—the comprehensive profiling of small molecules in biological systems—has emerged as a pivotal “translational” omics approach for improving crop quality. By capturing the biochemical phenotype that directly relates to taste, nutrition, processing attributes and health-promoting compounds, metabolomics bridges genotype and end-product quality. Advances in analytical platforms (high-resolution mass spectrometry, NMR, imaging MS), bioinformatics, integration with other omics, and machine-learning driven interpretation have accelerated discovery of metabolite biomarkers, informed metabolic engineering, and enabled metabolomics-assisted breeding and diagnostic selection. This review synthesizes recent methodological advances and applications of metabolomics for crop quality improvement, discusses integration with breeding programs and metabolic engineering, highlights representative case studies (fruit flavor, nutritional biofortification, shelf-life), and outlines current challenges and prospects for routine deployment in crop improvement pipelines.

Introduction

Crop “quality” is multifaceted: sensory attributes (flavour, aroma, texture), nutritional composition (vitamins, essential amino acids, micronutrients), anti-nutritional/toxic compounds (cyanogenic glycosides, alkaloids), and post-harvest stability (shelf life, browning). While genomics identifies genetic variants and transcriptomics captures gene expression, metabolites are the direct biochemical determinants of quality and of the plant’s physiological state under genetic and environmental influence. Thus, metabolomics offers a direct readout of traits that consumers and value chains care about—making it uniquely suited to quality-oriented breeding and engineering.

Analytical and Computational Advances

1. Analytical platforms

a. Mass spectrometry (MS) — LC-MS and GC-MS remain the workhorses for broad untargeted and targeted profiling. Improvements in high-resolution accurate mass (HRAM) instruments, tandem MS (MS/MS), and ion mobility separation have enhanced metabolite coverage and identification confidence.

b. Nuclear magnetic resonance (NMR) — NMR offers highly reproducible, quantitative, and non-destructive profiling, valuable for absolute quantification of polar metabolites and for validation of MS findings. New cryoprobes and pulse sequences have improved sensitivity.

c. Imaging mass spectrometry (IMS) — MALDI-MS and DESI imaging allow spatial mapping of metabolites across tissues (e.g., fruit skin vs. flesh), linking metabolite localization to sensory or defence traits.

d. Hybrid and targeted workflows — Data-independent acquisition (DIA), multiple reaction monitoring (MRM) for absolute quantitation, and isotope-labelled flux experiments extend metabolomics from fingerprinting to fluxomics and targeted biomarker validation.

2. Sample prep and throughput: Standardized extraction protocols, automation (robotics), and miniaturized sample prep reduce batch effects and increase throughput—important for breeding programs that require hundreds–thousands of samples.

3. Data processing, annotation and databases: Improved spectral libraries, in-silico fragmentation prediction, and community databases (e.g., MassBank, METLIN, GNPS) have reduced the “unknown metabolite” bottleneck. Nonetheless, annotation remains a major challenge, particularly for plant secondary metabolites and novel derivatives.

4. Machine learning and multivariate analytics: Machine learning (ML) methods are increasingly used for feature selection, predictive modelling of sensory outcomes from chemistry, and integrating metabolomics with phenotype. ML helps prioritize biomarkers that robustly predict quality traits across genetic backgrounds and environments.

Integrative Approaches — Metabolomics in a Multi-Omics Framework

Metabolomics gains power when integrated with genomics, transcriptomics, proteomics and phenomics. Examples include:

1. mQTL / metabolic GWAS: mapping metabolite quantitative trait loci (mQTLs) links metabolite levels to genomic regions and candidate genes—creating metabolite-trait markers for selection.

2. Expression-metabolite networks: co-expression and causal network inference help identify enzymes and regulatory genes controlling metabolite abundance.

3. Fluxomics + transcriptomics: isotope tracing combined with transcript/protein data reveals bottlenecks and control points amenable to engineering. These integrated strategies transform metabolomics results into actionable targets for breeding and metabolic engineering.

Applications to Crop Quality Improvement

1. Sensory quality: taste and aroma: Volatile organic compounds (VOCs) determine aroma; untargeted GC-MS metabolomics coupled with sensory panels and machine learning has been used to identify a small subset of volatiles that explain consumer preference in tomato, strawberry and other fruits. Mapping VOCs to genetic loci (mQTLs) has enabled marker-assisted selection for flavour.

2. Nutritional enhancement and biofortification: Vitamins, carotenoids, folates, essential amino acids: metabolomics provides high-throughput, accurate quantification for biofortification programs (e.g., provitamin A carotenoids in maize and sweet potato). Combined metabolomics + genomics enables identification of genotypes with desirable nutrient profiles.

3. Reduction of anti-nutritional/toxic compounds: Metabolomics identifies natural variation in anti-nutrients (e.g., phytic acid, certain alkaloids) and enables screening for reduced levels without compromising other quality traits.

4. Post-harvest quality and shelf life: Metabolite markers of oxidative processes, polyamine metabolism, and cell-wall modifying compounds predict firmness loss and shelf life. Imaging MS has localized metabolites associated with browning and senescence, guiding targeted interventions (varietal selection or post-harvest treatments).

5. Functional/health compounds and phytochemicals: Profiling of polyphenols, flavonoids, glucosinolates and other bioactives supports breeding for functional foods with validated health benefits. Metabolomics also helps optimize agronomy and harvest timing to maximize these compounds.

Table 1. Crop-Specific Metabolomics Approaches for Quality Improvement:

Crop	Targeted Quality Traits	Metabolomics Technologies / Analytical Platforms	Major Findings and Applications
Rice (<i>Oryza sativa</i> L.)	Aroma, grain quality, nutritional value, stress-linked metabolites	GC-MS, LC-MS/MS, NMR spectroscopy, UHPLC-QTOF-MS	Identified aroma-related metabolites (2-acetyl-1-pyrroline) in Basmati rice; elucidated pathways controlling grain chalkiness and amylose synthesis; detected metabolic signatures associated with Zn and Fe biofortification.
Wheat (<i>Triticum aestivum</i> L.)	Bread-making quality, gluten-free nutritional alternatives,	LC-MS/MS, FT-IR, GC-MS	Profiling revealed variation in amino acids, polyphenols, and sugars influencing dough rheology; identified metabolic biomarkers linked to end-use quality and processing performance under different environments.

	antioxidant composition		
Maize (<i>Zea mays L.</i>)	Kernel quality, carotenoid content, nutritional enhancement	GC–MS, LC–MS, UHPLC–QTOF-MS	Metabolic profiling uncovered differential carotenoid and phenolic compounds improving provitamin A and antioxidant capacity; aided in selection of biofortified varieties.
Barley (<i>Hordeum vulgare L.</i>)	Malting and brewing quality, flavor, enzymatic activity	NMR, GC–MS, LC–MS	Identified maltose, amino acids, and organic acids influencing beer flavor and foam stability; used metabolomic markers for selecting high-malt-quality genotypes.
Soybean (<i>Glycine max L.</i>)	Oil quality, isoflavone content, flavor, antioxidant profile	LC–MS/MS, NMR, GC–TOF-MS	Quantified isoflavones (genistein, daidzein) affecting nutritional and sensory quality; linked lipid metabolites to oxidative stability and seed oil content.
Chickpea (<i>Cicer arietinum L.</i>)	Protein and carbohydrate digestibility, cooking quality	GC–MS, LC–MS/MS	Identified sugar alcohols, amino acids, and secondary metabolites affecting cooking time and seed hardness; used as biomarkers for digestibility improvement.
Groundnut (<i>Arachis hypogaea L.</i>)	Oil stability, flavor compounds, allergenicity	GC–MS, LC–MS, NMR	Characterized fatty acid composition and oxidation-derived volatiles; detected lipid oxidation inhibitors enhancing oil shelf life; guided breeding for reduced allergen precursors.
Tomato (<i>Solanum lycopersicum L.</i>)	Flavor, color, nutritional content (lycopene, vitamin C)	GC–MS, LC–MS/MS, NMR, UPLC–QTOF-MS	Identified metabolites contributing to umami and sweetness (glutamate, sugars); dissected carotenoid and volatile pathways affecting flavor; enabled metabolic breeding for enhanced lycopene.
Potato (<i>Solanum tuberosum L.</i>)	Frying color, texture, starch quality, flavor	GC–MS, LC–MS, NMR	Profiling revealed reducing sugars and amino acids affecting acrylamide formation and frying color; identified metabolites linked to processing quality and storage stability.
Banana (<i>Musa spp.</i>)	Postharvest flavor, shelf life, ripening control	LC–MS, GC–MS, FT-ICR–MS	Characterized ripening-associated metabolites (sugars, esters, amino acids); provided metabolic markers for delayed softening and extended shelf life.
Grapes (<i>Vitis vinifera L.</i>)	Wine quality, aroma, color, phenolic composition	LC–MS, GC–MS, NMR	Identified terpenes, phenolic acids, and anthocyanins affecting wine flavor and color intensity; guided precision viticulture for desired flavor profiles.
Tea (<i>Camellia sinensis L.</i>)	Flavor, aroma, antioxidant capacity	LC–MS/MS, GC–MS, NMR	Profiling of catechins, theaflavins, and volatile aroma compounds; used metabolomic fingerprints to differentiate tea quality grades and geographic origin.
Coffee (<i>Coffea arabica L.</i>)	Aroma, flavor precursors, caffeine content	GC–MS, LC–MS, NMR	Identified chlorogenic acids, sugars, and trigonelline levels influencing cup quality; metabolite biomarkers used for flavor consistency and roast optimization.

Apple (<i>Malus domestica</i> Borkh.)	Texture, sweetness, antioxidant content, storage quality	LC-MS, GC-MS, NMR	Detected phenolic compounds, organic acids, and sugars determining taste; linked metabolite changes with firmness and browning resistance during storage.
Strawberry (<i>Fragaria ananassa</i>) ×	Aroma, flavor, nutritional value	GC-MS, LC-MS, NMR	Identified volatile esters, terpenoids, and phenolics associated with desirable flavor and sweetness; guided metabolomic-assisted breeding for consumer-preferred traits.
Pepper (<i>Capsicum annuum</i> L.)	Pungency, color, antioxidant potential	LC-MS, GC-MS	Quantified capsaicinoids and carotenoids determining spiciness and color intensity; used as selection markers for nutraceutical quality improvement.
Pea (<i>Pisum sativum</i> L.)	Nutritional composition, off-flavor reduction	GC-MS, LC-MS	Identified lipid oxidation volatiles responsible for beany flavor; guided metabolic selection for improved sensory quality and protein digestibility.
Rapeseed (<i>Brassica napus</i> L.)	Oil quality, glucosinolate content	LC-MS, GC-MS, NMR	Characterized fatty acid and secondary metabolite profiles; reduced anti-nutritional glucosinolates via metabolomic-guided selection.
Citrus spp.	Flavor, vitamin content, antioxidant potential	GC-MS, LC-MS, NMR	Detected flavonoids, limonoids, and organic acids controlling taste; applied metabolomic markers for juice quality enhancement.

Metabolomics-Enabled Breeding Strategies

1. Diagnostic breeding and metabolite biomarkers: Metabolite markers (single compounds or signatures) can serve as intermediate selection criteria—“diagnostic breeding”—to select lines with desired end-product quality even early in development. Razzaq et al. (2022) discuss the use of metabolite biomarkers to accelerate breeding, particularly for complex quality traits where direct selection is slow or expensive.

2. Metabolomics-assisted genomic selection (mGS): Incorporating metabolite profiles as predictors or covariates in genomic selection models can increase prediction accuracy for quality traits, especially when metabolites capture environment-responsive physiology better than SNP markers alone.

3. Translational metabolomics: from discovery to field deployable assays: A practical pipeline: (1) large-scale untargeted discovery to identify candidate biomarkers; (2) targeted, quantitative validation (MRM/LC-MS); (3) development of low-cost assays (e.g., ELISA, portable sensors, or low-cost kit) for screening in breeding nurseries.

Metabolic Engineering Guided by Metabolomics

Metabolomics identifies rate-limiting steps and off-target effects of pathway modifications, informing rational metabolic engineering. Examples include targeted manipulation of carotenoid and folate pathways to enhance nutritional quality and modification of volatile biosynthetic genes to improve aroma. Metabolomics is also critical for safety assessment (detecting unintended metabolite changes).

Representative Case Studies

1. Tomato flavour restoration: Extensive metabolomic and sensory work on tomato has mapped sugars, organic acids, amino acids (e.g., glutamate), and several VOCs that together explain palatability differences. Metabolite genetic mapping led to re-introduction of flavor-associated alleles into modern varieties.

2. Rice nutritional variation: Integration of metabolomics and transcriptomics has revealed metabolite shifts associated with polyploidization and specific breeding strategies, guiding selection of lines with improved amino-acid profiles and micronutrient content.

3. Fruit crops (berry, peach): Metabolomic profiling across development and ripening stages identified sugar/acid balance determinants and anthocyanin pathway regulators; such knowledge has been used to breed cultivars with higher anthocyanin and improved color and antioxidant capacity.

Challenges and Limitations

1. Metabolite identification and annotation: A substantial fraction of plant metabolites remains unannotated. Plant secondary metabolism is vast and species-specific, improving libraries and structural elucidation methods remains a priority.

2. Environmental and G×E variation: Metabolite levels are highly environment sensitive. Biomarkers must be validated across locations, seasons and management regimes to be useful in breeding.

3. Throughput and cost for breeding programs: Although high-throughput methods are improving, routine profiling of thousands of breeding lines is still costly. Development of low-cost targeted assays for a small set of validated biomarkers is essential.

4. Data integration and standardization: Multi-omics integration requires robust statistical frameworks and standards for metadata and sample handling to minimize batch effects and improve reproducibility.

Emerging Trends & Future Prospects

Emerging trends in metabolomics hold significant promise for advancing our understanding and improvement of plant quality traits. Spatial metabolomics, particularly imaging mass spectrometry (IMS), will enable the precise localization of metabolites within tissues, linking metabolite distribution to texture, flavor, and defense traits. Single-cell metabolomics, though still an emerging field, has the potential to resolve cell-type-specific contributions to quality traits, providing unprecedented resolution. High-throughput targeted plates and sensor arrays will facilitate the translation of discovery biomarkers into field-compatible screens, streamlining the breeding process. The integration of artificial intelligence (AI) and mechanistic models will enhance predictive breeding and metabolic engineering by coupling mechanistic metabolic models with machine learning. Furthermore, as metabolomics plays a crucial role in informing genetic edits and metabolic engineering, it will also be central to safety and compositional assessment for regulatory approval, ensuring that genetically modified crops meet stringent safety standards. These advancements will collectively accelerate the development of crops with improved nutritional content, flavour, and resilience.

Practical Recommendations for Researchers & Breeders

To effectively apply metabolomics in plant breeding, researchers and breeders should follow several practical recommendations. First, precisely define the target quality phenotype, whether it's related to consumer preference, nutrient specification, or shelf-life metrics. Next, utilize large, well-designed panels that include diverse genotypes and environments to ensure the robustness of discovered biomarkers. Standardized sampling and extraction protocols are crucial to minimize technical variation. A combination of untargeted discovery and targeted validation, such as Multiple Reaction Monitoring (MRM), should be adopted, followed by converting validated markers into low-cost assays. Finally, integrating metabolomic data into breeding pipelines through metabolite quantitative trait locus (mQTL) mapping, metabolite-informed genomic selection, and diagnostic assays can enhance the efficiency and effectiveness of breeding programs.

Conclusion

Metabolomics has matured from a discovery tool to an enabling technology for crop quality improvement. When combined with genetic mapping, transcriptomics, and modern computational methods, metabolomics provides actionable biomarkers and mechanistic insight that accelerate both conventional breeding and metabolic engineering. Continued advances in analytical throughput, metabolite annotation, integrative analytics, and conversion of metabolite signatures into field-compatible assays will determine how widely

metabolomics is adopted in routine breeding programs. The coming decade promises deeper translation of metabolomics discoveries into better-tasting, more nutritious, and longer-lasting crops.

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Advances in Transcriptomic Technologies for Quality Improvement in Crops - A Review

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Summary

Transcriptomics, the study of the entire set of RNA transcripts produced by the genome under specific conditions, has revolutionized plant science research and crop improvement. With rapid advances in RNA-sequencing (RNA-seq), single-cell and spatial transcriptomics, long-read sequencing, and direct RNA sequencing, researchers can now investigate gene expression with unparalleled precision. These tools reveal complex molecular mechanisms regulating crop quality traits such as nutritional composition, flavor, color, texture, and postharvest stability. This review synthesizes current advancements in transcriptomic technologies, outlines their experimental and analytical pipelines, and emphasizes their application in improving crop quality. Integration of transcriptomics with other omics and modern breeding approaches holds immense promise for accelerating the development of nutritionally superior, climate-resilient crop varieties.

Introduction

Crop quality is a multifaceted trait encompassing nutritional value, processing quality, flavor, aroma, texture, and visual appeal. These attributes are governed by intricate gene expression networks modulated by developmental stages and environmental conditions. Traditional breeding often struggles to improve such complex traits due to limited understanding of their molecular regulation. Transcriptomics bridges this gap by profiling global gene expression patterns, thereby elucidating the genes and regulatory pathways associated with quality attributes (Upton et al., 2023).

The continuous evolution of transcriptomic technologies—from conventional microarrays to next-generation sequencing (NGS) and, more recently, single-cell and spatial transcriptomics—has enabled researchers to study transcriptional dynamics with high sensitivity, accuracy, and resolution. This technological revolution provides powerful insights into the molecular basis of quality-related traits and facilitates targeted genetic improvement strategies (Lv et al., 2024).

Evolution of Transcriptomic Technologies

1. Microarray and Early Transcriptomics: Initially, transcriptomics relied on cDNA microarrays, which could detect known transcripts but lacked sensitivity for low-abundance or novel genes. Although microarrays offered insights into global gene expression, they were limited by hybridization bias and dependence on prior sequence information (Martin et al., 2013). The advent of NGS-based RNA sequencing (RNA-seq) resolved these issues by allowing unbiased and quantitative transcript detection.

2. Bulk RNA-Sequencing: Bulk RNA-seq remains the most widely used approach to quantify transcript abundance across tissues and treatments. It enables differential expression analysis, co-expression network construction, and expression quantitative trait locus (eQTL) mapping. Improvements in sequencing chemistry and bioinformatics pipelines have enhanced sensitivity, enabling better detection of low-abundance transcripts crucial for quality traits such as aroma and nutrient biosynthesis (Upton et al., 2023).

3. Long-Read Transcriptomics: Third-generation sequencing platforms such as PacBio Iso-Seq and Oxford Nanopore Technologies (ONT) provide full-length transcript information, resolving alternative splicing, isoform diversity, and gene family complexity. These methods are particularly beneficial in polyploid crops like wheat and sugarcane, where alternative splicing can alter starch or protein quality (Zhu et al., 2024).

4. Direct RNA Sequencing: Unlike conventional RNA-seq, ONT's direct RNA sequencing reads native RNA molecules without reverse transcription or amplification, preserving RNA modifications (epitranscriptomic marks). Such modifications (e.g., m6A methylation) influence transcript stability and translation efficiency, impacting nutritional and postharvest quality (Zhu et al., 2024).

5. Single-Cell and Spatial Transcriptomics: Single-cell RNA sequencing (scRNA-seq) and spatial transcriptomics are recent breakthroughs that enable high-resolution mapping of gene expression at cellular and tissue levels. These methods are invaluable for studying heterogeneity in tissues such as fruits, grains, and seeds, where different cell types contribute to nutrient accumulation or flavor biosynthesis (Lv et al., 2024). Spatial mapping further localizes these transcriptional activities within specific anatomical regions, providing new insights into the regulation of quality-related pathways.

Experimental Design and Data Analysis

1. Sampling Strategy: Appropriate tissue selection and developmental staging are crucial for quality-related transcriptomic studies. For example, starch biosynthesis genes in cereals or carotenoid biosynthesis genes in fruits are expressed during specific developmental windows. Proper replication and randomization ensure statistical robustness.

2. Bioinformatics Pipelines: Modern bioinformatics workflows for transcriptome analysis include:

a. Read preprocessing: Adapter trimming and quality filtering.

b. Alignment/quantification: Tools like STAR, HISAT2, or alignment-free quantifiers like Salmon and Kallisto.

c. Differential expression analysis: DESeq2, edgeR, or limma-voom for statistical inference.

d. Network and functional analysis: Weighted Gene Co-expression Network Analysis (WGCNA) identifies modules associated with traits such as protein content or flavor volatiles (Upton et al., 2023).

e. Integration with metabolomics: Transcriptomic data correlated with metabolite profiles enhances the identification of candidate genes controlling nutritional and sensory attributes.

3. Data Integration and Visualization: Integration of transcriptomic data with genomics, proteomics, and metabolomics offers a holistic understanding of gene function and metabolic regulation. Visualization tools like Cytoscape, MapMan, and OmicShare facilitate interpretation of gene networks linked to quality traits.

Applications in Crop Quality Improvement

1. Nutritional Enhancement: Transcriptomic profiling identifies key genes and transcription factors regulating nutrient biosynthesis pathways. For instance, expression studies in rice have revealed genes controlling grain protein content and amino acid balance, while in maize, transcriptomics uncovered regulators of oil biosynthesis in kernels (Upton et al., 2023).

2. Colour and Pigment Biosynthesis: Carotenoids and anthocyanins not only determine visual appeal but also enhance nutritional value. Transcriptome studies in tomato and maize have identified stage-specific expression of carotenoid biosynthetic genes such as *PSY1* and *LCYB*, facilitating breeding for biofortified crops (Martin et al., 2013).

3. Aroma, Flavour, and Metabolite Quality: Secondary metabolites like terpenoids, phenolics, and volatiles define crop aroma and flavor. Transcriptomic approaches have elucidated the regulation of terpenoid biosynthesis in fruits and volatile compound formation in cereals (Lv et al., 2024).

4. Texture and Processing Quality: Cell wall-degrading enzymes (pectinases, expansins) and starch-modifying enzymes strongly influence texture and processing quality. Transcriptomic analyses of ripening fruits such as mango and tomato have pinpointed genes that soften texture and can be targeted for shelf-life improvement.

5. Postharvest and Stress-Related Quality: Transcriptome-based studies during postharvest storage and stress exposure (heat, drought, or cold) reveal expression changes affecting colour retention, flavour, and nutritional stability. Identification of stress-responsive transcription factors like NAC and WRKY supports breeding for postharvest resilience.

Table 1. Applications of Transcriptomic Technologies for Quality Improvement in Crops:

Crop	Transcriptomic Technology Used	Target Trait / Focus Area	Major Findings / Outcomes
Rice (<i>Oryza sativa</i>)	RNA-Seq and microarray analysis	Grain quality (starch composition, aroma, protein content)	Identification of differentially expressed genes involved in amylose biosynthesis (Wx and SBEI genes) and aroma-related BADH2 pathway; improved understanding of grain chalkiness regulation.
Wheat (<i>Triticum aestivum</i>)	RNA-Seq	Grain protein and dough quality	Transcriptomic profiling revealed key genes in glutenin and gliadin biosynthesis; transcription factors TaSPA and TaGlu-1B implicated in end-use quality.
Maize (<i>Zea mays</i>)	RNA-Seq	Nutritional enhancement and kernel quality	Transcriptome data identified DEGs linked to carotenoid biosynthesis (crtRB1, lcyE) and starch metabolism; potential for biofortified maize breeding.
Tomato (<i>Solanum lycopersicum</i>)	RNA-Seq and qRT-PCR	Fruit ripening and flavor enhancement	Transcriptome analysis identified expression networks regulating carotenoid biosynthesis (PSY1, LCYB) and sugar–acid metabolism improving fruit flavor and shelf life.
Soybean (<i>Glycine max</i>)	RNA-Seq	Seed composition (oil and protein content)	Identification of transcription factors (GmDof4, GmDof11) influencing oil biosynthesis; transcriptome insights guided molecular breeding for improved seed quality.
Barley (<i>Hordeum vulgare</i>)	RNA-Seq	Malting and brewing quality	Transcriptomic studies revealed expression of genes related to β -amylase and hordein accumulation affecting malt quality and fermentation performance.
Potato (<i>Solanum tuberosum</i>)	RNA-Seq	Tuber quality and starch content	Transcriptomic profiling revealed differential expression of genes involved in starch metabolism and tuberization (AGPase, GBSS); insights for improved texture and yield.
Grapevine (<i>Vitis vinifera</i>)	RNA-Seq and Iso-Seq	Fruit flavor and aroma compounds	Identified transcriptional regulation of terpenoid, flavonoid, and anthocyanin biosynthetic pathways influencing berry quality and wine aroma.
Tea (<i>Camellia sinensis</i>)	RNA-Seq	Flavor, aroma, and quality traits	Transcriptomic data revealed differential gene expression related to catechin and theanine biosynthesis contributing to tea quality.
Banana (<i>Musa</i> spp.)	RNA-Seq	Post-harvest quality and ripening	Identified ripening-associated transcription factors (MaNAC, MaMADS) and genes regulating cell wall softening, improving post-harvest management.

Integration with Breeding and Gene Editing

Transcriptomics plays a pivotal role in accelerating functional validation and breeding pipelines by identifying candidate genes for marker-assisted selection, enabling expression quantitative trait locus (eQTL) and transcriptome-wide association studies (TWAS) for complex traits, and supporting CRISPR/Cas-mediated editing of regulatory genes controlling key biosynthetic pathways, such as those involved in nutrient or flavor biosynthesis. By integrating transcriptomics with genomic selection, breeders can enhance prediction accuracy by incorporating expression-derived markers, which can significantly reduce breeding cycles. This multi-faceted approach enables breeders to make more informed decisions, leveraging the power of transcriptomics to drive genetic improvement and develop crops with desirable traits, ultimately leading to improved crop yields, quality, and resilience.

Challenges and Future Directions

Despite significant advances in plant transcriptomics, several challenges persist, including the complexity of plant cell walls, which complicates single-cell analyses, and the high costs associated with transcriptomic studies, limiting their routine adoption in breeding programs. Furthermore, integrating multi-omics datasets poses a challenge due to the need for standardized computational frameworks. Additionally, transcriptomic candidates require biological validation through functional assays to confirm their phenotypic effects, which can be time-consuming and resource-intensive. Nevertheless, the future of transcriptomics in plant breeding holds promise, with prospects including the routine integration of transcriptomics into breeding pipelines, the expansion of reference atlases for underutilized crops, and the development of advanced AI-driven modeling for accurate expression-trait prediction, ultimately enhancing the efficiency and effectiveness of plant breeding programs.

Conclusion

Advancements in transcriptomic technologies have revolutionized our understanding of crop quality. From bulk RNA-seq to single-cell and spatial methods, these tools reveal the transcriptional architecture underlying key agronomic and nutritional traits. Integrating transcriptomics with genomics, metabolomics, and gene editing is paving the way toward precision breeding of superior crop varieties with improved flavor, nutrition, and resilience. The future of crop quality improvement lies in translating these molecular insights into field-level applications through data-driven, multi-omic strategies.

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Molecular Detection of Phytoplasma in Agricultural Crops

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Abstract

Phytoplasmas are wall-less, phloem-restricted bacteria that cause severe diseases in agricultural crops, leading to significant yield losses worldwide. Accurate and early detection of these pathogens is critical for disease management and epidemiological studies. Conventional detection methods, including symptomology, microscopy, serological assays, and biological tests, provide preliminary insights but often lack sensitivity and specificity. Advances in molecular diagnostics, such as nested PCR, quantitative PCR (qPCR), and restriction fragment length polymorphism (RFLP), have greatly improved the precision and reliability of phytoplasma identification. These techniques not only enable the detection of low-titre infections but also allow for strain characterization and epidemiological surveillance. Overall, molecular diagnostics offer faster, more sensitive, and strain-specific detection tools compared to traditional methods, forming the foundation for effective disease management, vector control, and crop protection strategies.

Introduction

Phytoplasmas are wall-less, pleomorphic bacteria belonging to the class Mollicutes. They were first reported by Doi *et al.* (1967) while studying aster yellows. Unlike most bacteria, phytoplasmas cannot be cultured on artificial media and lack a rigid cell wall. These obligate parasites inhabit the sieve tube elements of phloem tissue and are transmitted by phloem-feeding insect vectors such as leafhoppers, planthoppers, and psyllids. Since phytoplasmas cannot be cultured on any artificial medium, their detection and identification rely entirely on indirect and molecular diagnostic techniques (Bertaccini, 2007; Lee *et al.*, 2000). The accurate detection of phytoplasma is crucial for disease diagnosis, epidemiological studies, and the implementation of efficient management strategies to prevent crop losses. Traditionally, conventional methods were the first line of detection. These include symptomatology, microscopy, and serological assays. Symptom observation provides preliminary identification in the field, where affected plants typically exhibit yellowing, little leaf, phyllody, witches' broom, and stunted growth. However, such symptoms are often nonspecific and may overlap with those caused by nutrient deficiencies or viral infections (Marcone *et al.*, 1997). Microscopy based detection through light or transmission electron microscopy allows visualization of phytoplasma cells as pleomorphic, membrane-bound bodies within the phloem sieve tubes, giving direct evidence of infection. Although serological techniques like Enzyme-Linked Immunosorbent Assay (ELISA) have been used to detect phytoplasma antigens, their application is limited by the difficulty of producing specific antibodies for non-culturable organisms (Clark & Adams, 1977). The development of molecular methods, particularly nucleic-acid-based assays, revolutionized phytoplasma detection by providing high specificity and sensitivity. The isothermal diagnostic platforms are the latest addition to this and the Loop Mediated Isothermal Amplification (LAMP) assay has been applied for the detection of phytoplasma from several hosts (Nair *et al.*, 2021).

Conventional Techniques for Detection

Symptom observation: It is the primary and simplest method used for the preliminary detection of phytoplasma infection in plants. Since phytoplasmas inhabit the phloem and disrupt normal plant physiology, infected plants exhibit distinct morphological and physiological abnormalities. Careful observation of these symptoms in the field or greenhouse provides an initial indication of the presence of the pathogen, allowing researchers or farmers to identify suspect plants before laboratory confirmation. One of the most common symptoms is little leaf, where leaves are significantly reduced in size and often have abnormal shapes. This symptom results from the disruption of normal leaf development caused by

phytoplasma interference with plant hormone regulation. Another characteristic symptom is phyllody, where flowers are transformed into leaf-like structures due to phytoplasma-induced alteration of floral organ development. This symptom is common in sesame phyllody, leading to complete loss of reproductive capacity in the affected plants. Closely related is virescence, in which floral tissues develop a green pigmentation, causing green flowers instead of normal colored petals. Virescence often co-occurs with phyllody and is a strong indicator of phytoplasma infection. Witches' broom is another hallmark symptom, characterized by excessive proliferation of lateral shoots from nodes, giving the plant a broom-like appearance. The proliferation of shoots results from the disruption of apical dominance caused by phytoplasma interference with hormonal balance, particularly auxins and cytokinins.

Microscopic Methods: Light Microscopy give thin sections of symptomatic tissue are stained with dyes like Dienes' stain or Azure A. Phytoplasma cells appear as small, pleomorphic, dark-stained bodies in sieve tubes. This method has low sensitivity and can be misleading due to similar-looking cellular components (McCoy *et al.*, 1989). Transmission Electron Microscopy (TEM) provides high-resolution images of phytoplasma cells. TEM is confirmatory but time-consuming, costly, and requires expertise (Marcone *et al.*, 1997). TEM reveals intracellular structure and morphology. Scanning electron microscopy (SEM) shows surface features of infected tissues. Although these methods confirm phytoplasma presence, they require specialized equipment, technical expertise, and may fail in low-titer infections.

Serological methods: are based on the specific interaction between antigens and antibodies. These techniques rely on the detection of phytoplasma specific proteins or antigens present in infected plant tissues. Since phytoplasmas cannot be cultured *in vitro*, these antigens are obtained directly from infected plant sap, and their recognition by specific antibodies provides evidence of infection (Clark & Adams, 1977). The most commonly used serological method is the Enzyme-Linked Immunosorbent Assay (ELISA). In this technique, plant extracts containing phytoplasma antigens are immobilized on the wells of a microtiter plate. Specific antibodies, conjugated to an enzyme such as horseradish peroxidase or alkaline phosphatase, are added to the wells. Upon addition of a chromogenic substrate, the enzyme catalyzes a color reaction, indicating a positive interaction between the antibody and the phytoplasma antigen. ELISA is particularly advantageous for screening large numbers of plant samples quickly and is relatively simple and cost-effective compared to other laboratory techniques. It has been widely used in routine diagnostic laboratories for detecting plant pathogens (Clark & Adams, 1977; Lee *et al.*, 2000). Dot-ELISA, which is a simplified version of ELISA. In Dot-ELISA, plant sap or purified antigen is spotted directly onto a nitrocellulose membrane. Dot-ELISA is particularly useful in field conditions or laboratories with limited resources, as it does not require sophisticated equipment (Bertaccini, 2007).

Molecular Detection Techniques: Molecular detection methods have revolutionized phytoplasma diagnostics by providing high sensitivity, specificity, and reliability compared to conventional methods. These methods primarily rely on the detection of phytoplasma nucleic acids, most commonly DNA, and allow identification even in low-titer infections or asymptomatic plants.

Polymerase Chain Reaction: most widely used molecular method is the Polymerase Chain Reaction (PCR), which amplifies conserved regions of the phytoplasma 16S rRNA gene. Universal primers, such as P1/P7 and R16F2n/R16R2, are commonly used to amplify specific DNA fragments of approximately 1.2–1.8 kb, enabling the detection of a broad range of phytoplasma strains. PCR is highly sensitive and can detect phytoplasma DNA even in samples with very low pathogen load. (Schneider *et al.*, 1995).

Nested PCR: Is an enhanced version of conventional PCR, designed to improve sensitivity and specificity. In nested PCR, the first amplification uses universal primers, followed by a second amplification using internal primers targeting a smaller region of the initial PCR product. This approach allows detection of phytoplasmas present in extremely low concentrations, which may be undetectable by standard PCR. However, nested PCR carries a higher risk of contamination, necessitating careful laboratory practices (Lee *et al.*, 1998). Uses two sets of primers in successive amplification rounds. It improves detection of low-titer infections and enhances specificity, though it is time consuming and prone to contamination.

Restriction Fragment Length Polymorphism (RFLP): PCR-amplified DNA is digested with restriction enzymes to produce unique banding patterns on agarose gels. These patterns allow differentiation of phytoplasma strains into 16Sr groups and subgroups, which is essential for epidemiological studies, disease management, and understanding pathogen diversity. Differentiates

phytoplasma strains by analyzing restriction enzyme digestion patterns of PCR-amplified DNA, particularly the 16S rRNA gene. Widely used for strain classification.

Real-Time PCR (qPCR): is a modern molecular method that quantifies phytoplasma DNA in real time using fluorescent dyes or probes. qPCR is highly sensitive and rapid, enabling not only detection but also quantification of phytoplasma load in plant tissues. This method is particularly useful for studying disease progression, vector transmission efficiency, and host-pathogen interactions.

Conclusion

Phytoplasmas are destructive pathogens responsible for major crop losses due to their wide host range and vector-mediated transmission. Traditional methods such as microscopy and staining are useful for initial screening but lack sensitivity. Molecular diagnostics, including PCR-based assays, qPCR, LAMP, and RFLP, provide reliable and rapid detection. Emerging advanced technologies hold promise for even greater accuracy and efficiency. Early, precise detection is central to managing phytoplasma diseases, guiding breeding for resistance, and safeguarding agricultural productivity.

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Metagenomics: A Modern Diagnostic Tool for Complex Plant Diseases: A Review

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Summary of Article

Metagenomics is the culture-independent, sequence-based analysis of all nucleic acids in a sample typically via shotgun sequencing used to profile entire microbial communities and discover both known and novel pathogens. It is an easy and accurate method of causal organism detection before the appearance of disease symptoms. Which enables early detection of pathogens, saves money and time. Most of the viral plant diseases are unable to identify based on the disease symptomatology. Where metagenomics helps in detection of pathogens using molecular techniques. Recent advancement in metagenomic studies create wider scope for detection of plant pathogens at molecular level. This article reviews its principles, workflow, applications in disease detection, and current limitations, along with future perspectives for agricultural diagnostics.

Introduction

Plant diseases often involve interactions between multiple pathogens and their host plants. Traditional diagnostic techniques such as ELISA, PCR, and culture-based methods are limited because they require prior knowledge of the target organism and may fail to detect emerging or mixed infections (Thomas *et al.*, 2012). Metagenomics is a culture-independent, sequencing-based approach that analyzes total DNA or RNA directly from infected plant tissues, soil, water, or insect vectors. By applying high-throughput sequencing (HTS) and bioinformatic analyses, it enables comprehensive profiling of microbial communities at various taxonomic levels, including the discovery of novel pathogens (Ye *et al.*, 2019). The typical metagenomic workflow involves sample collection, nucleic acid extraction, library preparation, sequencing, data quality control, taxonomic classification, and visualization. Each step influences the accuracy and reliability of the final diagnosis (Figure 1).

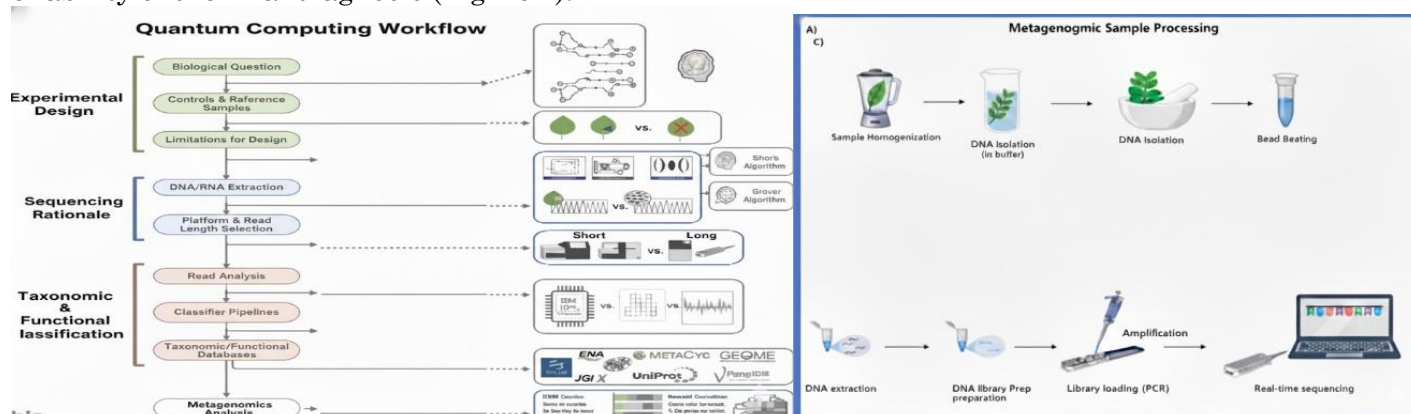


Figure 1. Schematic diagram of the metagenomic workflow used for plant disease diagnosis

Principles and Workflow of Metagenomics

A standard metagenomic diagnostic pipeline consists of several critical steps:

Sample Collection: Samples are typically collected from symptomatic plant tissues (leaves, stems, roots, seeds), soil, irrigation water, or insect vectors. The goal is to obtain a representative snapshot of the microbial community while minimizing contamination.

Nucleic Acid Extraction: High-quality DNA or RNA extraction is essential. Plant tissues contain inhibitors such as polysaccharides and phenolics, which must be removed to avoid interference with

downstream reactions. Commercial kits (e.g., Qiagen DNeasy Plant Mini Kit) or CTAB-based methods are widely used.

Library-Preparation

Extracted nucleic acids are fragmented and ligated with sequencing adapters to prepare libraries compatible with different platforms. Targeted metagenomics focuses on specific marker genes (e.g., 16S rRNA for bacteria, ITS for fungi), whereas shotgun metagenomics sequences the entire genetic content.

1. High-Throughput Sequencing: Depending on objectives and resources, either short-read or long-read sequencing platforms are used.

2. Bioinformatics Analysis: Raw reads undergo quality control, host genome filtering, taxonomic classification, and statistical analysis. This step is crucial for accurate identification of pathogens.

3. Validation: Candidate pathogens detected by metagenomics are typically validated using targeted PCR, qPCR, or inoculation assays to confirm biological relevance.

Sequencing Platforms

Illumina sequencing provides short, accurate reads and is widely used for deep sequencing projects. It is excellent for profiling microbial communities but requires lab infrastructure.

Oxford Nanopore Technologies (ONT) has revolutionized field-based diagnostics. Portable devices like MinION provide real-time long-read sequencing, enabling rapid detection of pathogens in situ (Chalupowicz *et al.*, 2019). Though individual read accuracy is lower than Illumina, improvements in basecalling algorithms have enhanced reliability.

Pacific Biosciences (PacBio) offers long reads with high accuracy but is costlier and less portable. Bioinformatics transforms raw sequence data into meaningful biological insights. Quality control is performed using tools such as FastQC and Trimmomatic. Host DNA is removed by mapping reads to reference plant genomes.

Taxonomic Assignment Can Follow

Alignment-based methods: (e.g., BLAST, DIAMOND) highly accurate but computationally intensive.

K-mer-based methods: (e.g., Kraken2, Centrifuge) much faster, suitable for large datasets. Community diversity is analyzed through α -diversity (within-sample richness and evenness) and β -diversity (between-sample differences), often visualized using **PCoA**, **NMDS**, or **heatmaps**. Network analyses can reveal microbial interactions within disease complexes.

Boxwood Blight: Nanopore sequencing detected *Calonectria pseudonaviculata* rapidly and accurately in symptomatic and asymptomatic boxwood plants. Detection was achieved within 6–8 hours, enabling timely management interventions (ShuYang *et al.*, 2022).

Soybean Viral Diseases: Metagenomic RNA sequencing revealed a diverse virome in symptomatic soybean samples across eight U.S. states. It identified known viruses such as TSV and BPMV as well as novel viruses including *Soybean ilarvirus 1*, highlighting the method's power in uncovering emerging threats (Elmore *et al.*, 2022).

Mixed and Latent Infections

In tomato and other crops, metagenomics has resolved complex disease etiologies involving multiple co-infecting bacteria, fungi, and viruses cases that often defy conventional diagnostics. These studies demonstrate metagenomics' ability to provide comprehensive, strain-level resolution of disease agents, supporting better disease management and epidemiological tracking.

Conclusion

Metagenomics has emerged as a transformative technology for diagnosing complex plant diseases. Its culture-independent, high-throughput nature enables the detection of known, unknown, and multiple pathogens simultaneously. While challenges remain, continued technological improvements and

standardization efforts will make metagenomics a cornerstone of modern plant health surveillance, biosecurity, and sustainable agriculture.

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Emerging Barrier Technologies in Multilayer Packaging: Ensuring Food Safety while Enabling Recycling Focus on Coatings, Adhesives, or Barrier Layers (E.G. Nanomaterials) That Ensure Safety (Microbial, Oxygen/Moisture Barrier Etc.)

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Abstract

Multilayers packaging has become an indispensable element in the contemporary food preservation concept, offering a very strong barrier against oxygen, moisture, light, and microorganisms, which is very hard to recycle. The main components in cheaper multilayered structures are plastics, paper, and metal that together serve to keep the food protected and to prolong its life. The situation is that once the layers are bonded, there is often no way out, and their mechanical recycling consumes a lot of energy and is bad for the environment. The duality of this operational/reclaim ability has spurred a great deal of research into the development of barrier systems that unite the two opposite poles i.e. performance and sustainability.

The new technology is bringing about drastic change whereby the recycle or bio-based alternatives are not only being introduced alongside but also, they are being regarded as contenders for the traditional multilayers in terms of the protection they provide. One of the most popular techniques is nanotechnology, where nanoclays, nanocellulose, and metal oxide nanoparticles serve to enhance the barrier of gas and moisture beside the hold of materials. Besides, there are thin film coatings applied through plasma or atomic layer deposition (ALD-) which have high barrier and reclaim ability. Biobased polymers such as polylactic acid (PLA) and polyhydroxyalkanoates (PHAs) are getting stronger with the help of nanocomposites and specialist coatings. Moreover, the switchable adhesive systems use Diels Alder chemistry to facilitate the easy removal post-use which is very helpful in material recovery and circular design.

The material revolutions are simultaneously taking place with the development of recycling technologies based on chemicals and solvents which can yield high-purity polymers for reuse. Though there are still issues regarding their framework and cost-effective. As new materials and coatings enter the food-contact applications, it is just as essential.

Keywords: Multilayer Packaging, Barrier Technologies, Nanocomposites, Chemical Recycling, Circular Economy, Food Safety, Sustainable Materials.

Introduction

It is precisely due to their incredible food protection capabilities, prolongation of shelf life, and assurance of product integrity that maintaining packaging with multiple layers has turned into an inevitable part of modern food-packaging systems. Such a packing made by layering different materials like plastics, papers, and in some instances metals, is like a barricade that no biological or environmental threats like oxygen, light, humidity and even microbes can penetrate. When looking at these attributes, they become even more important in international food supply chains where the quality of the product might already be at risk due to long transport routes and varying storage conditions. Multilayered packing, although it has been proven to be essential for the preservation of products, is still a great drawback to recycling due to its complicated structure. The difficulty-indeed the impossibility-of separating the layers of different materials creates a situation where mechanical recycling is almost non-existent, leading to incineration or landfilling. This

complication of the relationship between sustainability and functionality is one of the most significant concerns that the packaging industry has to deal with today.

Scientists and business pioneers are developing barrier technologies and material systems that keep the functional performance of the multilayer structures while increasing their recycling capability in order to overcome this difficulty. The use of these technology innovations that enable the separation of materials at the end of life includes water-soluble tie layers, delaminating or reversible adhesives, and barrier coatings through nano-engineering. Moreover, with the progress made in producing bio-based polymers and coatings, there arises the possibility of substituting sustainable materials for the conventional fossil-based ones. Being able to recycle without compromising the safety of the product, such innovations are aimed at the dictating of the environment vs. food protection argument. The nature of these advancements aligns material science, environmental engineering and policy reform towards producing sustainable yet high-performing packaging solutions. Thus, packaging design is taking a big leap as the world is turning its sight to the circular economy principles.

Current Challenges in Recycling Multilayer Packaging

The multilayer packaging systems which have been widely used still present a big threat to sustainability. Besides that, their end-of-life management has not been properly dealt with. The composition of the materials is hybrid in nature having body of a combination of polymers such as ethylene-vinyl alcohol (EVOH), polyethylene (PE), polypropylene (PP), and polyethylene terephthalate (PET) and layers of paper or aluminium which together give the main features of superior mechanical and barrier properties. Those materials also share the same problem that conventional recycling plants are designed for single-polymers; thus, it makes the recycling process tough. The incompatible polymers and adhesives which find their way into the recycling stream of the multilayer composites stop the even melt blending which yields the production of low-value recycled materials that are also weak mechanically. Multilayer films that cannot be processed with the current infrastructure have become a good example of this problem as witnessed by the studies conducted by Schmidt, J., et al., [CrossRef] (2022) and de Mello Soares et al. [CrossRef]

(2022) which only serve to confirm the issue as being wide-spread.

Besides the conflict between materials, the total use of glues, inks, and coatings also contributes to the complication of recycling procedures. Such additives, though, are essential for both the strength of the product and its appearance, are still the main hindrances to the delaminating and retrieving of the various components. As a result, mechanically recycled multilayer package materials become contaminated or consist of mixed fractions with low value applications. Consequently, such a large amount of waste is either dumped in the landfills or incinerated which in turn resources are depleted and other environmental issues such as carbon emissions are created. As per life cycle assessments conducted in the European markets of Austria and Germany, multilayer films usually have a larger carbon footprint than mono-material alternatives mainly due to their complex composition and poor recyclable nature.

The situation has been further complicated by economic and logistical issues. Although advanced recycling methods, such as solvent-based delamination and chemical depolymerization, are technically possible, they remain prohibitively expensive. Furthermore, they require considerable process optimization and infrastructural investment. The large-scale implementation is still not possible without a market-driven demand for recycled polymers or coordinated policy incentives. The circularity is further hindered by the lack of regionally uniform recycling laws and the different waste sorting habits of consumers. Seier, M., et al., [CrossRef] (2023) predict that systemic change, which is characterized by the cooperation of manufacturers, consumers, recyclers and policymakers, would take place; just technological innovations would not be sufficient.

Advances in Barrier Technology

The barrier properties of any packaging material determine its resistance to permeability by gaseous substances, vapours, light, and even microbes. The different layers in multilayer laminates generally exhibit the above traits as they combine adequate materials, each having the specific property designed for use in that layer. Nevertheless, the research has shifted to developing mono-materials or easily recyclable

materials that can deliver the same performance as sustainability issues become more pressing. High barrier properties with low environmental impact are now possible through recent progress in plasma coatings deposition, the use of bio-based materials, and nanotechnology.

Nanocomposites are considered to be one of the most important and innovative inventions in this area. The addition of nanoparticles such as metal oxide nanostructures, nanoclays, and nanocellulose to the polymer matrix significantly improves the barrier properties against gases and moisture while reducing the overall material usage. Lim, L.T., et al., [CrossRef](2014) state that adding layered silicate nanoclays to polymers will create a tortuous diffusion path, thus decrease oxygen permeability and increase product shelf life. Besides, Sharma, C., et al. [CrossRef](2017) assert that nanoparticles may transfer antimicrobial properties which in turn decrease the chances of microbial spoilage. Nanocomposite systems enable the production of lighter, thinner packages with good performance while consuming less raw material and generating less waste. The adoption of advanced coatings is another progressive field. Atomic layer deposition (ALD) and plasma-enhanced chemical vapor deposition (PECVD) methods make it feasible to form extremely thin and barrier films with high performance on plastics. The barrier consists of coatings made of silicon oxide, aluminium oxide, or other inorganic compounds which can perform as effectively as aluminium foil barriers while maintaining their recyclability. Research from Kiese, S., et al., [CrossRef](2019) and Korkmaz, E., et al., [CrossRef](2025) has shown that such coatings might close the performance gap between mono-materials and multilayers and thus allow the packaging industry to shift to circular materials without compromising product safety. Attention has also been given to bio-based materials that, as it turns out, are the main candidates in the list of eco-friendly packaging options. Polymers like polylactic acid (PLA) and polyhydroxyalkanoates (PHAs) that are derived from renewable resources are naturally biodegradable albeit under specific conditions. However, these plastics generally possess poor gas and moisture barrier properties. Nonetheless, through nanomaterial incorporation and bio-based coating applications, scientists have been able to enhance the functional performance of such materials. For instance, Walker, S., et al., [CrossRef](2020) report that combining PLA with chitosan or nanocellulose coatings can cut down oxygen transmission rates incredibly, making them similar to the performance of traditional plastics. Moreover, new adhesive systems reported by Ahmed, S., et al., [CrossRef](2023) and Kaiser, K. M., et al., [CrossRef](2020), for example, have introduced reversible bonding chemistries based on Diels-Alder reactions that render delamination easy during recycling. Thus, effective recovery of materials is obtained without compromising the protective integrity required for food safety.

Recycling Approaches and Innovation

Efficient recycling of multilayer packaging requires technological solutions that can manage the intrinsic material complexity coming along with multilayers. The most commonly used method of recovering polymers is mechanical recycling, where the materials are sorted, cleaned, shredded, and then used to make new goods. In multilayer structures, however, the weak interfacial bonding that stems from the immiscibility of the polymers results in low mechanical strength and limited application of the recycled materials. Compatibilizer additives, which are mainly designed to enhance polymer phase interaction, could lead to better quality recycled materials, but according to Ragaert, K., et al., [CrossRef](2019), their high-cost and limited scalability restricts the industrial adoption.

On the contrary, chemical recycling offers a more reliable process that uses various techniques such as pyrolysis, solvolysis, or depolymerization in breaking down the polymers into monomers or oligomers. Through this process, high-grade feedstock materials which can be reprocessed into new products without a decline in quality are being retrieved. Li, T., et al., (2024) [CrossRef] and Adam, H. B., et al., (2025) [CrossRef] lately presented evidence that the technique of solvent-based delamination could be used to selectively dissolve the adhesives and polymer layers while preserving the quality of the collected materials simultaneously. These advanced methods have not yet fully addressed the issues regarding solvent recovery, energy consumption, and cost-effectiveness, nevertheless, the impact they would have on the recycling industry is so huge that it might end up bringing about total circularity.

These approaches are being validated as practical through collaborations between the industry and research. For instance, Ügdüler, S., et al., [CrossRef](2025) proved closed-loop recycling to be a practical process by developing a scalable delamination method for PET/PE multilayers. The notion of "design for

recyclability" which sees packaging made with compatible materials, reversible adhesives, or detachable layers to facilitate end-of-life processing, is becoming widely accepted. Hence, reactive recycling contributes to proactive circularity through the use of such designs where sustainability has been integrated into the product from the very start.

Safety and Regulatory Consideration

The creative thinking behind the use of packaging materials may still impose food safety's importance in the entire cycle of their development and application. Organizations such as the European Food Safety Authority (EFSA) and the U.S. Food and Drug Administration (FDA) are the ones who oversee the application of materials that are in contact with food. In the case of multilayer packaging, which is composite by nature and may allow the interaction between components or between the product and food, there are special challenges in food safety. Migration of adhesives, nanoparticles, or residues of solvents pose safety issues that require thorough assessment by means of standardized testing.

According to Ragaert, K., et al., [CrossRef](2019), it is difficult to evaluate the safety of multilayer materials because their compositions consist of different and various substances. The case is even worse with recycled materials since they might retain some contaminants or impurities resulting from bad sorting or from their previous use. On the other hand, Li, T., et al., [CrossRef](2024) argue that solvent-based recycling can produce very high purity outputs that can be used again in food-contact applications. Nevertheless, close monitoring and total elimination of the residual solvents are necessary to reach the regulatory limits. Besides, the adoption of eco-friendly materials on a large scale is limited by the differences in food-contact legislation across regions. The unification of international safety standards would not only restore consumers' trust in packaging made from recycled materials but also ease the regulatory process. According to Seier, M., et al., [CrossRef](2023), transparency in the labelling and traceability of recycled materials is very important for ensuring public acceptance and safety.

Future Prospect and Circular Economy Alignment

The future of multilayer packaging is going to depend on the coming together of the areas of material science, technological innovation, and the principles of the circular economy. Sustainability is the primary factor driving industrial change, and the packaging design is being viewed from a systems perspective by manufacturers. The "design for circularity" approach that incorporates recyclability at all stages, from material selection to end-of-life recovery, attempts to eliminate waste and improve resource efficiency. Ruippo, L., et al., [CrossRef](2022) highlight that technological progress, until now, has only been one aspect of the change and that policy reform and consumer engagement are also essential for moving the packaging economy from a linear to a circular one.

To gain circularity, new recycling techniques particularly those based on chemicals and solvents will be extensively used. Such methods can function together with the clever design and efficient sorting infrastructure to create near-closed-loop systems in which the quality of recovered materials is not considerably reduced at the end of their use in production. Advanced chemical recycling can be used to obtain high-quality applications for polymer recovery as they are more or less equivalent to virgin materials, so stated Li, T., et al., [CrossRef](2024). The standardized recyclability labelling together with extended producer responsibility (EPR) regulations can significantly contribute to these initiatives by creating a road map of sustainability innovation and responsibility throughout the value chain. These kinds of schemes can align the industrial objectives with the environmental regulations, thus speeding up the worldwide shift to sustainable packaging systems as mentioned by Tran, T.Y.A., et al., [CrossRef](2025).

Conclusion

In the quest to maintain food safety, reduce spoilage, and prolong product shelf life, multilayer packaging still remains an essential innovation. On the other hand, its impact on the environment still constitutes a barrier to achieving sustainability goals. Numerous new solutions from bio-based polymers and nano-technology coatings to reversible adhesives and solvent recycling have demonstrated that it is possible to reconciling performance with recyclability. The realization of a fully circular packaging system will require joint collaboration among various stakeholders such as material scientists, manufacturers, legislators, and consumers, who are along the entire value chain. There comes a pivotal moment for the packaging industry

where the fulfillment of the global sustainability targets necessitates innovations that keep the environment safe and maintain the quality of products at high levels. Therefore, the protection of new packaging materials not only for food but also for the environment will rely on a combination of systemic changes and technological breakthroughs.

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Biosensors For Rapid Onsite Plant Pathogen Detection

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Summary

Plant diseases caused by fungi, bacteria, and viruses result in major yield losses and economic damage. Traditional diagnostic methods such as ELISA and PCR are reliable but time-consuming and unsuitable for field use. Biosensors—analytical devices integrating biological recognition elements with physiochemical transducers—offer rapid, sensitive, and cost-effective detection of plant pathogens directly in the field. Advances in nanotechnology, microfluidics, and CRISPR-based tools have enabled portable and highly specific biosensing systems that can revolutionize plant disease diagnostics and management.

Introduction

Plant diseases significantly affect global food security. Conventional diagnostic methods, although accurate, require laboratory infrastructure and trained personnel. Biosensors provide a modern solution for early and onsite detection. These devices combine a biological recognition component—such as antibodies, enzymes, DNA, or aptamers—with a transducer that converts biological interactions into measurable signals. Their versatility, portability, and low cost make them suitable for field-level pathogen detection, supporting timely management decisions.

Electrochemical Biosensors

Electrochemical biosensors detect pathogens by converting biochemical interactions into electrical signals. They employ electrodes modified with DNA probes, antibodies, or aptamers. Techniques such as cyclic voltammetry (CV) and electrochemical impedance spectroscopy (EIS) quantify these changes. Incorporating nanomaterials like gold nanoparticles enhances sensitivity, allowing detection of pathogens at picogram levels.

Table 1. Electrochemical Biosensors for Plant Disease Detection:

Bio-recognition element	Technique	Crop	Pathogen	Detection limit
Antibody	Electrochemical impedance spectroscopy-based detection	Plum and tobacco	Plum pox virus	10 pg/ml
Antibody			<i>Pseudomonas syringae pv. lachrymans</i>	2.6 pg/ml
Antibody			<i>Candidatus Phytoplasma Aurantifolia</i>	1.5×10^3 pg/ml
DNA	Quartz crystal microbalance-based detection	Maize	Maize chlorotic mottle virus	2.5×10^5 pg/ml
DNA	Microfluidic immunosensor	Walnut	<i>Xanthomonas arboricola</i>	0.8 pg/ml
DNA			Plum pox virus	12.8 pg/ml
DNA	DNA hybridization voltammetric detection	Sugarcane	The sugarcane white leaf (SCWL) disease	4.7 pg/ml

DNA	Label-free impedimetric method employing gold nanoparticles—modified SPCE	Cacao	<i>Phytophthora palmivora</i>	0.3 pg/ml
DNA		Citrus	Citrus tristeza virus	$126\text{--}1.26 \times 10^3$ pg/ml

Optical Biosensors

Optical biosensors rely on light-based signal transduction, detecting changes in absorbance, fluorescence, or refractive index caused by biorecognition events. Colorimetric assays (like lateral flow tests) provide quick visual results, while fluorescence and surface plasmon resonance (SPR) biosensors enable highly sensitive detection. They combine speed and ease of use with reliable accuracy, making them suitable for both laboratory and field conditions.

Microfluidic (Lab-on-a-Chip) Biosensors

Microfluidic biosensors miniaturize laboratory processes into portable devices capable of handling small sample volumes. They integrate sample preparation, amplification, and detection on a single chip. These systems are ideal for rapid, on-site diagnostics of plant pathogens, reducing reagent use and analysis time.

Piezoelectric Biosensors

Piezoelectric biosensors operate based on mass changes on quartz crystal surfaces when a pathogen binds to immobilized probes, resulting in frequency shifts measurable as electrical signals. They allow real-time, label-free detection and can quantify pathogen concentration through frequency variation.

CRISPR-Based Biosensors

CRISPR-based biosensors utilize Cas enzymes (Cas12 or Cas13) guided by RNA to recognize specific pathogen DNA or RNA. Upon target recognition, reporter molecules are cleaved, producing fluorescence or colorimetric signals. These systems enable highly specific detection within an hour without laboratory equipment, providing field-level accessibility.

Thermal/Calorimetric Biosensors

Thermal biosensors detect heat changes during biochemical reactions between the target pathogen and the recognition element. Although sensitive, their field application is limited by environmental interference. Integration with IoT-based systems can improve their practicality for continuous monitoring.

Magnetoelastic Biosensors

Magnetoelastic biosensors use materials that change vibration frequency upon pathogen binding under a magnetic field. They allow wireless, label-free, and real-time monitoring of plant infections and have potential for low-cost, portable diagnostic devices.

Conclusion

Biosensors represent a transformative tool in plant disease diagnostics, enabling rapid, accurate, and on-site detection of pathogens. Emerging trends, such as CRISPR-based detection and lab-on-a-chip integration, promise further improvements in portability and sensitivity. Adoption of these systems can greatly enhance early disease management and ensure sustainable agricultural productivity.

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Molecular Identification of Whitefly Biotypes Using mtCOI Markers

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Summary of Article

Whiteflies, particularly *Bemisia tabaci*, are among the most damaging insect pests of agricultural crops across tropical and subtropical regions. Despite their morphological similarity, these insects represent a complex of cryptic species or biotypes that differ in host range, virus transmission efficiency, and insecticide resistance. Molecular identification based on mitochondrial cytochrome oxidase I (mtCOI) markers provides a reliable and efficient approach to distinguish between these biotypes. The mtCOI gene is maternally inherited and highly conserved, making it ideal for phylogenetic and diagnostic studies. This article reviews the molecular techniques for identifying whitefly biotypes using mtCOI markers and discusses their applications in pest management and resistance monitoring.

Introduction

Whiteflies (Hemiptera: Aleyrodidae) are small sap-sucking insects that pose serious threats to global agriculture through direct feeding damage and the transmission of plant viruses, notably Begomoviruses (Polston *et al.*, 2013). Among these, *Bemisia tabaci* (Gennadius) is one of the most economically important species, known to infest over 600 plant species. It is now recognized as a species complex comprising several morphologically indistinguishable but genetically distinct biotypes that differ in reproductive behavior, host range, and resistance to insecticides (De Barro *et al.*, 2011).

Biotypes of *B. tabaci* have been documented worldwide, including the B and Q biotypes, which are notorious for their invasiveness and resistance to various classes of insecticides. Traditional morphological identification fails to distinguish these cryptic species, highlighting the need for molecular diagnostic tools. Among the molecular markers, the mitochondrial cytochrome oxidase I (mtCOI) gene has emerged as the gold standard for the identification of whitefly biotypes (Frohlich *et al.*, 1999).

Molecular Tools and mtCOI Marker

The mtCOI gene encodes a key enzyme in the mitochondrial respiratory chain and is widely used as a DNA barcode for species identification. It evolves rapidly enough to discriminate between closely related species but remains conserved within species, allowing for reliable differentiation of *B. tabaci* biotypes. Mitochondrial DNA is maternally inherited and non-recombinant, which simplifies lineage tracing (Frohlich *et al.*, 1999). Molecular methods such as PCR amplification, sequencing, and restriction fragment length polymorphism (PCR-RFLP) have been extensively applied to characterize *B. tabaci* populations globally.

Procedure for Identification of Whitefly Biotypes Using mtCOI

1. Sample Collection: Adult whiteflies are collected from infested crops using aspirators and preserved in 95–100% ethanol to maintain DNA integrity.

2. DNA Extraction: DNA is extracted using CTAB or commercial kits such as Qiagen DNeasy. The quality is assessed via gel electrophoresis.

3. PCR Amplification: The ~650 bp fragment of the mtCOI gene is amplified using universal primers LCO1490 and HCO2198.

4. Gel Electrophoresis: PCR products are visualized under UV light to confirm amplification.

5. Sequencing and Analysis: Purified PCR products are sequenced, and the resulting chromatograms are edited and aligned using software like MEGA or BioEdit.

6. BLAST and Phylogenetic Analysis: Sequences are compared with reference mtCOI sequences in NCBI GenBank. Phylogenetic trees are constructed to assign biotypes based on sequence similarity (>98%).

Case Studies

A study conducted in Turkey by Dağlı et al. (2020) analyzed *B. tabaci* populations using mtCOI sequencing and identified B and Q biotypes with distinct haplotypes. Similarly, research in Java, Indonesia, revealed the predominance of the Asia I genetic group of *B. tabaci* associated with chili pepper crops (Srinivasan et al., 2013). These studies demonstrate the global applicability of mtCOI markers in resolving cryptic species complexes and guiding targeted pest management strategies.

Future Aspects

Emerging molecular approaches, including next-generation sequencing (NGS) and portable diagnostic assays like LAMP and qPCR, can enhance the speed and precision of field-level biotype identification. Integrating mtCOI-based studies with genomic data may also help track resistance gene flow among populations and assess the impacts of climate change on whitefly distribution.

Summary / Conclusion

The use of mtCOI markers has revolutionized the molecular identification of whitefly biotypes by providing a robust and reliable diagnostic framework. It enables accurate classification of cryptic species, supports early detection of invasive or resistant populations, and enhances the effectiveness of pest management programs. Future developments in molecular tools will further improve our understanding of whitefly population dynamics and contribute to sustainable crop protection strategies.

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The Role of qPCR in Quarantine Diagnosis of Plant Pathogens

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Summary of Article

Quantitative PCR (qPCR), also known as real-time PCR, has revolutionized the detection and diagnosis of plant pathogens in quarantine settings. This review highlights the principle, methodology, and applications of qPCR in the early and accurate identification of regulated pathogens such as *Xylella fastidiosa*, *Phytophthora ramorum*, and *Dickeya solani*. With its high sensitivity, specificity, and rapid turnaround time, qPCR supports global phytosanitary efforts, enabling efficient border inspections, on-site testing, and compliance with international standards. Case studies demonstrate its practical utility in detecting pathogens from plant tissues, soil, water, and even air samples. Despite limitations such as cost and the need for prior sequence knowledge, qPCR remains a cornerstone of modern plant disease diagnostics.

Introduction

Plant pathogens pose significant threats to global agriculture, food security, and biodiversity. The increase in international trade and movement of plant materials has heightened the risk of introducing and spreading quarantine-regulated pathogens. Early and accurate detection is crucial to prevent outbreaks and minimize economic losses. Traditional methods such as culturing, microscopy, and bioassays are often time-consuming, labor-intensive, and lack the sensitivity required for early intervention (Venbrux *et al.*, 2023).

The invention of Polymerase Chain Reaction (PCR) by Kary Mullis in 1984 marked a turning point in molecular diagnostics. Later, the integration of fluorescent detection systems gave rise to quantitative PCR (qPCR), which allows real-time monitoring of DNA amplification. This technology was rapidly adopted in quarantine programs worldwide, reducing detection times from years to hours. For instance, Australia's Post-Entry Quarantine (PEQ) program integrated qPCR in the late 1990s, significantly shortening diagnostic timelines.

qPCR operates on the principle of fluorescence-based detection of amplified DNA. Two common detection chemistries are SYBR Green, which binds to double-stranded DNA, and TaqMan probes, which are sequence-specific and offer higher specificity. The cycle threshold (Ct) value quantifies the initial target concentration, enabling both detection and quantification of pathogen DNA (Johnson *et al.*, 2013).

This review explores the role of qPCR in quarantine diagnostics, its advantages, limitations, and real-world applications through case studies, emphasizing its importance in safeguarding agricultural systems.

qPCR in Quarantine Diagnosis

qPCR has become the method of choice for quarantine diagnostics due to its numerous advantages:

Early and Accurate Detection: qPCR can detect pathogen DNA at very low concentrations, often before symptoms appear. Its high specificity, achieved through carefully designed primers and probes, minimizes false positives.

Rapid Turnaround Time: Unlike traditional methods that take days or weeks, qPCR delivers results within hours. This speed is critical for inspections at ports, borders, and nurseries (Grosdidier & Martin-Hernandez, 2017).

Detection of Regulated Pathogens: International phytosanitary agreements (e.g., IPPC, EPPO, USDA-APHIS) mandate the detection of specific pathogens. qPCR assays are validated for pathogens such

as *Ralstonia solanacearum*, *Phytophthora ramorum*, *Xylella fastidiosa*, and viruses like *Tomato brown rugose fruit virus* (ToBRFV).

Multiplexing Capability: Multiple pathogens can be detected in a single reaction using different fluorescent probes, increasing throughput and efficiency at quarantine facilities.

Compatibility with Various Sample Types: qPCR can be applied to diverse samples, including plant tissues, seeds, soil, water, and insect vectors, making it ideal for comprehensive surveillance.

On-Site Diagnostics: Portable qPCR systems enable field-based testing, supporting emergency responses and monitoring in remote areas.

Compliance and Documentation: The quantitative and reproducible nature of qPCR results supports phytosanitary certification and regulatory compliance (USDA APHIS, 2024).

Case Studies

Case Study 1: Detection of *Phyllosticta citricarpa*: Zajc *et al.* (2023) developed a qPCR assay for detecting *Phyllosticta citricarpa*, a quarantine-regulated citrus pathogen. The assay used ITS and multi-locus targets to ensure specificity. It successfully detected the pathogen in air samples from citrus orchards, with a sensitivity of fewer than 10 DNA copies. Amplicon sequencing confirmed the results, highlighting the method's reliability for aerobiological surveillance. The authors found that this method is suitable for early detection and monitoring in citrus-growing regions, particularly in the EU where the pathogen is under quarantine regulation.

Advantages and Disadvantages

Advantages:

- High sensitivity & specificity
- Quantitative pathogen load estimation
- Rapid results (hours)
- Multiplexing reduces testing time/resource
- Adaptable to portable field deployment.

Disadvantages:

- Requires known target sequences
- Sensitive to contamination
- Reagents and instruments can be costly
- Multiplex may lead to cross-talk or reduced sensitivity
- Cannot distinguish between viable and dead cells without supplementary methods.

Conclusion

Quantitative PCR has transformed plant pathogen diagnostics in quarantine settings. Its ability to provide rapid, sensitive, and specific detection supports global efforts to prevent the spread of invasive pathogens. While limitations exist, ongoing advancements in portable systems, multiplexing, and integration with next-generation sequencing (NGS) and CRISPR-based methods will further enhance its utility (Marcolungo *et al.*, 2022). qPCR will continue to play a vital role in protecting agricultural economies and ensuring biosecurity worldwide.

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DNA Barcoding for Identification of Fungal Pathogens: Advances, Challenges, and Future Directions

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Abstract

DNA barcoding has transformed fungal pathogen identification by providing a fast, standardized molecular tool that overcomes the limits of morphology-based taxonomy. The Internal Transcribed Spacer (ITS) remains the universal barcode, while multilocus and high-throughput sequencing increase resolution. Integration of bioinformatics, environmental DNA, and AI enhances accuracy across plant pathology, ecology, and diagnostics. Expanding reference databases and portable sequencing devices will further improve accessibility for early detection, disease control, and biodiversity monitoring (Schoch *et al.*, 2012; Nilsson *et al.*, 2019).

Introduction

Fungal pathogens cause severe agricultural and clinical losses worldwide (Fisher *et al.*, 2020). Accurate identification is vital for disease management, yet morphological methods are unreliable due to plasticity, cryptic speciation, and phenotypic overlap (Hawksworth & Lücking, 2017). DNA barcoding, proposed by Hebert *et al.* (2003), uses standardized DNA regions for species recognition. For fungi, the ITS region part of the nuclear ribosomal cistron is the official barcode (Schoch *et al.*, 2012). However, ITS alone sometimes fails to resolve closely related taxa, prompting multilocus approaches using TEF1 α , RPB1, and RPB2 (Stielow *et al.*, 2015).

Principle of DNA Barcoding

Barcoding identifies species by sequencing a short genomic region with both conserved and variable sites. The workflow includes DNA extraction, PCR amplification, sequencing, quality filtering, alignment, and database comparison. In fungi, ITS1–5.8S ITS2 ($\approx$ 500–700 bp) serves as the universal barcode because of its high interspecific variability, easy amplification, and broad taxonomic coverage. The UNITE database clusters ITS sequences into “species hypotheses,” improving identification consistency (Köljalg *et al.*, 2013).

Major Molecular Markers

- 1. ITS (nuclear ribosomal internal transcribed spacer):** Universal fungal barcode; resolves $\approx$ 80 % of species but may fail in complexes like *Fusarium* or *Penicillium*.
- 2. TEF1 α (translation elongation factor 1-alpha):** Useful secondary marker, especially in *Fusarium*, *Alternaria*; provides discrimination beyond ITS.
- 3. RPB1 / RPB2 (RNA polymerase subunits):** Offer deeper phylogenetic resolution; amplification is more challenging due to variable introns and primer design.
- 4. COI (cytochrome c oxidase I):** Standard in animals; less used in fungi (mitochondrial introns hinder its universal utility).

Integrative (multilocus) barcoding that combines ITS and secondary genes enhances resolution and supports robust taxonomy (Dayrat, 2005).

Applications

Agriculture & Pathology: Barcoding enables early and accurate detection of pathogens such as *Fusarium oxysporum*, *Colletotrichum* species, and *Phytophthora* spp., facilitating timely disease management and biosecurity surveillance (O'Donnell *et al.*, 2015). It helps track invasive species and understand pathogen population structure.

Environmental & Ecological Studies: Metabarcoding and environmental DNA (eDNA) methods detect fungal communities and latent infections, revealing hidden diversity in soil, air, and water (Tedersoo *et al.*, 2021).

Quarantine & Rapid Detection: Portable sequencers (e.g. MinION) and point-of-care assays enable on-site diagnostics, reducing delays in phytosanitary inspections (Eisenstein, 2020).

Taxonomy & Biodiversity Discovery: DNA barcoding reveals cryptic species, accelerates formal species description, and facilitates integrative taxonomy in conjunction with morphology and ecology (Crous *et al.*, 2021).

Challenges & Limitations

The ITS region sometimes fails to resolve species with low genetic divergence (e.g. within *Aspergillus*, *Colletotrichum*), and intragenomic ITS variation can confuse identifications (Simon & Weiß, 2008). Public sequence databases may include misidentifications or low-quality entries, reducing reliability. PCR inhibitors, primer bias, and unequal amplification efficiency limit detection in mixed samples (Nilsson *et al.*, 2019). High intraspecific variability and taxonomic instability further complicate universal barcode adoption (Hibbett *et al.*, 2016).

Future Prospects

Recent advances in fungal DNA barcoding have integrated next-generation sequencing, multilocus approaches, and bioinformatics tools to enhance pathogen identification accuracy. Combining ITS with secondary loci such as TEF1- α , RPB1, and β -tubulin improves species resolution. High-throughput and third-generation sequencing technologies, including Illumina and Oxford Nanopore, enable rapid, long-read analyses of mixed samples and real-time pathogen detection. Environmental DNA and metabarcoding approaches expand insights into fungal diversity and ecology. Additionally, artificial intelligence and machine learning now assist in automated identification and data interpretation, making DNA barcoding a faster, more reliable, and field-deployable tool for fungal diagnostics (Schoch *et al.*, 2012; Tedersoo *et al.*, 2021).

Conclusion

DNA barcoding is now integral to accurate and rapid fungal pathogen identification. While ITS remains the backbone, multilocus and high-throughput strategies enhance resolution. The integration of AI, bioinformatics, field diagnostics, and comprehensive reference databases promises broad applicability across agriculture, ecology, and health. With continued development and standardization, fungal DNA barcoding is poised to become a central pillar of global pathogen surveillance, disease management, and biodiversity studies.

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Detection of Quarantine Pathogens: Methods and Challenges

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Summary

The global movement of plant material increases the risk of introducing exotic pests and pathogens that threaten agriculture and biodiversity. Plant quarantine plays a vital role in preventing such introductions through inspection, monitoring, and diagnostic testing of plants and planting materials. Traditional detection techniques, including symptom observation and serological tests, have now been complemented and largely replaced by molecular and sequencing-based tools that offer higher specificity, speed, and sensitivity. This review highlights conventional and advanced approaches used for detecting quarantine pathogens viruses, fungi, bacteria, and phytoplasma along with recent technological innovations such as PCR, LAMP, and nanopore sequencing. The paper also discusses major challenges in accurate diagnosis and emphasizes the need for portable, standardized, and high-throughput assays to ensure effective quarantine surveillance and biosecurity.

Introduction

Plant quarantine is a preventive measure established to restrict the entry and spread of exotic pests, pathogens, and weeds that could harm agricultural ecosystems. The Directorate of Plant Protection, Quarantine & Storage (DPPQS), functioning under the Ministry of Agriculture & Farmers Welfare, Government of India, acts as the nodal agency for plant protection and biosecurity. Its primary objectives include the inspection of imported and exported agricultural commodities, monitoring domestic quarantine pests, and ensuring compliance with international phytosanitary standards under the International Plant Protection Convention (IPPC) of FAO (Martin *et al.*, 2016).

Pathogen detection forms the backbone of plant quarantine. Early identification of infection, even in asymptomatic stages, prevents large-scale economic losses. However, the diversity of plant pathogens from viruses to bacteria, fungi, and phytoplasmas demands tailored diagnostic approaches that can differentiate between closely related species and pathovars (Cho *et al.*, 2015).

Detection of Quarantine Pathogens

Virus Detection: Traditional virus detection relied on visual inspection, indicator plant tests, and ELISA. For example, *Banana bunchy top virus* (BBTV) and *Citrus tristeza virus* (CTV) were often detected through symptom observation, while *Grapevine fanleaf virus* and *Tobacco mosaic virus* (TMV) were identified using indicator plant tests. However, these conventional methods are limited by low sensitivity and dependence on expert interpretation.

Modern molecular methods such as PCR, RT-PCR, qPCR, LAMP, immunocapture-PCR, and CRISPR-based assays have revolutionized virus diagnostics (Singh *et al.*, 2014). These advanced tools allow the detection of minute quantities of viral nucleic acids and enable multiplexing for simultaneous detection of multiple viruses. For instance, RT-PCR and qPCR are routinely used to identify *Tomato yellow leaf curl virus* (TYLCV) and *Tomato brown rugose fruit virus* (ToBRFV) with high precision, while LAMP assays are used for *Wheat streak mosaic virus* and *Banana bunchy top virus* in quarantine screening. Similarly, CRISPR-based assays are now being tested for Maize chlorotic mottle virus, providing portable, rapid, and highly specific detection. Despite these advancements, practical challenges such as PCR inhibition by plant compounds and difficulty in detecting novel or divergent viral strains persist.

Fungal Detection: Conventional fungal detection methods such as culture-based isolation and morphological examination are time-consuming and may fail to identify cryptic or morphologically similar

species. For example, *Fusarium oxysporum f. sp. cubense* is identified through conidial morphology, and *Rhizoctonia solani* is diagnosed using culture-based methods both requiring skilled taxonomic expertise.

Modern tools like multiplex PCR, real-time PCR (qPCR), and DNA barcoding have become standard in fungal diagnostics (Cho *et al.*, 2015). These molecular methods are applied for detecting quarantine fungi such as *Macrophomina phaseolina* and *Phoma exigua*. qPCR not only detects but also quantifies pathogen load, aiding in risk assessment and management decisions. DNA barcoding, employed in countries like New Zealand, has been effective for identifying *Phoma destructiva* and other cryptic fungal pathogens that evade culture-based detection. However, variations in reagents and inter-laboratory protocols can affect reproducibility (Trippa *et al.*, 2024). These techniques are especially valuable in quarantine facilities for screening imported or exported plant material for fungal contamination.

Bacterial Detection: Classical bacterial detection methods include selective culturing, biochemical assays, and serological techniques such as ELISA or phage plaque tests. Examples include *Clavibacter michiganensis subsp. sepedonicus* and *Ralstonia solanacearum*, detected through culture or serological assays, and *Erwinia amylovora*, identified via ELISA. While reliable, these approaches are slow and can yield false negatives when pathogen loads are low.

Recent advances utilize real-time PCR and multiplex PCR, significantly enhancing detection speed and specificity. For instance, qPCR has been successfully used for *Ralstonia solanacearum* complex quantification in soil, while multiplex PCR allows simultaneous detection of *Clavibacter michiganensis* and *Xanthomonas oryzae pv. oryzae*. These assays are now integrated into quarantine diagnostics to rapidly confirm bacterial infections in seed and plant tissue. Nevertheless, challenges such as low pathogen concentration, PCR inhibitors in plant extracts, and cross-contamination remain barriers to universal application (Chen *et al.*, 2023).

Phytoplasma Detection: Phytoplasmas, being non-culturable, present unique diagnostic challenges. Traditional detection using graft transmission or microscopy is slow and unreliable. For example, *Candidatus Phytoplasma palmae* and *C. Phytoplasma ulmi* were once detected through graft transmission tests, while *C. Phytoplasma mali* was identified by serological assays.

Modern molecular tools such as conventional PCR, nested PCR, and qPCR have greatly improved the detection and identification of phytoplasma strains like *Candidatus Phytoplasma asteris*, *C. Phytoplasma sacchari*, and *C. Phytoplasma mali* (Loi *et al.*, 2002). qPCR allows quantitative detection, while PCR-RFLP helps in strain classification critical for quarantine decisions. These assays have been widely applied in certification programs to prevent the introduction of phytoplasma-associated diseases in fruit trees and ornamentals. However, universal primers targeting the 16S rRNA region often fail to differentiate closely related lineages, necessitating subgroup-specific or multilocus assays for high-resolution diagnostics.

Challenges and Future Directions

Despite remarkable advances in molecular diagnostics, achieving a balance between broad-spectrum detection and precise strain-level identification remains a critical challenge. Current diagnostic platforms such as PCR, qPCR, and LAMP have improved sensitivity and speed, yet their effectiveness is often limited by the complex nature of plant tissues. Components like polysaccharides, phenolics, and humic acids can inhibit nucleic acid amplification, resulting in false negatives or reduced assay efficiency. Low pathogen titre and uneven distribution within plant tissues further complicate accurate detection, especially in early or asymptomatic infections (Marcolungo *et al.*, 2022).

Another significant constraint lies in the high cost and infrastructural demands of advanced molecular systems. Techniques like CRISPR-based detection, next-generation sequencing (NGS), and nanopore sequencing offer exceptional precision but require sophisticated laboratory setups, expensive reagents, and well-trained personnel factors that restrict their large-scale or field-level application (Zajc *et al.*, 2022).

Furthermore, the global harmonization of diagnostic standards remains an unresolved issue. Inter-laboratory variation in reagent quality, equipment calibration, and data interpretation can lead to inconsistent outcomes even with the same assay design (Trippa *et al.*, 2024). For quarantine certification and international trade, it is essential that diagnostic methods undergo standardized validation and accreditation processes as emphasized by Lacault *et al.* (2024). Future efforts should therefore focus on developing cost-effective, multiplex, and user-friendly diagnostic kits adaptable for field deployment.

Integration of artificial intelligence and biosensor technologies with molecular assays could further enhance rapid detection and data interpretation. Strengthening international collaboration for protocol harmonization and validation will be vital to ensure reliable, globally accepted quarantine diagnostics and to safeguard biosecurity in an increasingly interconnected agricultural system.

Conclusion

Modern molecular technologies have significantly advanced the detection of quarantine pathogens, enhancing accuracy, speed, and specificity. However, cross-reactivity, genetic similarity among closely related species, and the presence of PCR inhibitors continue to hinder diagnostic precision. To safeguard agricultural trade and biosecurity, there is a growing need for validated, portable, and multiplex detection systems that can function efficiently under field conditions. Integrating molecular tools with next-generation sequencing and bioinformatics will enable comprehensive, real-time surveillance of emerging plant pathogens worldwide. In addition, the adoption of high-throughput sequencing (HTS) platforms and CRISPR-based assays promises rapid and on-site diagnostics capable of distinguishing subspecies or pathovars with high resolution. Collaborative international efforts focusing on assay standardization, data interpretation, and regulatory validation will further strengthen the reliability of quarantine testing and promote safe global movement of agricultural commodities.

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Peepal (*Ficus religiosa*): A Priceless Gift to Society

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Introduction

The *Ficus* genus (Family: Moraceae), commonly known as 'fig', is considered one of the major components of tropical rainforests. It is among the largest and most diverse genera of angiosperms (seed-bearing plants). Approximately 750 species of *Ficus* are found worldwide, out of which 89 species and 26 subspecies have been recorded in India. This genus is mainly spread across subtropical and tropical regions. In India, *Ficus* trees are found from the southern regions to the north, even in the Himalayan areas up to an altitude of 2000 meters. In terms of biodiversity, India's northeastern region shows the highest diversity of *Ficus*, followed by peninsular India, and then the Andaman and Nicobar Islands, where they are also found in significant numbers. *Ficus* fruits are not only delicious but also available year-round, making them highly preferred by birds, animals, and insects. This is why *Ficus* species play a fundamental and sustainable role in the ecosystem (Lohot et al. 2019 & 2023; Sudhakar et al. 2017).

In India, many trees have been regarded as divine for centuries. Among them *Peepal* (*Ficus religiosa*) tree (Figure 1) holds a special place. Tree is a unique blend of Indian culture, religion, Ayurveda, and environmental significance. While it is seen as a symbol of religious faith, from a scientific perspective, this tree is also highly beneficial.



Fig.1. Peepal (*Ficus religiosa*) tree

Scientific Identification

Scientific Name: *Ficus religiosa*

Family: Moraceae (Fig family)

Local Names: *Peepal*, *Ashwattha*

Lifespan: The Peepal tree can live for more than 1,000 years

Origin: India, Nepal, Sri Lanka, and Southeast Asia

Religious Significance

In Hinduism: The Peepal tree is considered a symbol of the **Trinity of Hindu gods:**

- a. **Brahma** resides in its roots
- b. **Vishnu** in the trunk, and
- c. **Shiva** in the leaves.

On Saturdays, especially, women worship the *Peepal* tree, offer water to it, and circumambulate around it. This ritual is believed to bring **prosperity, happiness, and fertility**.

In Buddhism: Lord **Gautama Buddha** attained enlightenment under a *Peepal* tree in **Gaya (Bihar)**. Hence, it is also called the ***Bodhi*** tree and is one of the holiest trees in Buddhism. Even today, the ***Mahabodhi Tree*** stands at that sacred site.

In Jainism: The *Peepal* tree is also revered in Jainism. The **23rd Tirthankara, Parshvanatha**, is believed to have meditated under a Peepal tree.

Ayurvedic and Medicinal Importance

Every part of the Peepal tree - the roots, trunk, bark, leaves, fruits, and latex (milky sap) are considered medicinally valuable (Table 1).

Table 1. Ayurvedic and Medicinal Importance of the Peepal Tree:

Part	Usage	Benefits
Leaves	Boiled in water and consumed	Beneficial for asthma, cough, and diarrhea
Bark	Taken in powdered form	Useful for diabetes, inflammation, and fever
Latex (Sap)	Applied to boils and wounds	Helps in wound healing
Fruits	Consumed raw or dried	Relieves constipation, heart diseases, and digestive issues
Roots	Decoction prepared and consumed	Aids in treating skin diseases and blood disorders

Environmental Contribution

1. **24-Hour Oxygen Emission:** Most trees do not release oxygen at night, but the *Peepal* tree is an exception. It provides oxygen day and night, making it one of the most effective trees for air purification.
2. **Carbon Dioxide Absorption:** The *Peepal* tree plays a vital role in reducing urban pollution.
3. **Centre of Biodiversity:** Its dense shade, flowers, and fruits offer shelter to many birds, bees, insects, and small animals.
4. **Soil Conservation:** Its roots help bind the soil and prevent erosion.

Cultural Significance and Folklore

1. In many regions, after offering water to the *Peepal* tree, it is adorned with ***sindoor*** (vermilion) and ***roli*** (sacred red powder).
2. Married women worship the Peepal tree for the long life of their husbands.
3. In rural India, the Peepal is often regarded as the village deity.

Modern Research and Science

1. Recent studies reveal that Peepal leaves contain flavonoids, antioxidants, and tannins, which have anti-cancer, antibacterial, and anti-inflammatory properties.
2. Scientists also believe that sitting under the shade of the Peepal tree helps reduce mental stress.

Need for Conservation

With rapid urbanization and the race for modern development, trees like the *Peepal* are being neglected, despite being vital for our survival. We must:

1. Plant Peepal trees in schools, colleges, and temple premises.
2. Educate the younger generation about its importance.

3. Maintain cleanliness around these trees and prevent their felling.

Contribution of Peepal in Lac Production

It is one of the earliest known host trees for lac insects (Figure 2), first reported by **James Kerr in 1782** from **Patna, Bihar**. Other identified host plants include banyan, palash, and ber. Among these, *Ficus religiosa* is especially important for the summer lac crop. Lac insects have been observed on *Ficus religiosa* in several Indian states, including Rajasthan, Assam, Madhya Pradesh, West Bengal, Punjab, Telangana (Hyderabad), Karnataka, Maharashtra, Uttar Pradesh, Bihar, Jharkhand, Chhattisgarh, and Tamil Nadu. Outside India, it has been recorded in Shan State and Maymyo Division of Myanmar (formerly Burma) (Lohot et al. 2023).

Three major species of lac insects found on *Ficus religiosa* are:

1. ***Laccifer communis*** (Mahdihasan, 1923) - reported from Hyderabad, Telangana
2. ***Laccifer fici*** (Green, 1903; Kapoor, 1955) - reported from North Bihar
3. ***Kerria lacca*** (Kerr) - the most commonly cultivated and commercially significant species for lac production.



Fig.2. lac insect on Peepal (*Ficus religiosa*) tree

Conclusion

Ficus religiosa, or the Peepal tree, is a pillar of Indian society, where religion, science, and nature beautifully converge. It offers us peace, health, and pure air. It also serves as a valuable host plant for lac insects. Let us all take a pledge to protect this invaluable heritage, and to respect and conserve trees like the Peepal in our surroundings.

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Application of Biometrical Techniques in Genetic Improvement of Pulse Crops

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Introduction

Importance of Pulse Crops in Agriculture and Human Nutrition: Pulse crops, including chickpea, pigeon pea, lentil, mungbean, and urdbean, play a crucial role in global food and nutritional security. They are rich in protein, dietary fiber, essential amino acids, and micronutrients such as iron and zinc, making them a vital component of vegetarian diets (FAO, 2016). Moreover, pulses contribute significantly to sustainable agriculture due to their ability to fix atmospheric nitrogen through symbiosis with rhizobia, thus improving soil fertility and reducing the need for synthetic fertilizers (Ali & Kumar, 2006).

Challenges in Pulse Crop Improvement: Despite their importance, pulse crops face several production constraints, including low and unstable yields, susceptibility to biotic stresses (such as diseases and pests), and abiotic stresses (such as drought and heat). Additionally, pulses are often grown in marginal environments with limited inputs, further limiting their productivity (Singh et al., 2017). The genetic improvement of pulse crops is challenged by their complex reproductive biology, limited genetic diversity in breeding programs, and long breeding cycles.

Role of Biometrical Techniques in Enhancing Genetic Improvement: Biometrical techniques offer a scientific and statistical approach to analyze genetic variation, assess trait heritability, and identify superior genotypes for breeding programs. These methods help in quantifying the extent of genetic variability, evaluating trait associations, estimating combining abilities, and classifying germplasm based on multivariate data (Burton & Devane, 1953; Falconer & Mackay, 1996). Such insights are essential for designing efficient selection strategies and accelerating genetic gain in pulse crops.

This article aims to explore the applications of biometrical techniques in the genetic improvement of pulse crops. It outlines how these statistical tools aid in understanding genetic parameters, selecting promising genotypes, and improving breeding efficiency to develop high-yielding and stress-resilient pulse varieties.

Role of Biometrical Techniques in Genetic Improvement of Pulses

Biometrical techniques are indispensable tools in modern plant breeding. They provide a framework for analyzing complex genetic data, evaluating genetic parameters, and optimizing selection strategies. In pulse crop improvement, these tools help breeders make informed decisions to develop superior genotypes with enhanced yield, resistance, and adaptability.

1. Genetic Variability Assessment: Genetic variability is the foundation of any crop improvement program. Assessing variability among genotypes helps breeders identify traits with sufficient diversity to enable effective selection. Biometrical parameters such as the **Genotypic Coefficient of Variation (GCV)**, **Phenotypic Coefficient of Variation (PCV)**, **heritability (broad sense)**, and **genetic advance** are commonly used for this purpose.

For instance, high GCV and PCV values for traits like seed yield, number of pods per plant, or 100-seed weight indicate a broad range of variation, suggesting potential for genetic improvement (Burton & Devane, 1953). Heritability, when considered alongside genetic advance, helps determine whether a trait is governed mainly by additive gene action and thus effectively selectable (Johnson et al., 1955). In pulses, studies in chickpea and lentil have shown high heritability and genetic advance for yield and related traits, signifying the effectiveness of direct selection (Reddy et al., 2018).

Thus, variability studies guide breeders in identifying promising genotypes and traits to focus on in breeding programs.

2. Trait Association and Selection: Understanding the relationship between traits is critical in selecting genotypes that contribute positively to yield. **Correlation analysis** reveals the degree and direction of association between traits. However, correlation does not always imply causation, which is where **path coefficient analysis** becomes important as it partitions correlation into **direct and indirect effects**.

For example, in mungbean and pigeon pea, positive correlations have been observed between seed yield and traits like pods per plant, plant height, and biological yield (Kumar et al., 2017). Path analysis further indicates that pods per plant and biological yield often have strong direct effects on seed yield, making them ideal targets for selection.

These insights support **ideotype breeding**, where plant types with a desirable combination of traits are selected and developed (Donald, 1968). Such models are highly valuable in developing efficient, high-yielding pulse cultivars.

3. Combining Ability and Hybridization: In crops where hybridization is used, **combining ability analysis** is essential to identify parental lines that produce superior offspring. The **diallel cross** and **line × tester analysis** are the most widely used biometrical techniques to estimate **General Combining Ability (GCA)** and **Specific Combining Ability (SCA)**.

GCA reflects additive gene effects, whereas SCA indicates non-additive gene action, such as dominance and epistasis (Griffing, 1956). In pulses like pigeon pea and mungbean, GCA and SCA analyses have been used to identify promising parent lines and crosses for traits such as early flowering, disease resistance, and seed yield (Bohra et al., 2011).

Such analyses are particularly useful in **heterosis breeding**, which exploits hybrid vigor for improved performance. Although heterosis is less commonly used in self-pollinated pulses, its application in crops like pigeon pea has shown promising results due to partial outcrossing behavior.

4. Multivariate Analysis: Multivariate statistical tools such as **Cluster Analysis** and **Principal Component Analysis (PCA)** are used to classify genotypes based on multiple traits simultaneously. These techniques are essential for managing large datasets and identifying **genetic diversity** among germplasm lines.

Cluster analysis groups genotypes with similar characteristics, aiding in the selection of genetically divergent parents for crossing. PCA, on the other hand, reduces data dimensionality and highlights traits contributing most to variation (Jolliffe, 2002). In lentil and chickpea, PCA has been used to identify key traits like seed size, flowering duration, and plant height that influence yield potential (Singh et al., 2019).

These analyses help in **diversity-based selection**, enabling breeders to create genetically broad-based populations, which is crucial for long-term genetic gain and adaptability under changing climatic conditions.

Case Studies and Examples

Biometrical techniques have been extensively used in research and breeding programs to enhance the genetic potential of pulse crops. The following case studies provide evidence of how various biometrical tools are applied for trait analysis, selection, and hybrid development in different pulse crops.

1. Chickpea (*Cicer arietinum* L.): In a study by **Ramesh et al. (2018)**, 120 chickpea genotypes were evaluated for genetic variability and trait associations. The analysis revealed high genotypic and phenotypic coefficients of variation for seed yield per plant and number of pods per plant. High heritability combined with high genetic advance was observed for these traits, indicating the predominance of additive gene action and effectiveness of selection.

Key Findings:

- Strong positive correlation between number of pods per plant and seed yield.
- High heritability for yield and maturity traits.
- PCA grouped genotypes into clusters based on productivity and maturity, aiding parent selection.

2. Lentil (*Lens culinaris* Medik.): **Kumar et al. (2020)** conducted multivariate analysis on 60 lentil genotypes to assess genetic diversity. Cluster analysis grouped genotypes into five distinct clusters. High GCV and PCV were observed for biological yield and seed yield per plant. Path coefficient analysis showed that biological yield had the highest direct effect on seed yield.

Key Findings:

- Biological yield and number of pods per plant were major contributors to seed yield.
- PCA identified seed size and plant height as key traits influencing variability.
- Genotypes from diverse clusters were recommended for crossing to maximize heterosis.

3. Pigeon Pea (*Cajanus cajan* L.): A line × tester analysis conducted by **Bohra et al. (2011)** in pigeon pea revealed significant differences among lines and testers for yield-related traits. Specific combining ability (SCA) effects were significant for seed yield, suggesting the importance of non-additive gene action. Certain hybrids showed high heterosis over parents and checks.

Key Findings:

- Significant GCA and SCA effects for yield and plant height.
- High heterosis observed in hybrids for early flowering and seed yield.
- Identified high-GCA parents for future hybrid development programs.

4. Mungbean (*Vigna radiata* L.): **Singh et al. (2017)** analyzed 40 mungbean genotypes using biometrical tools. The study showed that traits such as pods per plant and harvest index had strong direct effects on seed yield. Heritability estimates were high for days to flowering, plant height, and seed yield, suggesting reliable selection for these traits.

Key Findings:

- Positive correlation between pods per plant and yield.
- High heritability and genetic advance for key traits like plant height and seed weight.
- Genotypes grouped through PCA showed substantial genetic divergence.

5. Urdbean (*Vigna mungo* L.): **Yadav et al. (2019)** studied genetic variability and trait association in urdbean under rainfed conditions. The study found high PCV and GCV for number of clusters per plant and seed yield, indicating good scope for improvement through selection. Path analysis identified number of pods per plant as the most important contributor to yield.

Key Findings:

- Moderate to high heritability for most traits.
- Clusters per plant and pods per plant showed strong positive path coefficients.
- Cluster analysis grouped genotypes with contrasting traits, aiding hybridization planning.

Summary of Key Biometrical Insights

Crop	Biometrical Tools Used	Key Traits Identified for Selection	Outcome
Chickpea	GCV, PCV, Heritability, PCA	Pods per plant, seed yield	Effective selection traits identified
Lentil	Path analysis, Cluster, PCA	Biological yield, pods per plant	Parental diversity established
Pigeon Pea	Line × Tester, GCA, SCA	Seed yield, early flowering	High-yielding hybrids developed
Mungbean	Correlation, Path, Heritability, PCA	Pods per plant, harvest index	Promising genotypes selected
Urdbean	Path analysis, GCV, PCV, Cluster analysis	Clusters per plant, pods per plant	Scope for genetic improvement confirmed

Conclusion

Biometrical techniques have proven to be foundational in the genetic improvement of pulse crops. They enable breeders to decipher complex genetic and phenotypic relationships among traits, assess variability, and make informed decisions regarding selection and hybridization. Through the application of statistical tools like ANOVA, heritability estimation, correlation and path analysis, combining ability studies, and multivariate techniques such as cluster and principal component analysis, researchers have been able to identify superior genotypes and formulate efficient breeding strategies. In modern pulse breeding programs, biometrical approaches are indispensable not only for enhancing genetic gain but also for ensuring stability, adaptability, and resilience in new cultivars. These methods provide the scientific rigor

necessary for dissecting trait architecture and addressing the challenges associated with low productivity, biotic and abiotic stresses, and climate variability.

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Vanya Silk: Opportunities in Jharkhand

Article ID: 72277

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India holds a special place in the global silk industry as the sole country that produces all five main types of silk — Mulberry, Tasar, Eri, Muga, and Oak Tasar. These are generally split into Mulberry Silk and Non-Mulberry Silk, the latter being referred to as Vanya Silk. While Mulberry silk is mainly made in southern states like Karnataka, Tamil Nadu, and Andhra Pradesh, Vanya silk is produced in forested and tribal areas, especially in Jharkhand, Chhattisgarh, and the North-Eastern states.

Vanya silk goes beyond being just a fabric — it reflects India's rich biodiversity, traditional knowledge, and cultural legacy. Among these, Tasar silk holds a unique place in Jharkhand as it is a key source of income for many tribal families involved in silk-making. With proper support, Jharkhand has the potential to become a major hub for sustainable silk production in the country.

Understanding Silk and its Importance

Silk has always been considered sacred in Indian culture. It is not simply a material but also a symbol of purity, wealth, and cultural identity. From weddings to religious ceremonies, silk garments are seen as symbols of good fortune and devotion. The fact that India's silk-producing areas are often close to temples highlights the deep connection between silk and spirituality in the country.

The word Vanya means “from the forest.” Vanya silks — Tasar, Eri, Muga, and Oak Tasar — are made by silkworms that eat natural plants instead of mulberry trees. These silks are known for their unique feel, durability, and natural golden or earthy appearance. They are eco-friendly and need little chemical input, making them perfect for the growing demand for sustainable textiles.

Each type of Vanya silk has its own specific region and environment where it is produced:

- Tasar silk is mainly made in Jharkhand, Chhattisgarh, and parts of Odisha.
- Eri silk, known as peace silk because it is produced without killing the silkworm, is mainly produced in Assam and Meghalaya.
- Muga silk, famous for its natural golden sheen, is unique to Assam.
- Oak Tasar silk is grown in temperate areas like Himachal Pradesh and parts of the Northeast.

Among these, Tasar silk is particularly important for Jharkhand — it is a tradition, a livelihood, and a benefit to the environment.

Tasar Silk in Jharkhand: A Tradition Linked to Nature

Jharkhand's natural environment, with its dense forests, suitable climate, and rich biodiversity, provides the perfect setting for Tasar silkworms. These silkworms feed on leaves from forest trees such as Asan (*Terminalia tomentosa*), Arjun (*Terminalia arjuna*), and Sal (*Shorea robusta*), which are plentiful in the region's forests.

Tribal communities like the Santhal, Munda, Oraon, and Paharia have been rearing Tasar silkworms for generations. This practice is deeply woven into their social and economic life. Traditionally, they collect wild Tasar cocoons from the forest, raise silkworms on host trees, and manually reel the silk. The resulting fabric is rough yet elegant, with a distinctive golden color that appeals to both domestic and international customers. Districts such as Dumka, Godda, Deoghar, Pakur, and Hazaribagh have become important centers for Tasar silk production.

The CSB - Central Tasar Research and Training Institute (CTR&TI), located in Ranchi, under the Central Silk Board, plays a key role in research, training, and sharing technology. It has introduced better silkworm breeds, improved disease control methods, and scientific rearing techniques to boost productivity and quality.

Economic and Social Value

Tasar sericulture is a major source of employment in Jharkhand. It provides a steady income to tribal farmers, especially women, who are involved in every step of the production process — from raising silkworms and harvesting cocoons to reeling and weaving. According to government data, more than a hundred thousand rural families in Jharkhand directly or indirectly rely on Tasar sericulture.

Women's self-help groups (SHGs) have been key in this sector, helping to create business opportunities and promote financial independence. The Jharkhand Silk Textile and Handicraft Development Corporation (Jharcraft) has played an essential role in training artisans, setting up production centres, and connecting producers with national and international markets.

The silk industry also supports forest-based livelihoods. Since Tasar rearing depends on maintaining forest ecosystems, it encourages local communities to protect trees and biodiversity. This connection between silk production and environmental conservation makes the industry a model for sustainable rural development.

Challenges in the Sector

Despite its promise, Jharkhand's Vanya silk industry faces several challenges:

- 1. Traditional Rearing Methods:** Many tribal farmers still follow traditional practices, which lead to lower productivity and greater risks from diseases and weather changes.
- 2. Limited Technology Access:** Modern sericulture technologies, such as improved rearing houses, good-quality seeds, and disease control methods, are not widely available.
- 3. Marketing and Infrastructure Issues:** There is a lack of effective marketing channels, transport facilities, and cold storage systems, which limit access to bigger and more profitable markets.
- 4. Credit and Support:** Small-scale producers often struggle to get institutional credit and insurance, which hinders their ability to grow their operations.
- 5. Branding and Awareness:** While Tasar silk has great aesthetic and ecological value, its branding and promotion at the national and international level need more development.

The Road Ahead: Strategies for Growth

To unlock Jharkhand's full potential in Vanya silk production, a multi-pronged strategy is required that combines technological innovation, policy support, and community empowerment.

- 1. Strengthening Research and Extension:** Continuous research through institutions like CTR&TI should focus on developing disease-resistant breeds, climate-resilient practices, and improved reeling and weaving technologies.
- 2. Capacity Building:** Regular training and exposure programs for farmers, particularly women and youth, can help professionalize sericulture and attract new participants.
- 3. Market Linkages and Branding:** Building a strong brand identity for "Jharkhand Tasar Silk" through geographic indication (GI) tagging, eco-labeling, and participation in trade fairs can enhance global visibility.
- 4. Infrastructure and Policy Support:** Investments in cocoon banks, common facility centres, and digital marketing platforms can streamline production and sales.
- 5. Sustainability and Value Addition:** Promoting organic and natural dyeing techniques, diversified silk products (like stoles, upholstery, and accessories), and eco-friendly packaging can align with sustainable fashion trends.

Conclusion

Vanya silk, and Tasar in particular, is more than an economic commodity — it is a living heritage that connects nature, culture, and livelihoods. In Jharkhand, it symbolizes resilience, sustainability, and the creativity of tribal communities who have nurtured this art form for centuries. With continued investment, institutional collaboration, and global marketing, Jharkhand can transform its sericulture landscape into a thriving, sustainable, and globally recognized industry. As the world shifts toward eco-conscious and

ethically sourced textiles, Vanya Silk from Jharkhand has the potential to emerge as a flagship product — weaving together the threads of tradition, sustainability, and prosperity.

Role of Photoreceptors in Regulating Growth, Development and Productivity of Crop Plants

Article ID: 72278

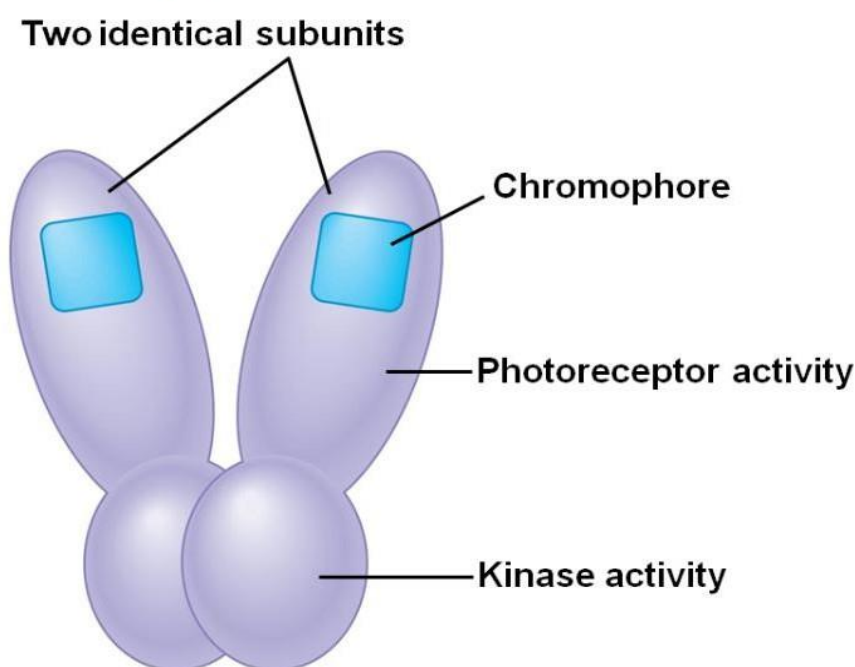
Saimanikiran Unnam¹

Photoreceptors are widely distributed among land plants, with most of the commonly cultivated crop species reported to contain members of at least one major photoreceptor family. While most of our understanding on the roles of photoreceptors in plant development has been derived from research on *Arabidopsis*, there is an increasing interest in photoreceptor-mediated developmental responses in an agricultural environment (González *et al.*, 2015). Since several plant developmental responses involve the action of one or more of these photoreceptors. Here, we discuss various photoreceptor-controlled developmental processes that can affect plant productivity and the practical implications for engineering such photoreceptors toward enhancing the productivity of crop plants (Mawphlang *et al.*, 2017).

Phytochrome

Molecular genetics approaches in plant photobiology have led to the isolation and characterization of photoreceptor genes from various species, most of which play critical roles in determining plant survival and development. Phytochromes, which are principal receptors for light in the red/far-red region of the spectrum (600–750 nm), play an essential role in regulating seed germination and seedling establishment in agriculturally important crops such as rice and tomato, while in maize, phytochromes have been implicated to contribute to the transcription of genes essential for photosynthesis. Under natural or field conditions, establishment of the emergent seedling post germination is a vital developmental process that determines the ability of the plant to survive, grow and reproduce. In photosynthesising organisms such as green plants, light is a crucial factor in determining the establishment of an emergent seedling. Maximizing photosynthesis during early development and following the formation of gaps during growth under dense canopies could therefore be critical for seedling survival. Under high plant densities, shade provided by neighboring vegetation triggers a series of developmental changes in growing plants involving several of the known photoreceptors (Ballare and Pierik, 2017).

Structure of a phytochrome



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The actions of phytochromes enables a plant to quantify shade around a seedling's environment by detecting changes in the Red/Far-red ratios (R:FR) and trigger a series of developmental responses that is thought to provide the plant with a competitive advantage over its neighbors. Such responses include stimulation of elongation growth, coupled with reduced leaf development, increased apical dominance and a reduction in branching. While such developmental plasticity to diminished light, termed as shade avoidance responses (SAR), might increase survival percentage under limiting light conditions, it could result in compromised productivity of crop plants especially in modern intensive cropping methods with high planting densities (Franklin, 2008).

The Pr form is biologically inactive (at least in plants), whereas the Pfr form is biologically active. With a few bacterial exceptions, the molecule is synthesized in the inactive Pr form, so that initial light-induced Pfr formation is the signal that the host organism has been exposed to light for the first time, as occurs for young seedlings emerging from subterranean darkness after germination.

In Arabidopsis, Devlin *et al.* (2003) have identified a number of shade responsive genes that are also regulated by phyA and phyB. Recently in Arabidopsis and tomato, phytochromes have been suggested to influence plant biomass along with carbon assimilation and starch metabolism. Altering responses of crop plants to light spectral quality by targeting genes such as phytochromes or their signaling components can therefore influence both resource partitioning and growth patterns in crop plants, which would presumably result in higher productivity even under intensive cropping patterns.

Cryptochromes

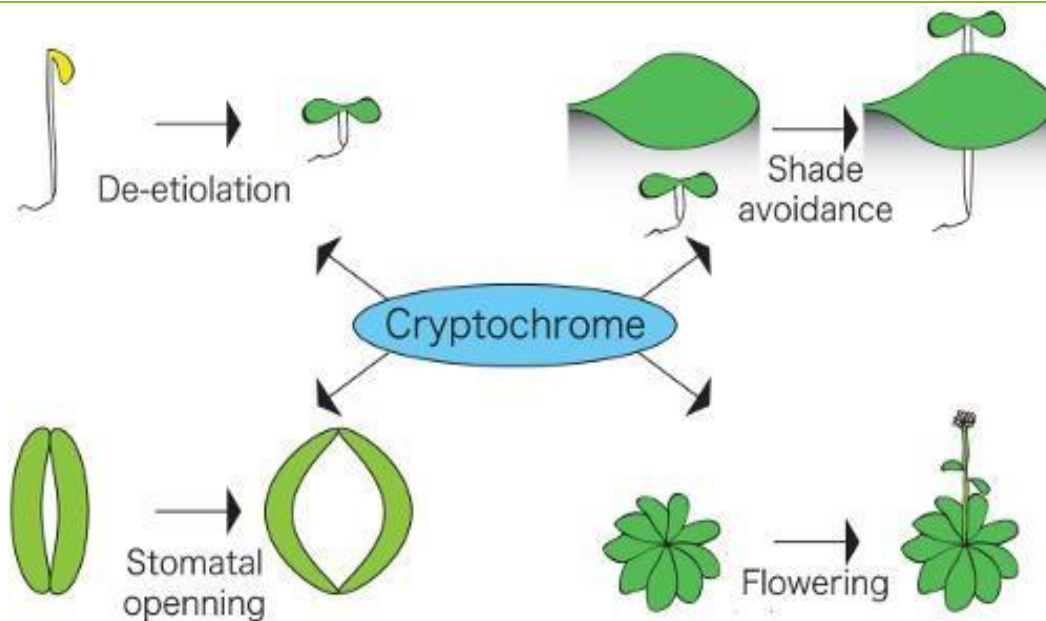
In plants, the cryptochrome family photoreceptors participate in several plant process, ranging from photomorphogenesis to entrainment of the circadian clock. Developmental processes such as plant height and flowering time which are agronomically important traits are also linked to cryptochrome activity. Since the isolation of the first CRY gene from Arabidopsis, CRYs have been reported from most major crops investigated having roles in seed germination, leaf senescence, stress responses and regulation of transcription.

As Arabidopsis is limited as a model plant for examining the molecular networks influencing agronomically important traits several workers have evaluated the role of photoreceptors in other crop models. In *Brassica napus*, an oilseed crop, the overexpression of CRY1 produced short-statured plants, which confer resistance to wind and water lodging, providing such plants with an adaptive advantage in these conditions. Tomato plants overexpressing CRY2 also displayed short hypocotyl and internode length along with delayed flowering.

Interestingly, in Arabidopsis, cryptochromes have also been reported to promote growth in a shaded environment, suggesting new a molecular target for altering shade responses in plants. Tomato transgenic lines overexpressing CRY2 overproduced anthocyanins and chlorophyll in leaves along with enhanced flavonoids and lycopene content in fruits. Tomato lines overexpressing CRY2 show major changes in the rhythmic oscillations of several genes involved in the entrainment of the endogenous clock, suggesting a role for the photoreceptors in the input to the tomato biological clock.

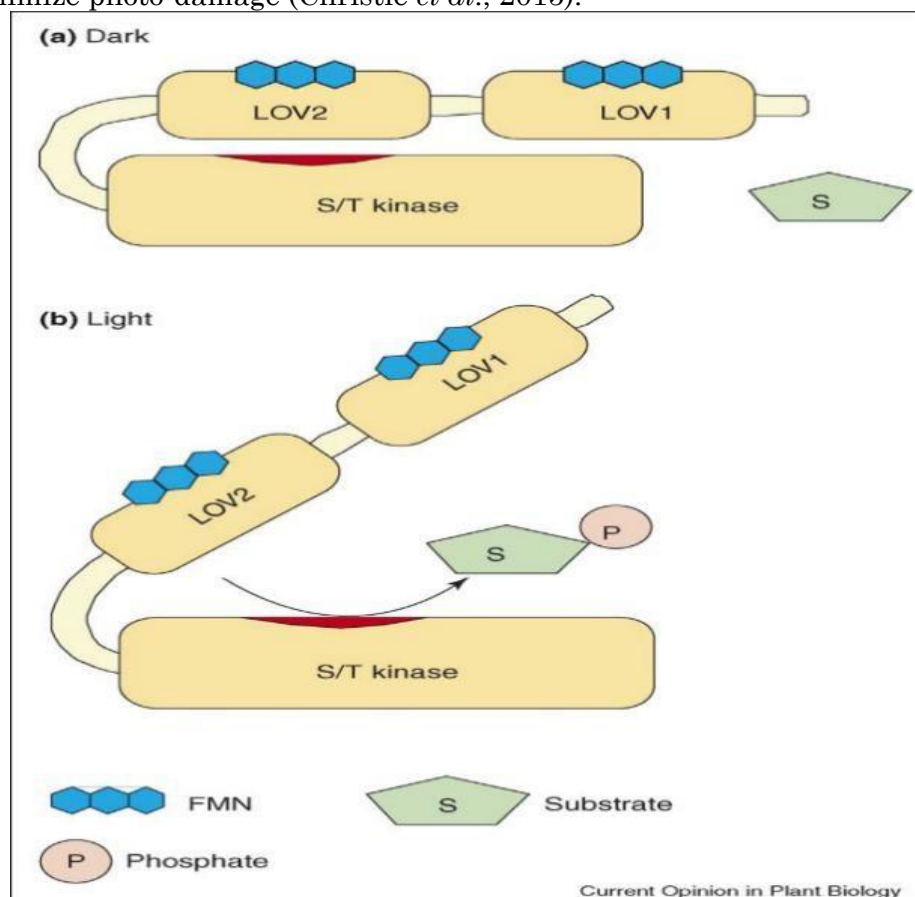
Interestingly, analyses of circadian clock mutants in Arabidopsis, revealed that genes involved in carbohydrate metabolism, including starch synthesis and degradation, were affected in all mutant lines tested. This suggests that inputs to the endogenous clock are vital to the proper regulation of critical physiological and developmental responses in plants.

Since cryptochromes play critical roles in the entrainment of the endogenous clock in response to light, its genetic manipulation could affect agronomically important traits, including starch metabolism, which would consequently impact productivity in crop plants.



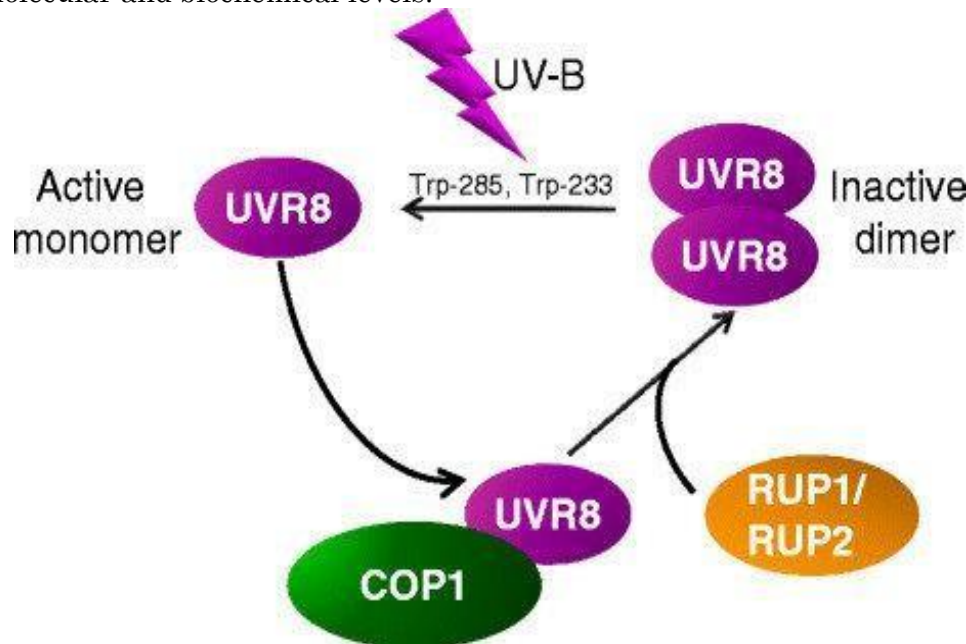
Phototropins

Phototropins are the principal photoreceptors for blue-light phototropism in plants. Besides phototropism, phototropins mediate other critical adaptive responses of plants to the surrounding light environment, which serve to enhance the photosynthetic status of the plants. The opening of stomatal pores, which allow for the exchange of water and carbon dioxide, is redundantly controlled by phototropins. The movement of chloroplasts in response to different light intensities is also regulated by the phototropins. When plants are exposed to low/weak light conditions, both phot1 and phot2 induce accumulation of the chloroplasts to the upper surface of the palisade mesophyll cells of leaves to maximize photosynthetic light capture. Under strong light conditions, phot2 mediates the rearrangement of chloroplasts parallel to the direction of the light source to minimize photo-damage (Christie *et al.*, 2015).



UVR8 and ZTL/FKF1/LKP2

Ultraviolet-B radiation (UV-B) is a key component of the radiation environment that is utilized by plants as a signal for UV acclimation and survival in sunlight. The discovery of the UV-B responsive UVR8 locus in plants and resultant has tremendously progressed our understanding of how this photoreceptor responds to UV-B at the molecular and biochemical levels.



While our knowledge of UVR8 function *in vivo* is still at a very nascent stage, its manipulation might have potential applications in crop improvement. The vegetative phase of plant growth is characterized by key developmental processes such as cell division and elongation, directional growth and branching. Low fluence UV-B regulates several of these developmental responses in plants, right from the seedling to adult stages. In adult plants, morphogenic responses to UV-B include alterations in leaf characteristics such as leaf area, leaf thickness, leaf mass and stomatal index. Plants exposed to UV-B radiation also show a decrease in chlorophyll content and in chl *a/b* ratio, along with a decline in photosynthetic efficiency. Conversely, the promotion of photosynthetic efficiency of *Arabidopsis* seedlings exposed to elevated levels of UV-B occurs via UVR8. Furthermore, lettuce seedlings exposed to UVB radiation at early stages of development also increased productivity and biomass, which could be due to the photoprotective effects of early UV-B exposure. UV-B radiation has also been reported to induce the accumulation of secondary metabolites such as flavonoids, which is reportedly controlled by UVR8 (Jenkins, 2014).

Land plants also contain a family of LOV (Light Oxygen or Voltage) photoreceptors referred to as ZEITLUPE/FLAVINBINDING KELCH REPEAT, F- BOX1/LOV KELCH PROTEIN2 (ZTL/FKF1/LKP2), having both photoreceptor and F-box protein activities within the same protein. Interestingly, genes coding for this family of photoreceptors are phylogenetically divided into two groups in dicots and monocots, suggesting different functions for these genes. However, the high levels of structural conserveness of ZTL and FKF1 homologs among different monocots and dicots may be suggestive of a certain level of functional conserveness of these genes across species. Indeed, mutant analyses in *Arabidopsis* and other species have revealed that ZTL/FKF1/LPK2 regulates similar developmental pathways across different species (Yon *et al.*, 2016). In *Arabidopsis* ZTL mutants, the presence of FKF1 and LKP2 compensates for the absence of ZTL in determining circadian rhythm, suggesting some level of functional redundancy between these photoreceptors, even though they are reported to have distinct roles in photoperiodic flowering. In crop plants, such as soybean, GmZTL3 a homolog of *Arabidopsis* ZTL has also been suggested to function as a photoreceptor controlling the timing of flowering (Xue *et al.*, 2012), a critical developmental response for crop plants.

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Coffee Varietal Wealth in India: A Legacy of Flavour and Diversity

Article ID: 72279

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Introduction

Coffee is more than a beverage it is a culture, a livelihood and a landscape that binds millions of farmers across the Western Ghats. India, the sixth largest coffee producer in the world, stands apart for its unique shade-grown coffees, cultivated under the canopy of evergreen trees and often intercropped with spices like pepper and cardamom. Beyond the scenic plantations and aromatic brews lies a remarkable scientific and genetic story the evolution of India's coffee varietal wealth. From the early introduction of coffee by the Sufi saint Baba Budan in the 17th century to the advanced hybrids developed by the Central Coffee Research Institute (CCRI) today, India's coffee cultivars represent a century-long journey of research, adaptation and excellence. This article explores the evolution, diversity and future of coffee varieties in India, emphasizing CCRI's pioneering contributions to the nation's coffee heritage.

The Journey of Coffee in India

The legend of Baba Budan narrates how seven coffee beans were smuggled from Yemen's port of Mocha and planted in the hills of Chandragiri (now Baba Budangiri) in Karnataka around 1670 CE. This humble act sowed the seeds of a vast coffee culture that would later flourish across the southern states of Karnataka, Kerala and Tamil Nadu and in emerging regions such as Andhra Pradesh's Araku Valley and parts of the Northeast. By the mid-19th century, British planters had expanded cultivation across the Western Ghats. However, the devastating Coffee Leaf Rust (*Hemileia vastatrix*) epidemic of the late 1800s almost wiped out Arabica plantations, forcing growers to explore disease-resistant lines and eventually to adopt Robusta (*Coffea canephora*). Recognizing the need for organized research, the Central Coffee Research Institute (CCRI) was established in 1925 at Chikmagalur, Karnataka under the Coffee Board of India. Since then, CCRI has been at the heart of India's coffee improvement programmes, releasing a rich array of varieties to meet challenges of pests, diseases and changing consumer tastes.

Arabica Varietal Evolution at CCRI

Arabica coffee (*Coffea arabica*) is prized globally for its delicate aroma, mild acidity and complex flavour notes. However, it is also more vulnerable to diseases and pests. CCRI scientists have worked extensively to enhance its resilience without compromising cup quality. Over the years, about thirteen Arabica selections (SLN or Sln.) have been released from CCRI, each tailored for specific altitudes, disease pressures and flavour preferences. The key varieties include:

S.288 (SLN 1): One of the earliest selections developed in the 1930s, S.288 laid the foundation for India's Arabica breeding. It was chosen from a spontaneous hybrid between *C. arabica* and *C. liberica*, giving it enhanced vigour and a degree of rust tolerance.

S.795 (SLN 3): Perhaps India's most iconic Arabica variety, S.795 was developed by crossing S.288 with Kent. Released in the 1940s, it became the backbone of Indian Arabica production due to its high yield, good cup quality and moderate rust resistance. Its balanced flavour smooth body with subtle mocha undertones earned it global acclaim and wide acceptance in domestic and export markets.

Sln.5A and Sln.5B: These selections resulted from interspecific breeding between *C. arabica* and *C. canephora*. They were aimed at enhancing rust resistance and productivity in rust-prone regions.

Sln.6: Developed during the 1970s, this variety incorporated the robust disease resistance of *C. canephora* while retaining the beverage quality of Arabica. It performed well under high-rainfall conditions.

Sln.9: A popular selection among growers in the mid- and high-elevation regions of Karnataka and Tamil Nadu, Sln.9 offers stable yields and a bright cup. It is widely used in blended specialty coffees.

Sln.12 (Cauvery): Cauvery, often described as India’s “Catimor,” was released to combine compact plant stature with rust resistance and high yield. It has been especially successful under intensive management systems and is valued by smallholders for its productivity and uniformity.

Chandragiri: Released in 2007, Chandragiri is a pure Arabica line derived from the cross *Villa Sarchi* × *Hybrid de Timor (HDT)*, followed by pedigree selection. It exhibits high rust tolerance, compact growth and uniform ripening qualities that make it ideal for modern plantations. The cup quality is clean, mild and comparable to international specialty grades.

Recent F₁ Hybrids (2025 Releases): Marking a new chapter in Indian coffee breeding, CCRI in 2025 released the F₁ hybrid S-4595 for commercial planting and three others S-5059, S-5085 and S-5086 for multi-location trials. S-4595 shows strong tolerance to white stem borer, one of Arabica’s most destructive pests, while maintaining desirable bean size and cup character. These hybrids signal CCRI’s shift toward combining conventional breeding with molecular tools to produce next-generation cultivars resilient to climate stress and emerging diseases. Together, these varieties represent India’s Arabica heritage scientifically improved, field-tested and attuned to the nation’s varied landscapes.

Robusta Varieties: The Strength of Indian Coffee

Robusta (*Coffea canephora*) occupies nearly 60 % of India’s coffee area, particularly in low- and mid-elevation zones of Wayanad, Coorg and Kerala’s Malabar region. Its bold beans, higher caffeine content and resistance to pests and drought make it an ideal companion crop in mixed plantations.

CCRI’s major Robusta releases include:

- 1. S.274:** One of the oldest and most widely cultivated Robusta varieties. It produces bold beans, heavy yields and thrives under mixed shade.
- 2. CxR (Congensis × Robusta):** An interspecific hybrid that combines vigour, uniform fruiting and enhanced cup quality.
- 3. Peridinia and Sln.13 series:** Selected for higher yield potential, adaptability and consistent bean size. These Robusta varieties are the foundation of India’s “Indian Cherry” and “Parchment” grades that dominate instant coffee and espresso blends. When processed using the monsooning technique, Robusta beans acquire mellow acidity and a rich body, prized by European roasters.

Regional Expressions of Varietal Diversity

India’s coffee diversity is not limited to plant genetics it is amplified by **terroir**, the unique combination of altitude, soil, rainfall and shade.

- 1. Chikmagalur and Coorg (Karnataka):** Home to S.795 and Sln.9, these high-altitude regions produce aromatic, balanced Arabicas with a fine acidity and mild spice notes.
- 2. Wayanad and Malabar (Kerala):** Dominated by Robusta varieties like S.274 and CxR, known for heavy body and chocolaty tones. The famous **Monsooned Malabar** owes its distinctive flavour to coastal processing.
- 3. Nilgiris and Thandikudi (Tamil Nadu):** Grow both Arabica (Sln.9, Cauvery) and Robusta varieties under diverse elevations, producing bright, clean cups.
- 4. Araku Valley (Andhra Pradesh):** Recently emerged as a specialty Arabica region, cultivating organic selections of S.795 and Chandragiri under tribal cooperative models.

This regional spread not only diversifies India’s coffee portfolio but also strengthens its climate resilience and market reach.

Breeding for the Future

CCRI continues to refine its breeding strategies to meet modern challenges. New programmes integrate molecular markers, genomic selection and biotechnological tools for faster screening of rust-resistant and drought-tolerant lines. Crosses involving Hybrid de Timor, Catimor and Caturra parents are being evaluated for cup quality and adaptability.

Simultaneously, researchers are exploring climate-smart coffee systems, combining improved varieties with agroforestry, organic nutrient management and precision irrigation. The goal is not just higher yields but sustainable, quality-driven production suited for changing global preferences.

Conclusion

India's coffee varietal wealth tells a story of innovation rooted in tradition. From the early Kent and S.288 selections to the recent F_1 hybrids, each variety represents decades of scientific effort, field testing and farmer collaboration. The Central Coffee Research Institute has been instrumental in shaping this legacy providing varieties that balance productivity, disease resistance and cup excellence. As the world's climate and markets evolve, India's genetic diversity in coffee offers a crucial advantage. Sustaining this diversity through conservation, participatory breeding and dissemination of high-quality planting material will be key to maintaining India's global reputation for fine coffees. In every cup of Indian Arabica or Robusta lies the story of a nation's research, resilience and rich flavour heritage.

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Multiplex PCR for Detection of Viral Pathogens in Banana

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Abstract

Banana (*Musa* spp.) is one of the most important fruit crops worldwide but is severely affected by viral pathogens such as Banana bunchy top virus (BBTV), Cucumber mosaic virus (CMV), Banana streak virus (BSV), and Banana bract mosaic virus (BBRMV). Traditional diagnostic methods such as ELISA are often limited in sensitivity and specificity, particularly when viral loads are low or mixed infections occur. To overcome these limitations, multiplex polymerase chain reaction (multiplex PCR) has emerged as an efficient molecular technique capable of detecting multiple viruses simultaneously in a single reaction using multiple primer sets. This study focuses on the development and application of multiplex PCR for the simultaneous detection of major banana-infecting viruses, especially BBTV and CMV. High-quality DNA or RNA was extracted from infected and healthy banana samples, followed by cDNA synthesis where required. Virus specific primers were designed to target conserved genomic regions with similar melting temperatures and distinct amplicon sizes, allowing clear visualization on agarose gel electrophoresis. Optimization of reaction parameters, including MgCl₂ concentration, primer compatibility, and annealing temperature, ensured reliable amplification without cross-reactivity. Case studies employing multiplex RT-PCR and bead-based LiquiChip assays demonstrated rapid, sensitive, and high throughput detection of BBTV, BSV, CMV, and BBRMV, confirming the assay's accuracy in both laboratory and field conditions. The developed multiplex PCR protocol significantly reduces time, cost, and reagent use compared to single-target assays, making it ideal for large-scale virus indexing, quarantine screening, and epidemiological surveillance. This approach enhances the early diagnosis and management of viral diseases in banana, supporting the production of virus free planting materials and sustainable crop cultivation.

Introduction

Banana (*Musa* spp.) is among the most important fruit crops in the world, ranking fourth after maize, rice, and wheat in terms of food importance. Global production reached nearly 192 million metric tons in 2024 (FAO, 2024). However, the banana industry faces serious losses due to viral diseases, particularly Banana bunchy top virus (BBTV) and Cucumber mosaic virus (CMV), which severely affect the yield and quality of the Cavendish cultivar and other commercial varieties (Ilyas & Briddon, 2008). Banana bunchy top virus (BBTV), belonging to the Nanoviridae family under the genus Babuvirus, was first recorded in Fiji in 1879 and has now spread to major banana-growing regions including India, Australia, and Africa (Debbarma et al., 2019). The virus is transmitted primarily through the banana aphid (*Pentalonia nigronervosa*). Infected plants show severe stunting, rosetting of leaves, narrow chlorotic lamina, and the characteristic “bunchy top” appearance. The BBTV genome is composed of six circular single-stranded DNA (ssDNA) components, each encoding proteins essential for replication, movement, and host infection (Arumugam *et al.*, 2017). Cucumber mosaic virus (CMV), a member of the genus Cucumovirus within the family Bromoviridae, infects a broad host range, including banana, and causes symptoms such as mosaic patterning, leaf distortion, and overall dwarfing of the plant. CMV possesses a single stranded RNA genome divided into three segments that encode essential replication and movement proteins (Shan-e-Ali Zaidi *et al.*, 2019). Conventional detection methods such as ELISA (Enzyme-Linked Immunosorbent Assay) and nucleic acid hybridization are used widely due to their convenience; however, they often lack sensitivity when viral titers are low or when mixed infections occur (Yadoun *et al.*, 2023). Advanced molecular methods such as Polymerase Chain Reaction (PCR), Immuno-capture PCR (IC-PCR), and Real-time PCR have significantly improved detection sensitivity. Despite these improvements, single target PCR can be time-consuming and

cost-inefficient when multiple pathogens are to be tested simultaneously. To overcome this limitation, Multiplex PCR (mPCR) offers a rapid, sensitive, and cost-effective diagnostic solution.

Principle and Concept of Multiplex PCR

Multiplex PCR is a modification of the conventional PCR technique that allows simultaneous amplification of multiple target DNA sequences within a single reaction tube. This is achieved by incorporating multiple primer pairs, each specific to a distinct target region. The technique reduces reagent use, processing time, and sample volume while providing internal controls within the same reaction (Henegariu *et al.*, 1997). Each primer pair must be designed to produce amplicons of distinct sizes to enable clear visualization by agarose gel electrophoresis. The reaction conditions, particularly annealing temperature and Mg^{2+} concentration, must be carefully optimized so that all primer sets function efficiently without interfering with one another. There are two basic types of multiplex PCR systems: single-template multiplex PCR uses one template DNA and multiple primer pairs targeting different loci. Multi-template multiplex PCR amplifies several templates using multiple primer pairs in the same reaction. This system is more complex due to potential cross hybridization and primer competition.

Methodology for Detection of Banana Viruses Using Multiplex PCR

1. Sample Collection and DNA/RNA Extraction: High-quality nucleic acids are the foundation of successful multiplex PCR. For banana virus detection, leaf samples showing mosaic, chlorosis, or bunchy top symptoms are collected. DNA (for BBTv) or RNA (for CMV) is extracted using commercial kits or classical methods such as the CTAB or phenol-chloroform extraction. RNA samples must be treated with DNase I to remove contaminating genomic DNA, while DNA samples are treated with RNase to eliminate RNA residues. Purity is checked by the A260/A280 ratio using a spectrophotometer, and integrity is confirmed through agarose gel electrophoresis.

2. Primer Design: Designing compatible primers is the most critical step in multiplex PCR. Each primer pair should: be 18-25 nucleotides long, have a GC content between 40-60%, Possess a melting temperature (T_m) of 58-62°C, ideally within 2°C of each other, Produce amplicons of distinct sizes (e.g., 150 bp, 250 bp, 350 bp, 500 bp), Primers are designed using tools like Primer3 or NCBI Primer-BLAST and validated individually in singleplex PCR before combining in multiplex reactions.

PCR Reaction Setup

A standard 25 μ L reaction mix contains: 10X PCR buffer-2.5 μ L, $MgCl_2$ (25 mM) – 1.5 μ L, dNTPs (10 mM each) - 0.5 μ L, Forward and reverse primers (0.5 μ L each per target), Taq DNA polymerase-1.25 U, Template DNA (10-100 ng), Nuclease-free water to 25 μ L.

1. Thermal cycling conditions typically include: Initial denaturation: 95°C for 3–5 min, 30-35 cycles of, denaturation: 95°C for 30 s, Annealing: 58-62°C for 30 s, Extension: 72°C for 45-60 s, Final extension: 72°C for 5-10 min

2. Electrophoresis and Visualization: Amplified products are separated on a 2-3% agarose gel, stained with ethidium bromide or SYBR Safe, and visualized under UV light. Distinct bands corresponding to each virus indicate successful amplification.

Optimization Parameters

Successful multiplex PCR requires careful optimization of several factors: Primer compatibility: Avoid cross-dimers or secondary structures. Magnesium ion concentration: Influences enzyme activity and specificity. Excess template can lead to non-specific amplification. Annealing temperature: Must accommodate all primer sets without bias.

Amplicon size differentiation: Enables accurate interpretation of multiple bands.

Applications

Multiplex PCR is widely used across plant pathology and biotechnology: Simultaneous pathogen detection: Identification of BBTv, CMV, BBrMV, and BSV in a single reaction. Epidemiological surveillance: Rapid field screening of planting materials. Certification programs: Ensuring virus-free tissue cultured plantlets

for distribution. Quarantine and breeding: Indexing of germplasm collections and parental lines for virus-free propagation.

Genetic and mutation analysis: Detecting gene deletions or variations associated with viral resistance.

Advantages

High efficiency multiple targets analyzed simultaneously. Cost-effective reduced reagent and labor requirements. Built in control presence of internal primers ensures reaction validity. Sensitive and specific capable of detecting mixed or low-level infections.

Limitations

Requires extensive optimization to prevent cross-amplification. Primer design is complex and time-consuming. May have unequal amplification efficiency among targets. Limited quantitative accuracy compared to real-time PCR.

Conclusion

The study highlights the effectiveness of multiplex PCR as a rapid, sensitive, and reliable molecular tool for the simultaneous detection of multiple viral pathogens infecting banana crops. Unlike conventional diagnostic methods such as ELISA or singleplex PCR, multiplex PCR enables the amplification of several target sequences in a single reaction, thereby saving time, reagents, and labor while maintaining high accuracy. The method developed and discussed here successfully identifies major banana viruses such as Banana bunchy top virus (BBTV), Banana streak virus (BSV), Banana bract mosaic virus (BBBrMV), and Cucumber mosaic virus (CMV), even at low infection levels or in mixed infections. The optimized parameters including primer design, annealing temperature, and reaction conditions ensure specificity, reproducibility, and cost-effectiveness, making the assay suitable for both laboratory diagnostics and field applications. Case studies demonstrated that multiplex RT-PCR and bead-based LiquiChip assays further enhance throughput and reliability in virus detection, supporting large-scale screening and certification of virus-free planting materials.

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Cocopeat and its Prospects in Indian Agriculture

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Cocopeat is a natural, spongy material made from coconut husks. When coconuts are processed to extract coir fibers (used in ropes and mats), the leftover dusty material is collected, cleaned, and sometimes compressed into blocks—this is cocopeat.

What is Cocopeat?

Sl. No.	Attribute	Description
1	Scientific name	Coir pith or coir dust
2	Source	Byproduct of coconut processing
3	Texture	Soft, fine, soil-like
4	Color	Light brown to reddish
5	pH	Slightly acidic (5.5–6.5)

Properties of Cocopeat



Figure 1: Properties of cocopeat

Applications in Agriculture

- Seed Germination:** Used in trays or pots as a medium for sprouting seeds. Also promotes fast root growth due to softness and moisture retention.
- Soil Conditioner:** Mixed with soil to improve moisture retention, aeration, and loosen heavy clay soils.
- Potting Mix:** Commonly mixed with compost, sand, or vermicompost for growing plants in pots.
- Hydroponics:** Used as a soil-free growing medium in hydroponic farming systems.
- Nursery and Greenhouse Cultivation:** Ideal for raising seedlings or saplings in polybags and trays.
- Soilless Farming:** Especially useful in urban gardening and terrace farming.

Benefits in Agriculture

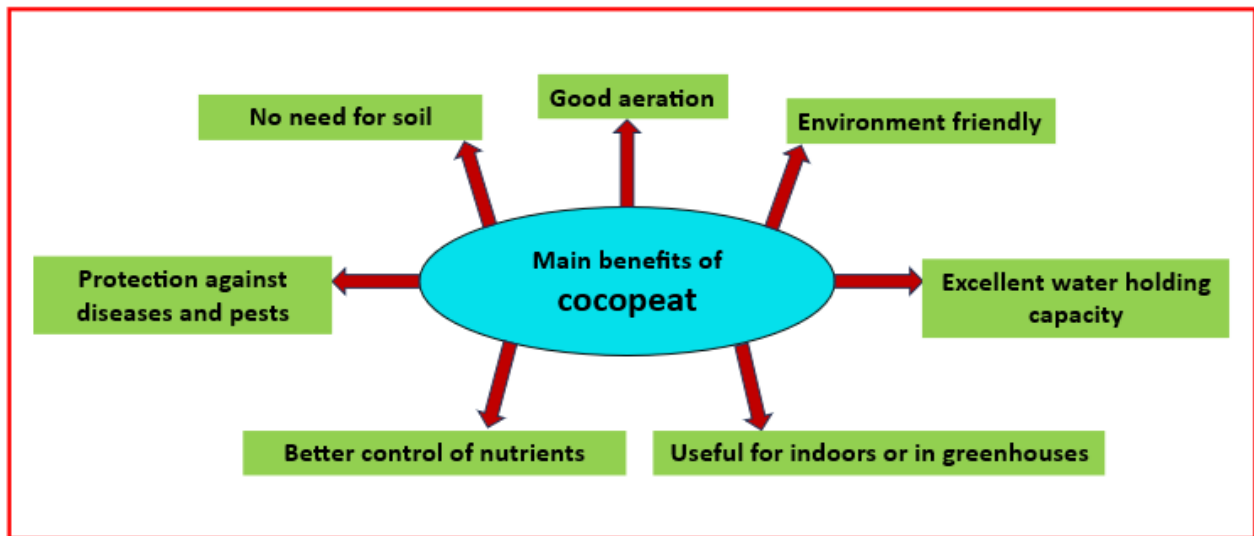


Figure 2: Benefits of cocopeat in agriculture

How is Cocopeat Made?

1. Collecting Coconut Husks
2. Retting (Soaking the Husks)
3. Fiber Extraction
4. Washing and Drying
5. Sieving and Grinding
6. Compressing (Optional)
7. Packaging.

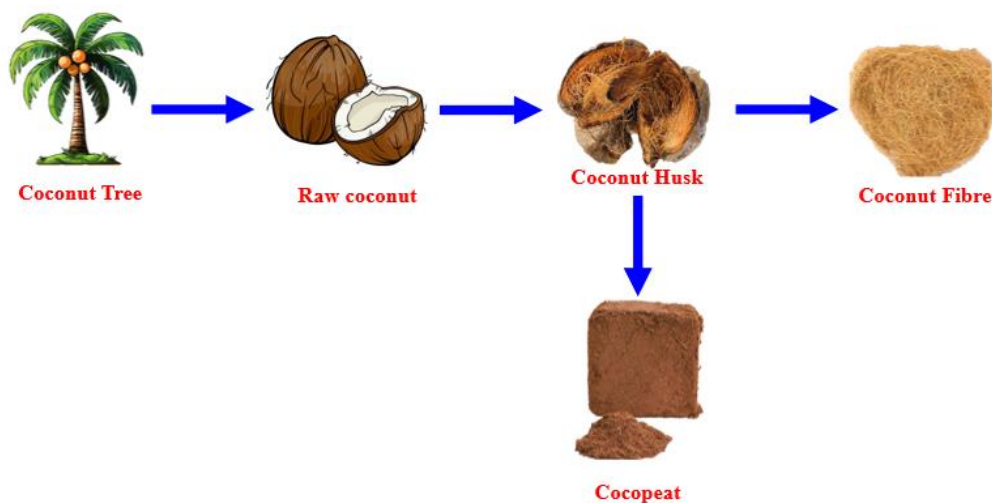


Figure 3: Process of making cocopeat

How to Use Compressed Cocopeat?

1. Place the block in a large container.
2. Add 4–5 liters of clean water per kg of cocopeat.
3. Wait for it to fully expand (takes 15–30 minutes).
4. Fluff it up and remove any lumps—it's now ready to use!

Prospect of Cocopeat Production Industry

The **cocopeat production industry** holds great promise in India due to several factors, including the country's vast coconut-growing areas, growing demand for sustainable agricultural products, and the shift

toward modern farming techniques. Let's break down why cocopeat production is a promising industry in India:

1. Abundant Raw Material Availability:

- a. **India is one of the largest producers of coconuts** in the world, particularly in regions like Kerala, Tamil Nadu, Karnataka, and Andhra Pradesh. This gives India a significant advantage when it comes to sourcing raw materials (coconut husks) for cocopeat production.
- b. The byproduct of coconut husks (used primarily for coir and other products) can be efficiently repurposed to make cocopeat, reducing waste and adding value to the coconut industry.

2. Rising Demand for Eco-friendly Products:

- a. **Sustainable agriculture** is becoming a growing trend in India, particularly in urban farming, terrace gardening, and organic farming. Cocopeat, being an eco-friendly and renewable resource, is gaining popularity among urban gardeners, nurseries, and commercial farmers.
- b. With the increasing emphasis on organic farming and sustainable agriculture practices, there is significant demand for soil alternatives like cocopeat that provide better moisture retention, root aeration, and disease resistance compared to conventional soil.

3. Growing Market for Hydroponics and Greenhouses:

- a. **Hydroponic farming** (soil-less agriculture) is gaining traction in India, especially in urban areas and states with water scarcity. Cocopeat is an excellent growing medium for hydroponics and greenhouse farming.
- b. **Greenhouses and vertical farming** are becoming increasingly popular for growing high-value crops like vegetables and herbs in controlled environments. Cocopeat serves as an ideal medium for these growing techniques because it retains moisture while providing aeration to the roots.

4. Rising Awareness of Sustainable Farming:

- a. With increasing awareness of environmental concerns, such as soil degradation, water scarcity, and the need for organic farming, cocopeat is viewed as a promising alternative to traditional soil-based farming.
- b. **Government initiatives** promoting organic and sustainable farming practices can further boost the demand for cocopeat, especially as it reduces the reliance on chemical fertilizers and improves soil health.

5. Export Potential:

- a. India has a strong opportunity to **export cocopeat** to countries with limited access to raw coconut products, especially to regions where hydroponics, greenhouse farming, and organic gardening are growing.
- b. The **global market for cocopeat** is expanding, particularly in countries like the United States, Europe, the Middle East, and Southeast Asia. India can capitalize on this demand for cocopeat as a **valuable agricultural product** in international markets.

6. Employment and Economic Benefits:

- a. The cocopeat industry can create employment opportunities, especially in rural areas, by involving local workers in the collection of coconut husks, processing, packaging, and distribution.
- b. The industry also has the potential to support small-scale farmers who can sell their coconut husks to cocopeat manufacturers, providing them with an additional income stream.

7. Low Production Costs and High Profit Margins:

- a. The cost of producing cocopeat is relatively low because it uses a waste byproduct (coconut husks), and India's large coconut-growing regions provide a steady and cost-effective supply of raw materials.
- b. After processing, cocopeat is sold in a highly compressed form, making it **lightweight** and cost-efficient to transport, offering high-profit margins.

Challenges and Considerations

While the cocopeat industry in India is promising, there are a few challenges to consider:

- 1. Quality Control:** There is a need for standardized production and quality control processes to ensure that cocopeat meets international standards for moisture content, cleanliness, and consistency.
- 2. Processing Infrastructure:** The cocopeat production process requires investments in machinery for processing, washing, drying, and compressing the cocopeat. Smaller producers may face challenges in acquiring such infrastructure.
- 3. Competition:** While India has an advantage in raw material availability, the cocopeat production industry faces competition from other coconut-producing countries like Sri Lanka, the Philippines, and Indonesia.
- 4. Environmental Impact:** Over-extraction of coconut husks for cocopeat production could impact the **coir industry** and the local environment. Sustainable practices in harvesting and production should be prioritized.

Conclusion

The **cocopeat production industry** is highly promising in India due to the country's vast coconut cultivation, rising demand for sustainable farming solutions, and export potential. With the right investments in processing technology and quality control, India could position itself as a leading producer and exporter of cocopeat, benefiting from both domestic and international markets. The industry also presents an opportunity for rural employment, environmental sustainability, and economic growth.

Edible Landscaping: Combining Beauty with Utility

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Abstract

Edible landscaping is an innovative and sustainable approach that merges aesthetic garden design with practical food production. By integrating fruits, vegetables, herbs, and edible flowers into ornamental landscapes, this practice enhances visual appeal while promoting biodiversity, resource conservation, and self-sufficiency. It challenges traditional landscaping norms by demonstrating that beauty and productivity can coexist harmoniously. Through thoughtful design principles such as functional aesthetics, layered planting, and microclimate optimization edible landscaping contributes to sustainable living and ecological balance. This method represents a forward-thinking paradigm in modern horticulture, aligning environmental stewardship with human well-being.

Keywords: Aesthetics, biodiversity, edible landscaping, sustainability, urban gardening.

Introduction

Edible landscaping represents a paradigm shift in garden design, merging the aesthetics of traditional ornamental landscapes with the functional benefits of food production. Unlike conventional gardens that segregate ornamental plants from edibles, edible landscaping deliberately integrates vegetables, fruits, herbs, and edible flowers into the overall design, ensuring that every plant serves both visual and utilitarian purposes (Fetouh, 2018). This approach aligns with sustainable gardening principles by promoting the efficient use of space, water, and nutrients. For instance, companion planting a core concept in edible landscaping allows plants with complementary growth habits to share space harmoniously. Tomatoes can be interplanted with basil, which enhances flavor, repels pests, and adds contrasting foliage texture, creating both an attractive and productive display. Edible landscaping also encourages a multisensory garden experience. Beyond visual appeal, many edible plants offer fragrance, texture, and taste. Herbs such as rosemary, lavender, and mint not only enhance the garden's aroma but also provide fresh ingredients for culinary use. Similarly, edible flowers such as nasturtiums and calendulas contribute vibrant color while being suitable for salads, teas, or garnishes, blurring the line between aesthetic and practical functions (Singh & Kaur, 2020). From an ecological perspective, edible landscaping supports biodiversity and ecosystem health. Planting a variety of edibles attracts pollinators like bees and butterflies, as well as beneficial insects that control pest populations naturally. Fruit trees and berry bushes provide habitats and food sources for birds and small mammals, thereby creating a more resilient and dynamic garden ecosystem. Moreover, edible landscaping fosters sustainable living and food security. By growing fruits, vegetables, and herbs at home, gardeners reduce dependence on store-bought produce, minimizing carbon footprint and packaging waste. This self-sufficiency not only promotes healthier diets with fresh, chemical-free produce but also instills a sense of environmental stewardship and connection with nature (Fetouh, 2018; Hazzard, 2016). In addition, edible landscaping offers flexible design opportunities. Gardeners can use raised beds, container gardens, vertical structures, and mixed borders to combine visual appeal with productivity. The creative arrangement of colors, textures, and plant heights allows for dynamic landscapes that are both functional and artistic, demonstrating that food production need not compromise beauty.

Philosophy of Edible Landscaping

Traditional landscaping often emphasizes ornamental plants, separating functional food crops into isolated vegetable or herb plots. This segregation reinforces the perception that beauty and utility are mutually exclusive in garden design. Edible landscaping, or "foodscaping," challenges this notion by integrating edible species directly into decorative garden settings. The philosophy underscores that food-producing plants vegetables, fruits, herbs, and edible flowers can serve as visual focal points while contributing

practical benefits such as nutrition, fragrance, and seasonality (Hazzard, 2016). By blending functionality with aesthetics, edible landscaping transforms the garden into a multidimensional space. It invites gardeners and visitors to engage with the landscape through sight, smell, taste, and touch. For example, a border of colorful chard interspersed with flowering herbs not only enhances visual texture but also encourages culinary experimentation. This approach fosters environmental stewardship, as gardeners become more conscious of plant growth cycles, soil health, and pollinator activity, thereby promoting sustainable practices alongside ornamental beauty (Fetouh, 2018).

Design Principles

Edible landscaping relies on strategic design principles to balance aesthetic appeal with productivity. The following key principles guide successful implementation:

1. Functional Aesthetics: Plants are selected for dual purposes: ornamental appeal and practical utility. Leafy vegetables such as kale, Swiss chard, and cabbage provide striking foliage patterns and colors, while herbs like rosemary, thyme, and basil offer fragrance, texture, and culinary uses. Such multifunctional planting ensures that every element contributes both to the visual composition and to harvestable produce, blurring the line between garden art and food cultivation.

2. Layered Planting: Incorporating plants of varying heights, growth habits, and lifespans creates a layered effect, enhancing year-round visual interest. Perennials such as fruit trees, berry bushes, and asparagus provide long-term yields and structural garden elements, while annuals introduce seasonal color, rapid harvests, and dynamic changes in texture. This vertical and temporal layering also maximizes space efficiency, a critical consideration in urban and suburban gardens.

3. Microclimate Utilization: Understanding site-specific conditions is essential. Sunlight exposure, soil type, moisture retention, and drainage patterns influence plant health and productivity. Grouping species with similar requirements reduces competition and optimizes growth. For example, sun-loving tomatoes may be planted near basil, while shade-tolerant lettuces thrive under taller fruit trees. Proper microclimate management ensures sustainability while enhancing plant vigor.

4. Edible Ornaments: Many plants traditionally considered ornamental can be cultivated for both beauty and consumption. Edible flowers such as pansies, nasturtiums, and calendulas introduce vivid colors and delicate textures, while remaining suitable for salads, garnishes, or herbal teas. The integration of edible ornaments demonstrates that visual elegance and functional use are not mutually exclusive, but complementary elements of a well-designed landscape.

Benefits of Edible Landscaping

Edible landscaping offers a unique combination of ecological, economic, and aesthetic benefits, making it an increasingly popular approach in sustainable garden design.

1. Enhanced Biodiversity: Integrating a diverse array of vegetables, fruits, herbs, and edible flowers fosters a rich ecosystem within the garden. The variety of plant species attracts pollinators such as bees and butterflies, which are essential for fruit and vegetable production. Additionally, beneficial insects like ladybugs and predatory wasps are drawn to the garden, naturally controlling pest populations. This increased biodiversity enhances the resilience and overall health of the garden ecosystem, reducing the need for chemical interventions and supporting long-term ecological balance (Hazzard, 2016).

2. Sustainable Living: Edible landscaping encourages self-sufficiency by reducing reliance on store-bought produce. Homegrown fruits, vegetables, and herbs decrease the environmental footprint associated with transportation, packaging, and storage of commercial food. Moreover, growing food locally promotes seasonal eating, reduces food waste, and strengthens the gardener's connection to natural growth cycles. These practices collectively contribute to a more sustainable lifestyle and environmentally responsible gardening (Kowalchuk & Leong, 2017).

3. Aesthetic Appeal: A thoughtfully designed edible garden can rival traditional ornamental landscapes in beauty. Plants with striking foliage, vibrant flowers, or colorful fruits provide visual interest throughout the seasons. For example, purple kale, red chard, and nasturtium flowers add striking textures and colors, while simultaneously providing edible yields. This dual-purpose approach ensures that gardens are not

only productive but also visually engaging, enhancing the overall enjoyment of outdoor spaces (Fetouh, 2018).

Practical Implementation Tips

Successfully establishing an edible landscape requires careful planning, gradual implementation, and sustainable practices:

1. Start Small: For beginners, starting with small, manageable plots such as raised beds, containers, or balcony gardens reduces the risk of overcommitment and allows for gradual learning. This approach enables gardeners to monitor plant performance, experiment with combinations, and expand their edible landscape as confidence and experience grow (Dirr, 2019).

2. Soil Health: Healthy soil is the foundation of productive edible landscapes. Ensuring proper fertility and drainage is critical for plant growth. Regular incorporation of organic matter, such as compost or well-rotted manure, enhances soil structure, increases nutrient availability, and improves water retention. Maintaining soil health supports sustainable yields while reducing dependence on chemical fertilizers (Singh & Kaur, 2020).

3. Water Management: Efficient irrigation is crucial for both plant health and resource conservation. Systems like drip irrigation or soaker hoses deliver water directly to the root zone, minimizing evaporation and runoff. Mulching around plants further retains soil moisture, moderates temperature, and suppresses weeds, enhancing overall water-use efficiency in the edible landscape (Hazzard, 2016).

4. Pest Management: Edible landscapes benefit from integrated pest management (IPM) strategies that prioritize ecological balance. Encouraging beneficial insects, using companion planting, and applying organic sprays, when necessary, helps manage pests naturally without harming non-target organisms or contaminating edible crops. Such practices maintain garden productivity while aligning with environmentally sustainable principles (Kowalchuk & Leong, 2017).

Flowers and Ornamentals Used in Edible Landscaping

Plant Name	Edible Part	Culinary/Other Uses	Landscape Value
Nasturtium (<i>Tropaeolum majus</i>)	Flowers, leaves, seeds	Flowers: salads, garnishes; Leaves: peppery flavor; Seeds: pickled like capers	Bright flowers, trailing or climbing habit, vibrant foliage
Pansy (<i>Viola tricolor</i> var.)	Flowers	Salads, desserts, tea, cake decoration	Colorful blooms, low-growing border plant
Calendula (<i>Calendula officinalis</i>)	Petals	Salads, soups, teas, natural dye	Bright orange/yellow flowers, long blooming period
Borage (<i>Borago officinalis</i>)	Leaves, flowers	Flowers: drinks, salads; Leaves: cooked as spinach	Star-shaped blue flowers, attracts pollinators
Marigold (<i>Tagetes</i> spp.)	Petals	Salads, rice dishes (coloring), herbal tea	Bright colors, pest-repellent properties, border plant
Chamomile (<i>Matricaria chamomilla</i> / <i>Chamaemelum nobile</i>)	Flowers	Herbal tea, flavoring	Small daisy-like flowers, ground cover or border plant
Feverfew (<i>Tanacetum parthenium</i>)	Leaves, flowers	Tea, medicinal uses	Daisy-like flowers, medicinal herb, adds texture
Daylily (<i>Hemerocallis</i> spp.)	Flower buds, flowers	Salads, soups, stir-fry	Large, colorful blooms, vertical interest

Hibiscus (<i>Hibiscus sabdariffa</i> / other edible varieties)	Flowers, calyces	Teas, jams, salads	Large tropical flowers, vibrant color, dramatic foliage
Lavender (<i>Lavandula</i> spp.)	Flowers	Tea, desserts, flavoring	Fragrant spikes, perennial, attracts pollinators
Rose (<i>Rosa</i> spp.)	Petals, rose hips	Tea, desserts, jams, syrups	Fragrant, colorful blooms, climbers or shrubs
Cornflower (<i>Centaurea cyanus</i>)	Petals	Salads, teas, decoration	Blue flowers, attracts pollinators, contrast color
Chive blossoms (<i>Allium schoenoprasum</i>)	Flowers	Salads, soups, garnishes	Small purple flowers, edible herb, attractive clusters
Dandelion (<i>Taraxacum officinale</i>)	Flowers, leaves	Flowers: fritters, teas; Leaves: salads, cooked greens	Bright yellow flowers, wildflower aesthetic, attracts pollinators
Sweet Alyssum (<i>Lobularia maritima</i>)	Flowers	Garnishes, salads	Tiny white/purple flowers, ground cover, fragrant
Scented Geraniums (<i>Pelargonium</i> spp.)	Leaves, flowers	Desserts, teas, flavoring	Fragrant foliage, colorful flowers, borders and containers
Torenia (<i>Torenia fournieri</i>)	Flowers	Garnishes	Trailing habit, vibrant blue/purple flowers

Key Notes for Edible Landscaping Use

- 1. Companion Benefits:** Many of these flowers also attract pollinators (bees, butterflies) or repel pests (e.g., marigolds against nematodes).
- 2. Aesthetic Arrangement:** Combine colors, heights, and bloom times for year-round appeal.
- 3. Safety First:** Always ensure the variety is **edible**; some ornamental varieties may be toxic.

Conclusion

Edible landscaping represents a transformative approach to garden design, seamlessly merging aesthetic appeal with functional productivity. By strategically incorporating vegetables, fruits, herbs, and edible flowers into ornamental settings, gardeners create landscapes that are visually engaging, ecologically balanced, and nutritionally rewarding. Beyond providing fresh, homegrown produce, edible landscapes support biodiversity by attracting pollinators and beneficial insects, enhance soil and water management through sustainable practices, and foster self-sufficiency and environmental stewardship. This multifunctional approach demonstrates that beauty and utility are not mutually exclusive in garden design; rather, they can complement and reinforce one another. Thoughtfully designed edible landscapes offer year-round visual interest, seasonal variation, and culinary abundance, transforming ordinary outdoor spaces into dynamic, productive, and sustainable environments. By adopting these principles, gardeners contribute to healthier ecosystems, promote sustainable living, and cultivate a closer connection to nature.

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The Hidden Stress of Temperate Fruits: Understanding Physiological Disorders

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Summary

Temperate fruits like apples, pears, cherries and strawberries are valued globally for their nutrition and economic impact. However, physiological disorders caused by environmental stress, nutrient deficiencies, and handling practices often reduce their yield and quality. These disorders manifest as blemishes, affecting appearance, taste and shelf life, which lowers market value. This article explores common physiological disorders in temperate fruits, their causes and prevention strategies to help growers maintain quality and meet market demands.

Keywords: Bitter pit, Sunscald, Fruit cracking, Albinism.

Introduction

Temperate fruits are vital to global agriculture, supplying key nutrients and supporting economic stability in cooler regions. Physiological disorders affecting fruit quality not only diminish visual appeal but also alter taste, texture, and storability, potentially resulting in economic losses. It is essential for producers and industry professionals to understand the underlying causes of these disorders, as this knowledge facilitates the development of precise prevention and management strategies.

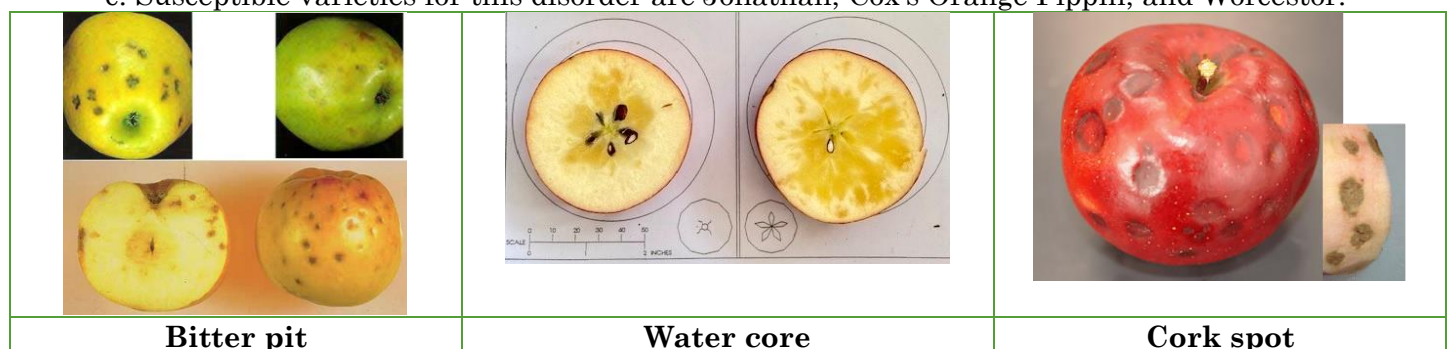
Apple

1. Bitter pit:

- It is recognized by the formation of small, brown, dry pockets below the peel and cortex.
- It is due to calcium deficiency and is controlled by spraying calcium chloride at 0.5%.

2. Water core:

- Water-soaked spots appear in the pulp, giving the fruit a dull, spongy appearance.
- It is due to excess boron and a delayed harvest.
- Susceptible varieties for this disorder are Jonathan, Cox's Orange Pippin, and Worcester.



3. Brown core:

- The fruit pulp becomes brown due to the storage of fruits at low temperatures (-1 to 2 degrees Celsius) and an increased level of potassium.
- Proper storage temperatures control this disorder.

4. Jonathan spot:

- The symptoms include the appearance of dark brown or black discoloration of fruit.
- It is caused by an excess of boron and controlled by spraying calcium chloride at 0.5–0.7 percent 2–6 weeks before harvest.

5. Cork spot: Brown spots appear in the peel and core, and they are controlled by spraying calcium chloride at 0.05%.

Pear

1. Hard end: The symptoms are the hardening and blackening of fruits during maturity, which are caused by unfavourable water conditions.

2. Pink calyx:

- This disorder is recognized by the formation of pink coloration near the blossom end of the fruit, which fails to ripen.
- It occurs when the nighttime temperature goes below 7.1 degrees Celsius and the daytime temperature goes below 21 degrees Celsius.

Peach

1. Sunscald:

- This occurs due to exposed trunk and scaffold branches, which lead to the scaling and peeling of bark.
- Painting the exposed surface with lime paste controls this disorder.

2. Gumming: The symptoms include gum exudation from fruits, which is caused by seed abortion, and heavy rain after a long period.

		
Peach - Gumming	Cherry – Fruit cracking	Strawberry - Albinism

Cherry

Fruit cracking:

- Fruit cracks are due to boron and calcium deficiency, fluctuating soil moisture, high temperatures, and low humidity.
- This disorder is controlled by 0.8% borax.

Strawberry

1. Albinism:

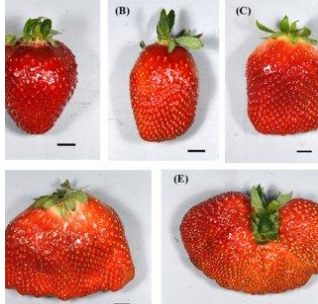
- Symptoms include the appearance of a white area on the surface of the fruits as well as a pale colour in the pulp.
- The fruits become susceptible to fruit rot during storage and lack uniform ripening. It is caused by dense planting, excess application of fertilizers, and black film mulching, which raises the temperature.
- It is controlled by avoiding close planting and the use of excessive fertilizers, and by avoiding the use of paddy straw as mulch material.

2. Malformation:

- Malformed fruits occur due to high nitrogen levels and improper pollination.
- It is controlled by arranging beehives and reducing excess nitrogenous fertilizers.

3. Fasciation:

- Witches broom appearance of plants, failure to produce runners, and abnormal flattening of fruits are symptoms of fasciation.
- It is due to unfavourable growth conditions.

		
Strawberry - Fasciation	Kiwi - Sunscorch	Persimmon – Calyx cracking

Kiwi

- Sun scorch:** high solar radiation causes a sunken, brown, and leathery scar on the surface of the fruit.
- Flats-** Due to improper pollination, fruits become flattened (fruit length exceeds width).

Persimmon

1. Calyx cavity:

- Trees producing a heavy crop load cause this disorder, which leads to cavities beneath the calyx of fruits.
- It is controlled by fruit thinning and proper pollination.

2. Sujika: Formation of white lines on the rind.

Conclusion

Physiological disorders in temperate fruits arise from complex interactions among environmental stress, mineral imbalance, and postharvest conditions. Though non-pathogenic, these disorders critically impact fruit quality, storage life, and market value. A deeper understanding of their physiological and environmental triggers is essential for developing sustainable orchard practices and maintaining consistent fruit quality under changing climatic conditions.

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Behind the Blemish: The Secret Science of Tropical Fruit Disorders

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Summary

Fruits are important sources of vitamins and minerals, but their quality is affected by several physiological disorders. Physiological disorders are abnormalities in plants caused by non-pathogenic factors, such as environmental stress, nutritional imbalance or genetic factors. This article reviews the various physiological disorders of tropical fruit crops and their control measures.

Keywords: Spongy tissue, Kottai vazhai, Granulation, Bronzing, Freckles.

Introduction

India is the world's largest fruit producer, but its yields and quality are frequently impacted by physiological disorders. These disorders can diminish the visual appeal of fruits and alter their flavor, texture and market value. Environmental stresses, nutrient imbalances and cultivation practices often contribute to these issues. For producers, identifying causes and preventive methods is essential. Such measures help ensure high-quality production, reduce post-harvest losses and meet consumer expectations.

Mango

1. Malformation: There are two types of malformation:

- Vegetative malformation: bunching of the leaf and shortening of the internodes
- Floral malformation: compactness of panicles and crowded flowers
- Controlled by spraying NAA at 200 ppm and growing resistant varieties such as Bhaudaran, Alib and Illaichi.

2. Spongy tissue:

- The pulp becomes sour, sponge-like patch and becomes non-edible. Alphonso is susceptible to this disorder.
- It is controlled by sod culture and mulching, as it occurs due to convective heat.

3. Black tip:

- Black spots appear at the distal end of the fruit, which becomes soft. It leads to pre-mature ripening and an early drop of fruits.
- As it is due to the gases such as carbon dioxide, carbon monoxide, and sulfur dioxide released by brick kilns, mango orchards should be located 1.8–2.0 km away from brick kilns.

These are major physiological disorders of mango; others are Jhumka, soft nose, taper tip, fruit pitting, jelly seed and girdle necrosis.

		
Mango malformation	Spongy tissue	Black tip

Banana

1. Kottai Vazhai: The susceptible variety is Poovan and there are prominent symptoms of enlarged ovules, which are controlled by spraying 2,4-D at 120 ppm.

2. Neer Vazhai:

- The fruits exude watery fluid, which is a severe problem in Nendran and Poovan.
- The fingers are unfilled, which leads to poor growth. It is controlled by spraying NAA.

3. White leaf:

- Unbalanced nitrogen application leads to the formation of white discoloration in the leaf.
- Other disorders are de grain, yellow pulp and goose flesh.

Citrus

1. Granulation:

- The symptoms are the drying of juice vessels and an insipid taste.
- This is a major preharvest physiological disorder of sweet oranges that occurs due to high temperatures, RH, heavy crop loads and the use of vigorous rootstocks.
- It is controlled by a spray of 2,4-D (12 ppm) and a micronutrient spray such as Zn + Cu + K (0.5%).

2. Fruit cracking: Fruit cracks because of fluctuations in soil moisture level, boron and calcium deficiency, and sudden rain following a prolonged drought.

3. Frenching:

- It is due to zinc deficiency and the symptoms are interveinal chlorosis, bushy appearance of plants and death.
- It is controlled by the spraying of 0.5 % zinc sulfate.

		
Granulation	Fruit cracking	Frenching

Guava

Bronzing:

- The symptoms are interveinal chlorosis, in which leaves turn a red or purplish color and fruit becomes hard.
- It is a complex nutritional disorder due to the deficiency of P, Zn and K.
- This is severe during the rainy season and the most resistant variety is Allahabad Safeda.

Grapes

1. Hen and chicken disorder:

- It is characterized by the presence of small berries and their uneven size.
- It is due to boron deficiency and is controlled by the application of borax 0.3 %.

2. Water berries:

- The affected berries will lose their firmness and become soft.
- The berries will become dull, shriveled and dry during harvest.
- It is due to excess nitrogen application and should be avoided. Application of borax 0.2% controls this disorder.

3. Uneven ripening: It is controlled by Ethephon 250 ppm, which promotes uniform ripening.

4. Pink berry:

- The berries change color to pink during ripening, making the bunch unattractive and unmarketable.
- It is a serious issue in the Thompson seedless and Tas-A-Ganesh varieties.
- It is controlled by dipping the berries in benzyl adenine (10 ppm).

5. Shot berry/Millerandage:

- The symptoms are the development of small berries due to improper pollination and fertilization and boron deficiency.
- It is controlled by the application of boron and dipping in ethephon at 25 ppm.

			
Guava- Bronzing		Grape – Hen and Chicken disorder	Grape – Uneven ripening
			
Grape – Shot berry	Papaya – Freckles	Papaya – Bumpy skin	

Papaya

1. Freckles: The appearance of spots on ripened fruits can be prevented by wrapping the young fruits in a white paper bag.

2. Bumpy skin is due to boron deficiency.

Conclusion

Physiological disorders in tropical fruits arise from imbalances in environmental, nutritional, and postharvest conditions that disrupt normal metabolic processes. These non-pathogenic issues, though often overlooked, significantly affect fruit quality, market value, and consumer perception. Strengthening our understanding of their physiological basis is vital for improving cultivation practices, enhancing resilience to climate stress, and ensuring the sustainable production of high-quality tropical fruits.

Preventing Malnutrition Among Women in India: Strategies for Sustainable Health

Article ID: 72285

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India, the second most populous country in the world, has experienced steady economic growth and recently achieved self-sufficiency in grain production. However, despite these advancements, the country continues to struggle with high levels of poverty, food insecurity, and malnutrition. India is home to nearly a quarter of the world's undernourished population, making it a critical area for global efforts to combat hunger. As per the Global Hunger Index (2025), India ranks 102 out of 123 countries with a score of 25.8 in the 2025. This Global Hunger Index score indicated India has a serious level of hunger. Women in India, particularly, face worsening health and nutritional challenges due to prevailing cultural norms and traditional practices. They are especially vulnerable to undernutrition during key life stages such as pregnancy and lactation. Studies have shown that the dietary intake of pregnant women in rural areas often falls below recommended levels. As a result, undernourished mothers are more likely to give birth to low-birth-weight infants, perpetuating a cycle of poor health and nutrition. The incidence of anaemia was found to be highest among lactating women followed by pregnant women and adolescent girls. Epidemiological studies pointed out that worldwide 50 percent of all pregnant women are anaemic, and at least 120 million women in less developed countries are underweight. Unawareness on health care during pregnancy thus results in negative outcomes for both the mother and the child. Right and proper education to the mothers had a significant influence on their nutritional status and their health.

Factors Responsible for Malnutrition

Malnutrition is a major health concern that significantly impacts both women and their children. Among women, the adverse effects of malnutrition are often compounded by factors such as intense physical labor, poverty, the demands of childbearing and child-rearing, and their unique nutritional requirements. These challenges increase their vulnerability to illness and lead to higher rates of morbidity. The consequences of poor health in women extend beyond the individual, affecting the well-being of entire families. Nutritional deficiencies in women often begin in early childhood and persist throughout their lives, creating a continuous cycle of poor health and diminished quality of life.

Women with poor health and nutrition are more likely to give birth to low birth weight infants. Women's health upsets a household's economic conditions as well as well as responsible for maternal mortality rate. In rural India it very commonly seen that women cook and feed all the family members and also share their portion with all. At the time of eating they only have one or two items which is in less amount also. They don't get proper food with all nutrients because sometimes they can't avail fresh fruits & vegetables, milk & milk products, egg, fish & meat. Besides these they don't have knowledge, skill and awareness about food items which is required for their body requirements at different situations like pregnancy and lactating stage. In a poor state of health a woman can't be able to perform her job efficiently. Therefore it is very much essential to empower the farm women by increasing their nutritional status.

In the last five decades the rate of decline in under nutrition has been slow; the mortality rate has come down by 50 per cent and the fertility rate by 40 per cent but the reduction in underweight rates is only 20 per cent. In 2016, 38.7% of children under five were defined as 'stunted' (of below average height), a strong indicator of chronic malnourishment in children and pregnant women, and a largely irreversible condition leading to reduced physical and mental development. Malnourishment within the adult population is also severe, with approximately 15 per cent of the total population defined as malnourished. The issue of malnutrition in India is complex, and determined by a combination of dietary intake and diversity, disease burden (intensified by poor sanitation and hygiene standards), and female empowerment and education. Improvements in dietary intake alone will therefore be insufficient to eliminate malnutrition, however it

forms an integral component alongside progress in other social and health indicators particularly sanitation.

During the UN Conference on Sustainable Development (Rio+20) in Brazil in June 2012 [4], Secretary-General Ban Ki-moon's proposed at the **Zero Hunger Challenge** aims for a future where every individual has adequate nutrition. He gave top priority to the elimination of hunger. This requires comprehensive efforts to ensure that every man, women and child enjoy their Right to Adequate Food; women are empowered; priority is given to family farming; and food systems everywhere are sustainable and resilient. In 2015, the United Nations (UN) adopted the goal of achieving zero hunger by 2030 as part of the Sustainable Development Goals (SDGs), with a key focus on ending all forms of malnutrition—including specific targets to reduce childhood stunting and wasting. The SDG commitment calls for a more comprehensive approach to food and nutrition, shifting the focus beyond mere energy intake to include all essential nutrients required for adequate nourishment. This has important implications for research and policymaking, demanding a broader, more inclusive perspective. To eliminate hunger and malnutrition in India, it is essential to adopt a holistic food security strategy—one that ensures food is not only available and accessible but also nutritious.

The challenge of Zero Hunger means to ensure:

1. Zero stunted children less than 2 years
2. 100% access to adequate food all year round
3. All food systems are sustainable
4. 100% increase in smallholder productivity and income
5. Zero loss or waste of food.

Strategies to Manage Food Resource at Household Level

1. Preventing childhood stunting involves nutrition-specific interventions, such as ensuring optimal breastfeeding and providing micronutrient-rich complementary foods.
2. Nutri-sensitive strategies, such as promotion and support exclusive breastfeeding for the first six months, followed by continued breastfeeding with the introduction of appropriate complementary foods.
3. Supplementing complementary foods for children aged 6-23 months is age-appropriate in quantity and quality, providing essential protein sources, and containing adequate micronutrients.
4. Enhancement in the diets of pregnant women and children with essential vitamins and minerals like iron, folic acid, vitamin A, and iodine, either through supplements or fortified foods.
5. Promote WASH practices such as Improve access to clean water, sanitation, and hygiene to prevent infections that can lead to stunting.
6. Providing maternal health services, and supporting socioeconomic programs
7. Ensuring zero wastage of food grains and food products
8. Post-harvest operation of cereals, pulses, vegetables & fruits available at local areas including preservation and value addition of fruits vegetables through indigenous techniques
9. Supplementation of milk & meat from domestic animals and preparation and preservation of milk and milk products through indigenous techniques
10. Nutri-gardens at backyard of the household and prefer locally available fruits and vegetables.
11. Preserve plants of different local varieties of fruits & vegetables.
12. Opt for eco-friendly technologies.

Suggestive Methods/ Practices for Ensuring Post-Harvest Loss and Zero Wastage of Food Products at Household Level

1. Improved cooking practices: There are various scientific methods which can be adopted by rural women very easily. These include sprouting, fermentation and combining different foods in a meal are ways to get the maximum nutritional value from some of our foods. These are given following:

- a. **Sprouting:** Sprouting dry pulses and grains dramatically increases their vitamin content, notably creating vitamin C and boosting B vitamins. The simple, low-cost process involves soaking

for 24 hours, then keeping them moist in a damp cloth for two to three days until the sprout reaches about 3/4 inch. Sprouted grains can be eaten raw or cooked, with care to preserve the vitamins. Notably, sprouted green gram yields three times the vitamin C of sprouted Bengal gram. This method is easily adopted, especially by rural women

b. Fermentation: Natural fermentation occurs when microorganisms interact with food, exemplified by foods like *dosa*, *idli*, or fermented wheat for *bathura*. This process, which turns milk into curd via lactic acid bacteria, makes food more nutritious. Microorganisms multiply, breaking down food and synthesizing complex vitamins (like riboflavin, B₁₂, and C), significantly increasing their content. Fermentation also enhances nutrient availability physically and chemically breaking down indigestible plant structures and protective coatings, making the nutrients more accessible during both cooking and human digestion.

c. Combinations of Food: If we consume a judicious combination of pulse, cereal and other plant foods, the net quality of proteins we receive would have the desirable pattern of essential amino acids. The proteins of cereals and pulses have a natural supplementary effect, and a deficiency of an amino acid in one food item can be made good by an excess of the same in another, if both foods are consumed at about the same time.

d. Fortification: Fortification is the process of adding specific nutrients to a food item to address dietary deficiencies caused by poor habits, cost, or regional food quality. The added nutrients are chosen based on necessity, cost-effectiveness, and the ability to blend without altering the food's taste or acceptability. Foods selected for fortification are those widely consumed by the population; examples include adding vitamin A and D to hydrogenated fats and iodine to common salt.

2. Prevention of Nutrient Losses during Food Preparation: While cooking, there are certain facts we must keep in mind, and certain general rules that must follow to come as close to a perfect balance of nutritional quality and palatability as well can. Some of the vitamins- the water-soluble ones are easy to lose. They get lost in the water we use for preparing or cooking, by exposure to sunlight and air, and by prolonged heating. Some of the rules to observe in processing and cooking food so that there is minimum loss, if there is any at all, of the nutrients in our foods are as follows:

- a. Wash vegetables before cutting.
- b. Cook vegetables on low flames with as far as possible no water and keep them covered while cooking.
- c. Do not overcook
- d. Cook rice in just as much water as it needs to cook. Do not use extra water which needs to be thrown, away
- e. Cut fruits just when you are ready to eat them
- f. Use acid foods, such as lime juice, tomatoes, vinegar, or curds in salads. It helps to retain the vitamin C value of the salad item.
- g. Avoid cutting the vegetables and fruits for long before cooking/eating.
- h. Use minimum water. Do not discard the extra water
- i. Try to finish cooking in the shortest time.
- j. Do not cook protein rich foods on high temperature as it leads to denaturing of proteins.
- k. Cook food in a covered pan as it not only helps to retain the nutrients and food flavors but also reduces the cooking time and thus the fuel consumption.
- l. To arrest browning in fruits and vegetables, these should be cut just before use, immersed in water or covered with salt, lemon or tomato juice.
- m. Do not discard the radish leaves/cauliflower stems.
- n. Do not use too many spices in food preparation with appropriate cooking methods; a homemaker can improve the nutritional status of her family and ensure their well-being.
- o. Cut as big pieces as required. In case of smaller pieces, the surface area increases, resulting in extra loss of vitamins and minerals.

3. Measures to Avoid Food Wastage: Wastage of food can occur at any stage of operation from harvesting food material to its consumption. Almost 10 percent of our cereal crops in this country are wasted at the farm level. If this is so with non-perishable crops, the wastage must be very much higher in the case of

semi-perishables and perishable food items. There can be wastage of food at two-stages- at the level of producer and at the level of consumer.

4. Low-Cost Food Preservation at Household Level: Home food preservation relies on methods like drying, and adding sugar, salt, or chemicals, using common kitchen tools. Drying uses natural air to preserve items such as vegetables, mango slices, and papads. Pickling uses salt, acids (like lime or vinegar), and oil (to block air) to preserve foods, with mangoes and limes being popular choices. Preservation with sugar (at a concentration of 68% or more) inhibits microbial growth, and is used to make jelly (fruit juice/pulp boiled with sugar to set), jam (whole fruit or pulp cooked with sugar to set), marmalade (fruit extract with thin slices of peel, often citrus), and murabba (whole or uniformly cut fruit preserved in a heavy, clear syrup that maintains the fruit's shape and flavor).

Combating Malnutrition through Agriculture

Farm women play a vital role in the development of agriculture and allied sectors. However, their poor economic status family responsibilities often lead to inadequate and unbalanced diets that fall short of meeting both quantity and quality nutritional needs. This nutritional deficiency not only compromises their health but also reduces their work efficiency and productivity. Insufficient intake of essential nutrients leads to "hidden hunger"—a form of malnutrition that has both physiological and pathological consequences. The over-reliance on cereal-based diets among farm women contributes to a lack of essential micronutrients in their bodies. To address these nutritional challenges a more sustainable and cost-effective approach is highly essential. Biofortification in the crops offers a practical and economical way to improve the nutritional status of farm women and contribute to global nutritional security. Encouraging farm families to cultivate biofortified crops can help meet their specific dietary needs while reducing dependency on external nutritional aids. In addition, an inclusive array of technologies and practices across crop cultivation, horticulture, dairy, and fisheries can be introduced and tailored to the needs of farm women. Interventions such as backyard nutri-gardens, community nurseries, mushroom cultivation, beekeeping, and value addition through packaging, minimal processing, and preservation can help women secure both nutritional and economic stability for their families. Furthermore, diverse farming systems—such as those based on fruit crops, vegetables, tubers, and mushrooms—can serve as reliable sources of household nutrition and income. There is also considerable potential in dairy farming, with the consumption of milk and dairy products contributing to improved nutrition. Fisheries and poultry farming offer additional opportunities due to their high market value and rich content of protein, vitamins, and minerals. Promoting the preparation and consumption of value-added products from these sectors can play a significant role in addressing nutritional deficiencies among farm women, while simultaneously enhancing household food security and livelihoods.

Conclusion

Hunger and malnutrition are two interconnected issues that often coexist and reinforce one another. Key underlying causes of malnutrition include poverty, unemployment, lack of education and awareness, limited access to nutritious food, clean water, proper sanitation and hygiene, as well as the absence of reliable data and adequate funding. Hence, to address the malnutrition issue, it is essential to focus on understanding these obstacles and implementing need based and targeted interventions on identified needs. This will be helpful in reducing malnutrition and zero hunger among the women and children in India.

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The Role of Precision Agriculture in Enhancing Lettuce Production

Article ID: 72286

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Introduction

The term "precision agriculture," often associated with GPS-guided tractors in vast cornfields, represents a paradigm shift from whole-field management to a hyper-localized approach. This farming strategy uses technology to observe, measure, and respond to inter- and intra-field variability in crops, ensuring each plant receives precisely what it needs for optimal health and productivity. While applicable to massive grain operations, its principles are finding a powerful and perhaps even more natural fit in high-value, intensively managed crops like lettuce. This integration of data, robotics, and sensing technology with the delicate biology of lettuce cultivation signifies a new era for growers. It blurs the traditional lines of farming, merging the agronomist's deep understanding of the crop with the data scientist's stream of real-time information to create a more efficient, sustainable, and productive system from seed to harvest.

The Lettuce Farmer in the Precision Era

The modern lettuce farmer integrates the constant stream of data from precision technologies with their embodied, tactile knowledge of the crop—knowledge developed through daily walks in the field, feeling the soil, and visually assessing plant health. For example, drones and satellites extend the farmer's vision, revealing patterns of water stress, nutrient deficiency, or pest infestation not visible to the naked eye, often before symptoms are apparent at ground level. However, farmers validate and interpret this spectral data by physically kneeling in the field, examining lettuce heads, and using their senses to diagnose the root cause of a problem. This creates a productive tension between the algorithm's suggestion and the grower's intuitive understanding of their land's micro-climates and soil variations. The precision-era lettuce farmer integrates these different forms of knowledge to form actionable insights, maintaining their agency in decision-making and resisting the idea that farming becomes a purely automated, screen-based activity. This perspective highlights that even in the most technologically advanced lettuce operation, the embodied experience of the farmer remains essential.

Key Precision Technologies in the Lettuce Field

Precision agriculture for lettuce is a rapidly developing field, deploying a suite of technologies tailored to the crop's specific needs and growth cycle. These tools focus on several critical areas:

- 1. Soil and Field Mapping:** Electromagnetic induction (EMI) sensors and soil sampling create high-resolution maps of soil texture, organic matter, and pH variability. This allows for variable-rate application of lime and amendments before planting, creating a uniform seedbed—a critical factor for consistent lettuce stand establishment.
- 2. Variable-Rate Irrigation (VRI):** Using soil moisture sensors and evapotranspiration data, VRI systems deliver precise amounts of water only where and when it is needed. This is crucial for lettuce, which has a shallow root system and is highly susceptible to both drought stress and diseases promoted by overwatering.
- 3. Drone and Satellite Scouting:** Multispectral and thermal imagery from drones captures the field's condition at a high resolution. This can detect early signs of water stress, identify areas of nitrogen deficiency (a key nutrient for leafy growth), and spot the early onset of fungal diseases like downy mildew, allowing for targeted intervention.
- 4. Automated Thinning and Weeding:** Computer-guided robotic systems use cameras to identify lettuce seedlings versus weed seedlings. They can automatically thin lettuce stands to the optimal spacing and

precisely eliminate weeds with mechanical tools or micro-doses of herbicide, reducing labor costs and chemical usage.

5. Precision Harvesting: Experimental robotic harvesters use machine vision to identify mature lettuce heads based on size, density, and color. They can then cut and pack the heads at a consistent quality, addressing the significant challenge of seasonal labor availability.

How does Precision Agriculture Boost Lettuce Yield and Quality?

1. Optimized Input Use: By applying water, fertilizer, and pesticides only where needed and in exact amounts, precision agriculture dramatically improves resource use efficiency. This reduces nutrient runoff into waterways and lowers production costs for the farmer.

2. Improved Uniformity and Stand Establishment: Addressing soil variability before planting leads to a more even emergence and stand of lettuce. This results in a higher marketable yield, as the crop matures more uniformly, simplifying harvest and meeting processor specifications.

3. Enhanced Pest and Disease Management: Early detection through remote sensing allows for problems to be addressed when they are small and localized. This prevents widespread outbreaks, reduces the need for broad-spectrum pesticide applications, and promotes integrated pest management (IPM) strategies.

4. Reduced Labor and Operational Costs: Automated thinning, weeding, and harvesting directly address the most labor-intensive and costly aspects of lettuce production. This increases operational efficiency and farm profitability.

5. Superior Product Quality and Safety: Precise water and nutrient management promotes the development of crisp, well-formed, and healthy heads. Furthermore, the reduced reliance on pesticides and the ability to trace inputs back to specific field zones enhance food safety profiles.

6. Data-Driven Decision Making: The historical data collected over seasons allows farmers to make better planting, variety selection, and management decisions, continuously refining their practices for their specific land.

Other examples include "smart" fertigation systems that inject fertilizers directly into irrigation lines based on real-time sensor data, and the use of in-field weather stations to provide hyper-local climate data for disease prediction models. The potential market for these technologies is strongest in large-scale commercial lettuce production, where small improvements in efficiency and yield translate into significant financial returns, and in controlled environment agriculture (CEA) like vertical farms, where monitoring and control are inherent to the system.

Ethical and Practical Considerations in Precision Agriculture

The adoption of precision agriculture in lettuce production brings forth several ethical and practical considerations. One significant concern is the high initial capital investment required for hardware, software, and technical training, which could create a "digital divide" between large agribusiness and small-scale, family-run farms. There are also questions regarding data ownership, privacy, and security—who owns the intricate data collected from a farm field, and how is it protected? This field inherently shifts the nature of farming knowledge, leading to philosophical discussions about the potential de-skilling of farmers and an over-reliance on algorithmic decision-making. It is anticipated that as automation increases, the social and economic impacts on farm labor communities will become a source of public discussion. Furthermore, the potential for increased electronic waste from outdated sensors and hardware poses a new environmental concern. The broader principle that those developing and implementing these powerful technologies should carry a proper amount of social responsibility suggests a need for policies that ensure equitable access and sustainable implementation.

Conclusion

Precision agriculture represents a significant advancement in the cultivation of lettuce, moving it from a blanket approach to a personalized, plant-by-plant strategy. While some technologies are mature and widely adopted, others, like fully automated harvesting, are still being refined. The successful integration of these tools highlights their potential to ensure high yields of superior quality lettuce, optimize the use

of precious resources like water and fertilizer, and reduce the environmental footprint of farming. The ongoing development of this technology promises to transform lettuce production, making it more resilient, sustainable, and efficient, and pushing the boundaries of what is possible in modern horticulture.

The History and Evolution of Vegetable Domestication

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Introduction

The term "domestication," derived from the Latin *domus* for 'house,' describes the long-term genetic relationship where a wild organism is altered to live alongside and benefit humans. While often associated with animals like dogs and cattle, this profound biological partnership fundamentally reshaped the plant kingdom, leading to the vegetables we know today. This process, emerging independently across the globe over 10,000 years ago, transformed nomadic hunter-gatherers into settled farmers, catalyzing the rise of civilizations. The humble vegetable, from the sturdy potato to the crisp lettuce, is not a natural given but a human-made invention, the result of millennia of selective breeding that altered everything from size and taste to reproductive strategy. This ongoing evolution signifies a deep, ancient convergence of human culture and plant biology, blurring the lines between the wild and the cultivated.

The Dawn of Domestication

The first farmers were not scientists but astute observers, integrating their embodied knowledge of the local environment—knowledge developed through generations of foraging, tasting, and testing—with the first principles of selective breeding. They chose to save and sow the seeds of plants with the most desirable traits: larger fruits, fewer bitter compounds, thinner skins, and seeds that remained attached to the plant for easier harvest (a trait known as non-shattering). For example, early cultivators in the Americas transformed the tiny, toxic wild tomato into larger, safer varieties by selectively propagating mutants with reduced levels of bitter alkaloids. However, these early farmers validated and interpreted their "genetic data" by physically tending their fields, using their senses to judge which plants were thriving and which tasted best. This created a productive tension between intentional selection and the embodied, intuitive understanding of the land. This integration of human agency with plant genetics formed the foundational knowledge of agriculture, resisting the idea that plant evolution is purely a natural phenomenon. This perspective highlights that even in our age of genetic modification, the foundational work of these early cultivators remains the essential bedrock of our food supply.

The Global Journey of Vegetable Staples

The domestication of vegetables was not a single event but a series of parallel revolutions across the continents, creating distinct culinary worlds that would only collide millennia later. This rapidly developing field of archaeobotany has traced the origins of our most common vegetables:

- 1. The Fertile Crescent:** In this region, ancestors of modern crops like peas, lentils, and carrots were first cultivated. These plants provided a critical package of proteins and carbohydrates that supported burgeoning settlements.
- 2. Mesoamerica:** This was the cradle of the "Three Sisters": maize (a grain often used as a vegetable), squash, and beans. The wild ancestor of maize, teosinte, is a grass with a handful of hard kernels, barely recognizable as the source of modern corn.
- 3. The Andes:** The high altitudes of South America gave us the potato and the tomato. The potato, in particular, was domesticated from a diverse group of wild tuber-bearing species, leading to the incredible variety seen today.
- 4. Asia:** Regions in China and Southeast Asia independently domesticated crucial vegetables like soybeans, radishes, and various leafy greens and cabbages, forming the basis of Eastern cuisines.

5. The Mediterranean and Europe: Vegetables like broccoli, cauliflower, and cabbage were all selectively bred from a single wild mustard species, *Brassica oleracea*, through a focus on different parts of the plant—leaves, flower buds, and stems.

How did Domestication Change Vegetables and Strengthen their Utility?

1. Altered Size and Morphology: Through selective pressure, farmers dramatically increased the size of the edible parts of plants. A wild carrot has a thin, woody root, while a domesticated carrot has a large, fleshy, and sweet taproot. Similarly, modern corn cobs are dozens of times larger than those of its ancestor, teosinte.

2. Reduced Defensive Compounds: Many wild plants produce toxic or bitter chemicals to deter predators. Domestication selected for varieties with lower levels of these compounds, making them safer and more palatable for human consumption, as seen in tomatoes and almonds.

3. Synchronized Germination: Wild plants often have seeds that germinate at different times to ensure some unpredictable conditions survive. Domesticated varieties were selected for uniform and rapid germination, making crop management more predictable and efficient.

4. Loss of Natural Seed Dispersal: A key domestication trait is the loss of natural seed dispersal mechanisms. Non-shattering seeds (in peas, wheat) and non-falling fruits (in maize) mean the harvest is retained on the plant for easy collection by humans.

5. Extended Harvest Window: For vegetables like lettuce and spinach, domestication favored a delay in bolting (flowering), extending the period for which leaves could be harvested.

6. Culinary and Cultural Diversification: As vegetables spread from their centers of origin, they were adapted to new environments and culinary traditions, leading to an explosion of varieties. The potato, for instance, diversified into thousands of types suited to different climates and dishes after its introduction to Europe.

7. Inspiration for Modern Genetics: The study of domestication traits, such as the genetic changes that turned teosinte into maize, is now a cornerstone of plant genetics and genomics, inspiring modern breeders and biotechnologists.

Other examples include the transformation of a small, spicy weed into the modern eggplant in Asia, and the development of the large, sweet watermelon from its small, bitter African ancestor. The process of domestication was essentially a global, millennia-long experiment in genetic engineering conducted by countless anonymous farmers. Their work created a vast living library of genetic diversity, which is now a critical resource for breeding crops resilient to climate change. Beyond mere sustenance, domesticated vegetables became deeply embedded in culture, trade, and cuisine, shaping human history from the Irish Potato Famine to the spice trade routes.

Ethical and Biological Considerations in Domestication

The process of domestication, while beneficial for humanity, brings forth several biological and ethical considerations. One significant concern is the dramatic reduction in genetic diversity that occurs when a wild population is narrowed into a domesticated lineage. This "domestication bottleneck" makes crops more vulnerable to diseases and pests, as seen in historical tragedies like the Panama disease that devastated the Gros Michel banana. Scientists and farmers are also grappling with the loss of traditional landraces and heirloom varieties as industrial agriculture favors genetic uniformity. This process inherently blurs the lines between natural evolution and human-directed design, leading to philosophical discussions about our responsibility for the organisms we have shaped. It is anticipated that as gene-editing technologies like CRISPR advance, the very concept of domestication will become a source of public discussion and controversy. Furthermore, the historical appropriation of genetic resources from their centers of origin, often without benefit to indigenous communities, raises concerns about bio-piracy and equitable sharing of benefits. The broader principle that humanity, having directed the evolution of these species, carries a profound responsibility for their conservation and sustainable use suggests a need for responsible stewardship.

Conclusion

Vegetable domestication represents one of the most significant advancements in human history, a slow-motion revolution at the intersection of culture and biology. While the initial phases are ancient history, the process of evolution continues in modern breeding programs and laboratories. The successful transformation of inedible or marginal wild plants into dietary staples highlights their potential to support dense human populations, adapt to new environments, and become embedded in cultural identity. The ongoing development of this relationship, from the first saved seed to the latest gene-edited variety, promises to continue transforming agriculture, diets, and our relationship with the natural world, pushing the boundaries of what plants can provide for human society.

Tomato Leaf Curl Disease (ToLCD) in Tomato

Article ID: 72288

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Introduction

Vegetables play a major role in the human diet and are widely used in everyday life. Among the vegetables, tomato (*Solanum lycopersicum* L.) is one of the most valuable vegetable crop consumed all over India. Tomatoes are short short-duration and winter season crop being cultivated everywhere in India. It is also known as the poor man's orange, a diploid ($2n=24$) plant belonging to the family Solanaceae. Tomatoes are consumed both as fresh and processed. Fresh and processed tomatoes are a rich source of dietary antioxidant lycopene, which protects the cells from oxidants that have been linked to cancer. The fruits are rich source of vitamins A, C, minerals, lipids, proteins and carbohydrates. It is widely grown in tropical and subtropical countries and the leading processed vegetable and the third most important vegetable crop after potato and onion in India, while the second in the world after potato.

India's annual tomato production stands at 20,300.19 thousand tonnes, with Madhya Pradesh emerging as the top producer, contributing 2,970,000 tonnes and 14.63% of the total output, followed by Andhra Pradesh at 2,217,000 tonnes and 10.92% of the total output. Other major tomato producing states include Karnataka, Tamil Nadu, Orissa, Gujarat and West Bengal. The tomato crop is affected by various biotic and abiotic factors. Among the biotic factors, tomato leaf curl disease (ToLCD) has emerged as one of the most devastating diseases of tomato on the Indian subcontinent and can cause total yield losses up to 100% if infected at a young age.

Tomato Leaf Curl Disease (ToLCD)

Begomovirus is the largest genus, harbouring several important species, including tomato leaf curl virus (ToLCV). The widespread occurrence and tremendous rate of spread to new regions, affecting tomato production worldwide, make it an important pathogen of huge economic importance.

Symptoms of ToLCV

1. Infected plant leaves are tiny and curl upward, with pronounced crumpling, interveinal and marginal yellowing (Fig 1).



Fig 1: ToLCV infected tomato plants

2. Infected plants internodes are shortened and stunted growth, plants frequently take on a bushy look, which is commonly referred to as 'bonsai' or 'broccoli'-like growth.
3. Flowers on infected plants frequently fail to develop and fall off (abscise).
4. Fruit yield is drastically decreased, especially when plants are infected at a young age, and losses of up to 100% are not unusual in areas with severe infestation.

Transmission of ToLCD

Tomato leaf curl disease caused by tomato leaf curl virus, belongs to Begomovirus and the family *Geminiviridae*. It is spread naturally by the whitefly (*B. tabaci*). During the adult stages, the virus can be efficiently spread. After 15-30 minutes of feeding on an infected plant, a whitefly acquires the virus within its salivary glands. After a 6 hours latent period (the interval between viral acquisition and transmission), the whitefly can spread the virus to another plant. Adult whiteflies may retain and disseminate the virus for 40 days after devouring infected plants and they can travel at least 10 kilometres (Naveed et al., 2023). Although young whiteflies can acquire the leaf curl virus from infected plants, only adult whiteflies are known to carry the virus.

Physical and Cultural Controls

1. At the beginning of the season, hang sticky yellow traps above the plants to provide early detection of white fly invasion. Tapping the plants with a stick will cause the whiteflies to fly up and stick onto the traps. Whiteflies are strongly attracted to the colour yellow, so avoid wearing yellow clothing around whiteflies or else you may carry them from plant to plant.
2. Use a floating row cover such as a Vege Net for early-season protection especially nurseries when grown in open conditions.
3. For small areas, vacuuming in the early morning can remove many of the adults before they have a chance to lay many eggs. They may also be collected in plastic bags and destroyed.
4. Handpick older leaves to remove young whitefly stages.
5. Avoid using a lot of nitrogen fertilizer, including manures, as succulent growth will increase whitefly population. It may be suggested to check for phosphorus and magnesium levels, as deficiencies in these are believed to contribute to whitefly infestations.
6. Spray a 5% solution of Neem Seed Kernel extracts mixed with neem oil. To prepare enough mixture of the extract to spray an area of 4000 m², 3-5 kg of neem kernel is required. Remove the outer seed coat and use only the kernel. If the seeds are fresh, 3 kg of kernel is sufficient. If the seeds are old 5 kg of seed can be used.

Precaution Measures Before, During and After the Crop Period

Proper planning before the start of the growing season is imperative for preventing epidemics. ToLCV-resistant cultivars must be used for plantation after procurement of seeds from trusted sources. Transplants must be virus and vector-free. The major problem of viral diseases is sometimes not the virus itself but the vector that spreads it. Thus, measures for controlling whitefly population might prove very useful in preventing outbreaks; the use of nets in nurseries may prevent whitefly infestation. Insecticides like imidacloprid, acetamiprid, dinotefuran, thiamethoxam etc can be used to control *B. tabaci* population (Polston & Lapidot, 2007). However, the major problem of using insecticides is that they take hours to act, whereas viral transmission to healthy plants takes merely 2 to 5 minutes. Further, use of pesticides leads to the development of insecticidal resistance in whiteflies. Once the growing period is over and fruits have been harvested, it is essential to remove all plant debris and follow proper crop sanitation practices. Weed management is another critical aspect, as TYLCV is reported to have a broad host range.

ToLCV Resistant Cultivars

Promoting and cultivating ToLCV-resistant tomato cultivars is the most effective, economic and environmentally friendly strategy to manage losses caused by ToLCV infestation. Further, resistant cultivars have greater adoption among the farmers.

Table 1: ToLCV resistant tomato cultivars:

S. No.	Variety	Characterises
1	Kashi Amul	It is an open-pollinated variety with an average fruit weight of 90-115 g and yield potential of 50-60 tonnes/ha. Recommended for cultivation in Karnataka, Kerala and Tamil Nadu. Resistant to ToLCV
2	Kashi Adarsh	It is an open-pollinated variety with an average fruit weight of 80-115 g and a yield potential of 60 tonnes/ha. Recommended for cultivation in Maharashtra and Madhya Pradesh. Resistant to ToLCV
3	Kashi Aman	It is an open-pollinated variety with an average fruit weight of this variety ranges from 80-110 g. and potential of 50-60 tonnes/ha. Recommended for cultivation in Punjab, Uttar Pradesh, Bihar and Jharkhand. Resistant to ToLCV
4	Kashi Chayan	It is an open-pollinated variety with average fruit weight of this variety ranges from 100-120 g. and potential of 50-50 tonnes/ha. Recommended for cultivation in Bihar, Jharkhand, Punjab, Uttar Pradesh, Goa, Madhya Pradesh and Maharashtra
5	Arka Rakshak	High-yielding hybrid with triple disease resistance (ToLCV, BW and early blight), fruits square round, large (90-100 g), deep red coloured, firm, suitable for fresh market and processing, yield potential is up to 75-80 t/ha.
6.	Arka Abhed	High-yielding hybrid with multiple disease resistance (ToLCV, bacterial wilt, early blight and late blight. Plants are semi-determinate with dark green foliage; Fruits are firm, oblate round & medium large (90-100g) with yield potential of 70-75 t/ha.
7.	Arka Samrat	High-yielding hybrid with processing quality, resistance to ToLCV, bacterial wilt and early blight and yield potential of 80-85 t/ha. Recommended for cultivation in Karnataka, Tamil Nadu, Kerala and Pondicherry.

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From Waste to Fuel and Soil Amendment: Biomass Pellet and Biochar: Production from Cotton Residues in Rayagada District of Odisha

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Abstract

Efficient crop residue management is vital for sustainable agriculture. In Rayagada, a major cotton-producing district, post-harvest burning of cotton stalks causes significant air pollution and soil degradation. This paper explores the conversion of this waste into valuable products. Transforming cotton stalks into biomass pellets provides a high-calorific-value, renewable fuel, supporting clean energy. Concurrently, producing biochar via pyrolysis creates a soil amendment that enhances fertility and sequesters carbon. Adopting these practices offers an eco-friendly, economically viable solution, promoting a circular bio economy, reducing environmental harm, and creating rural income opportunities.

Introduction

Efficient crop residue management plays a vital role in promoting sustainable agriculture by addressing environmental issues and creating value from agricultural waste. Every year, large volumes of residues such as rice straw, wheat straw, maize cobs, cotton stalks etc. are left as such in the crop fields after harvest. In many cases, these residues are burned, leading to air pollution, nutrient depletion, and greenhouse gas emissions, causing significant adverse effects to ecology and environment. The Rayagada district of Odisha serves as a major cotton-producing hub, where cotton cultivation dominates the agricultural landscape during the *Kharif* season. However, there is an absence of residue management practices for cotton in the region, as farmers predominantly resort to burning the crop residues after harvest. Transformation of these waste materials into useful products like agricultural biomass pellets and biochar (Fig. 1), offers an eco-friendly and economically viable solution (Zambon *et al.*, 2016).

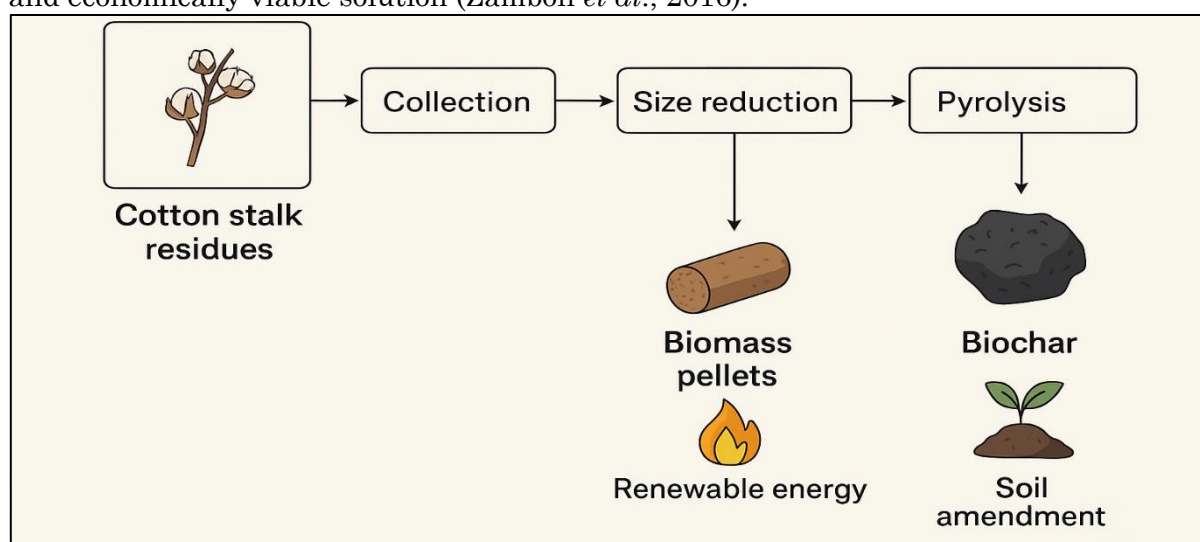


Fig 1: Conceptual framework – from waste to resource

Agricultural biomass pellets are dense, energy-rich biofuels formed by compressing dried crop residues under high pressure without the use of chemical additives. These pellets serve as renewable alternatives to fossil fuels in boilers, heating systems, and power plants. Their production not only reduces reliance on non-renewable energy sources but also supports rural development and the circular bio economy. Biochar, on the other hand, is produced through the pyrolysis of crop residues under limited oxygen conditions, resulting in a stable, carbon-rich material. When added to soil, biochar improves fertility, moisture

retention, and microbial activity while sequestering carbon, thereby mitigating climate change. Integrating biomass pellet and biochar production into crop residue management ensures the sustainable utilization of agricultural waste, contributing to cleaner energy production, enhanced soil health, and long-term environmental sustainability (Vincevica-Gaile *et al.*, 2025).

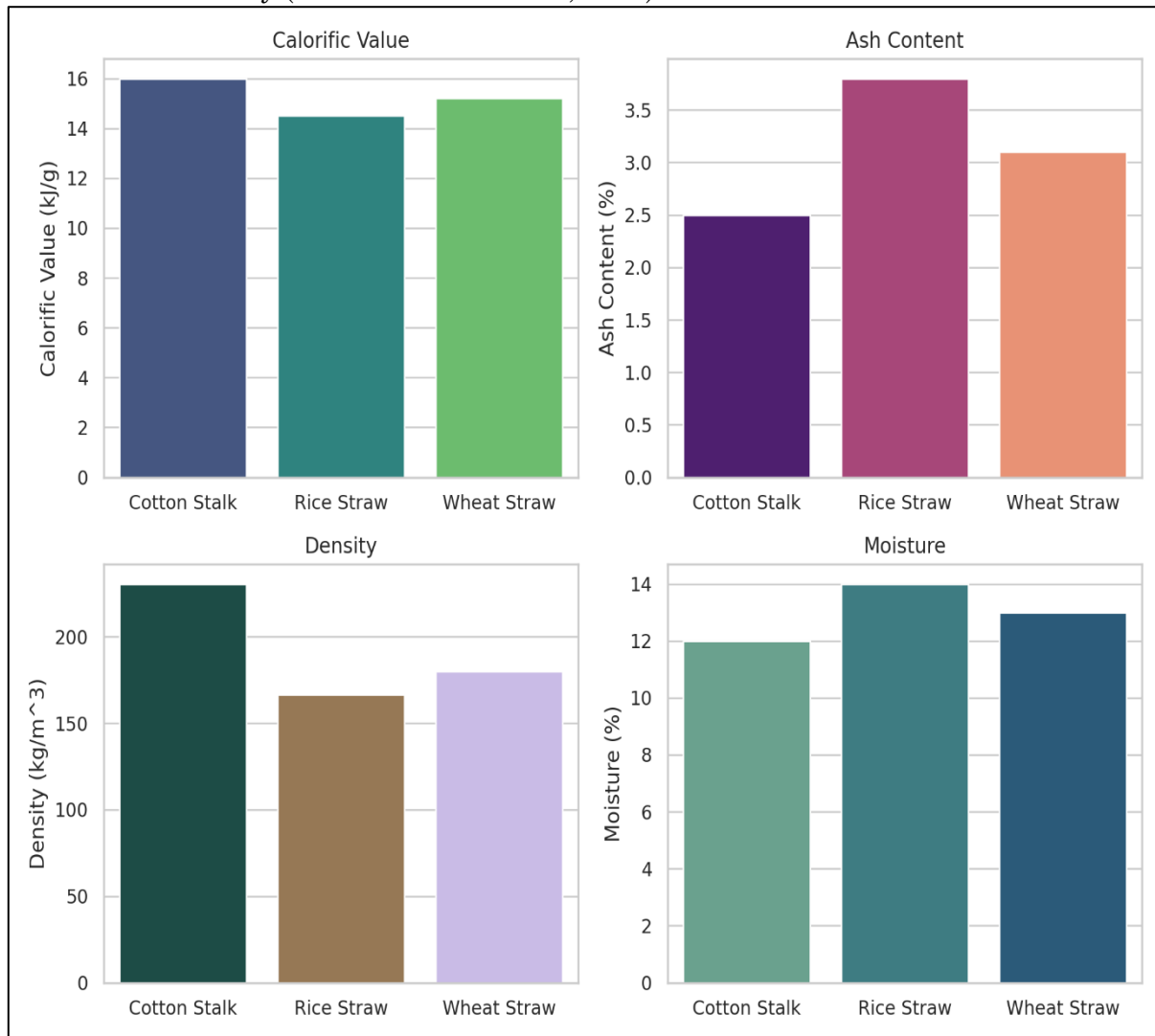


Fig. 2: Comparative fuel properties of cotton stalk pellets with other biomass pellets (Cotton Association of India, 2024)

Biomass Pellets

Agricultural biomass pellets are compact, cylindrical biofuels made by compressing agricultural residues such as rice husk, wheat straw, maize cobs, groundnut shells, and cotton stalks. Cotton stalk serves as an excellent raw material for biomass pellet production due to its favorable characteristics and wide availability. Since cotton is extensively cultivated, the stalks are easily accessible and cost-effective. They possess a high calorific value of 15.861–16.230 kJ/g, which is greater than that of rice stubble, making them a more efficient energy source. The stalks also have a low moisture content of about 10–15%, eliminating the need for additional drying and making them suitable for pelletization within a week after harvest. Furthermore, cotton stalks have a higher bulk density (230.55 kg/m³) compared to rice straw (166.29 kg/m³), facilitating easier storage and transportation. Pelletizing cotton stalks further enhances their fuel quality. The moisture content drops to 0.62%, ash content reduces to 2.02%, and density increases to 1120 kg/m³ (Fig. 2). The pellets are compact, with an average diameter of about 6 mm, and display an improved calorific value of 17.71 kJ/g—significantly higher than both raw cotton stalks and rice straw pellets (15.90 kJ/g). Therefore, these attributes make cotton stalk pellets a more efficient, cleaner and sustainable biofuel alternative (Lang *et al.*, 2023).

These cotton stalks can be converted into high-density pellets through drying, grinding, and compression, using natural lignin as a binder. The resulting pellets have a high calorific value and low moisture, making them efficient for heating and power generation. As a renewable, carbon-neutral fuel, they reduce air pollution, decrease fossil fuel dependence, enhance rural income, and support sustainable waste management, thereby advancing the circular bio economy (Vincevica-Gaile et al., 2025).

Manufacturing Process

- 1. Collection and Preparation:** Cotton stalks are collected from field and cleaned to remove unwanted materials like dust and stones.
- 2. Drying:** The biomass is dried to reduce its moisture content to around 10–15%, which is essential for efficient pellet formation and combustion.
- 3. Size Reduction:** The dried material is crushed or ground into fine particles (below 5 mm) using a hammer mill to ensure uniform size and better pellet quality.
- 4. Pelletizing:** The processed biomass is then fed into a pellet mill, where it is compressed at high pressure and temperature. The natural lignin in the biomass acts as a binder, helping the material form dense cylindrical pellets.
- 5. Cooling:** The freshly formed pellets are hot and soft; they are cooled with air to harden and stabilize their shape.
- 6. Screening and packaging:** The cooled pellets are screened to remove dust or broken pieces and then packed for storage or transportation.

Uses of Biomass Pellets

Biomass pellets are versatile, renewable fuels with numerous applications across domestic, industrial, and commercial sectors. They are used in thermal power plants for electricity generation and as fuel in industrial boilers, furnaces, and kilns across various industries. In households, pellets serve as a clean alternative for cooking and space heating, while hotels and institutions use them for water heating and food preparation. In agriculture, they provide efficient fuel for drying grains, spices, and tea. Moreover, using biomass pellets helps reduce greenhouse gas emissions, prevent residue burning, and promote sustainable waste management.

Biochar

Biochar is a carbon-rich substance produced from agricultural residues through pyrolysis, a process that involves heating biomass in a low-oxygen environment. Although it looks similar to charcoal, biochar is specifically designed to improve soil quality and provide environmental advantages. It acts as a stable carbon sink, helping store carbon in the soil for long periods. The production of biochar is highly beneficial as it converts farm waste into a valuable product, reduces crop residue burning, and minimizes air pollution. Additionally, it enhances soil fertility, boosts water retention, and supports carbon sequestration—thereby contributes to mitigate adverse effects of climate change. As an environmentally sustainable waste management approach, biochar production provides a viable and eco-friendly solution for enhancing the sustainability of agricultural systems. Common waste materials used for making biochar include cotton stalks, rice husk, wheat straw, maize stalks, sugarcane bagasse, sawdust, and wood chips (Wang *et al.*, 2019).

Procedure for Biochar Production

- 1. Collection and Preparation:** Crop residues or biomass are collected and cleaned.
- 2. Drying:** Biomass is dried to lower moisture content for efficient pyrolysis.
- 3. Pyrolysis:** Biomass is heated in a low-oxygen environment at 300-700°C, producing biochar along with syngas and bio-oil.
- 4. Cooling and Collection:** Biochar is cooled and collected; syngas and bio-oil can be used as fuels.
- 5. Application:** Biochar is applied to soil or used for filtration and compost enhancement.

Uses of Biochar

Biochar offers several important benefits for agriculture and the environment. It enhances soil quality by improving its structure, aeration, and ability to retain water, which promotes healthier crop growth. Biochar also aids in nutrient conservation by holding essential elements like nitrogen and phosphorus, minimizing fertilizer loss and improving soil fertility. Another key advantage is its role in carbon sequestration, as it captures and stores carbon in the soil for extended periods, helping to lower greenhouse gas emissions. Furthermore, biochar supports waste management by transforming agricultural and organic residues into a valuable resource (Fig. 3). It is also effective in water purification, acting as an adsorbent to remove contaminants and improve overall water quality (Wang *et al.*, 2019).

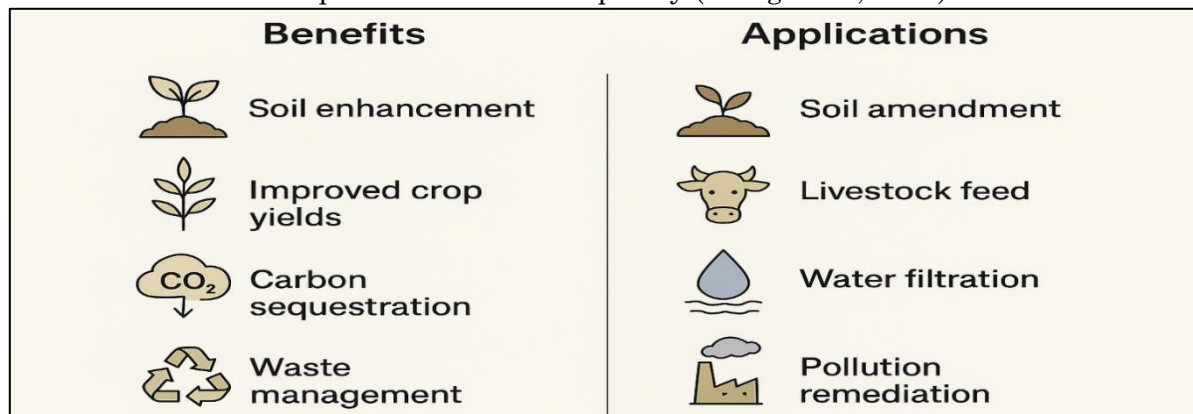


Fig. 3: Benefits and Applications of Biochar

Conclusion

Converting crop residues into biomass pellets and biochar is an eco-friendly way to manage agricultural waste. Biomass pellets serve as a renewable energy source, while biochar improves soil quality and stores carbon. This method reduces pollution, supports sustainable farming, and promotes a circular bio economy. Therefore, establishing biopellets and biochar production centres in the villages of Rayagada district could provide the farming community with an alternative source of income for uplifting economy of tribal population, while promoting sustainable agricultural practices.

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Comparative Genomics in Disease Resistance Mechanisms of Plants

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Abstract

Comparative genomics is a branch of biology that involves the analysis and comparison of genome sequences across different species, encompassing humans, mice, plants, insects, bacteria, and many other organisms. The study of genome sequences in a variety of species, including humans, mice, bacteria, chimpanzees, and other creatures, is known as comparative genomics.

This is like an entire instruction manual of an organism. By lining up and comparing these manuals from various species scientists can discover similarities and differences in their genomes. This helps us understand how species are related to each other and how they've changed over time through evolution. It has been instrumental in revealing the development of diverse disease resistance mechanisms, allowing researchers to pinpoint crucial genes and study their function. This powerful approach provides valuable insights into various areas, including plant health and disease, as well as the broader processes underlying evolution.

Introduction

Comparative genomics is a scientific discipline that explores the similarities and differences in the DNA sequences of various organisms. With the rapid advancement of sequencing technologies, vast amounts of genome data have become available, offering unprecedented opportunities to study genetic variation at both species and population levels. By analyzing conserved and divergent regions, researchers can trace evolutionary relationships, identify genes linked to specific traits, and uncover the molecular basis of adaptation.

Despite the wealth of genomic information, one major challenge in biology is understanding how genetic variation translates into functional diversity, disease susceptibility, and evolutionary change. Comparative genomics addresses this by providing a framework to study orthologs, paralogs, synteny, and divergence, thereby connecting sequence data with biological meaning. It has proven essential in medicine, agriculture, and evolutionary biology — from identifying disease-causing genes and drug targets to improving crop resilience and understanding biodiversity. This approach is particularly valuable for understanding plant defense mechanisms, revealing key resistance genes and their evolution, which is critical as plant pathogens continue to evolve under high selection pressure.

Principle of Comparative Genomics

Comparative genomics has proven itself invaluable, not only for illuminating evolutionary mechanisms and forces, but for informing the understanding of the genomes of various organisms. The essence of the field of comparative genomics is the sequence that stays conserved (similar) across multiple and/or distant species is likely to be constrained (similar due to evolutionary pressures), which implies a biological function. However, the converse is not necessarily true: A DNA sequence can, of course, have a biological function without being conserved with any other species' genome (Alföldi *et al.*, 2013). This is particularly relevant for newly evolved, lineage-specific genetic changes, where insufficient time has passed for the sequences to develop recognizable patterns of conservation. Conservation does not necessarily imply identity; Sequence can be constrained to prefer two or three out of the four bases.

Disease Resistance Mechanisms in Plants

Plant disease resistance is shaped by conserved genetic frameworks and species-specific adaptations. Comparative genomics plays a vital role in this field by analyzing whole genomes across species, revealing both shared features and unique variations that determine resilience or susceptibility. At the core of plant

defense are resistance (R) genes, particularly the *NBS-LRR* family, conserved across diverse plants like legumes and Solanaceae. These genes drive effector-triggered immunity (ETI). While their genomic positions are often stable, their pathogen-recognition functions evolve quickly. For example, in tomato, potato, and pepper, R genes occur at similar chromosomal locations but rarely protect against the same pathogens, showing stability in defense initiation yet rapid diversification in recognition. (Grube *et al.*, 2000)

Resistance also relies on regulatory networks, including transcription factors, hormone signaling, and promoter variations that fine-tune stress responses. Pangenomic studies highlight structural variations such as presence/absence polymorphisms, which uncover hidden resistance alleles. These insights guide biotechnological applications. Marker-Assisted Selection (MAS) and CRISPR/Cas9 enable precise incorporation of beneficial alleles. A notable case is the mango gene *Mi_A_CNL14*, a multifunctional “super gene” conferring both disease and cold stress resistance.

By integrating conserved defense genes, adaptive variability, and regulatory diversity, comparative genomics provides a foundation for developing resilient crops against evolving pathogens and environmental stress.

Application of Comparative Genomics in Plant Disease Resistance

Comparative genomics has become a central tool in advancing our understanding of plant defense systems. By examining complete genomes across species, it provides insights into gene function, evolutionary dynamics, and strategies for crop improvement. Its applications in plant disease resistance can be broadly categorized as follows:

1. Understanding Regulatory Networks: Comparative genomics helps uncover the complex regulatory systems plants use for defense. This approach reveals how promoters of resistance genes contain elements responsive to stress, hormones, and light, facilitating multi-stress regulation. It also reveals transcription factors like *WRKY*, *ERF*, and *MYB* that, along with hormone signaling pathways (SA, JA, ET, ABA), integrate signals from different stresses to coordinate defense (Nishimura, 2010). By comparing genomes, we can identify these unique regulatory mechanisms that have evolved to counter specific parasitic threats.

2. Identifying Resistance Genes: Comparative genomics helps in the discovery and characterization of resistance (R) genes, especially those from the *NBS-LRR* family. By using homology-based searches, researchers can detect these genes across both well-studied and lesser-known plant species, thereby expanding the pool of genetic resources available for crop protection.

NLR-IDs (NLR proteins with integrated domains) across 40 plant species, revealing a widespread evolutionary strategy where immune receptors are fused with other host proteins to serve as “baits” for pathogen effectors.

3. Understanding Gene Evolution: This approach reveals the evolutionary patterns of R genes, showing how their chromosomal locations remain relatively conserved while their functional roles diversify. Such insights highlight the balance between stability in defense mechanisms and adaptability to new pathogen challenges. For instance, the *NLR*-integrated kinase and *WRKY* domains were found to have evolved independently in several plant lineages, demonstrating that plants share a common mechanism of *NLR* evolution through gene fusions to withstand pathogen pressure.

4. Guiding Breeding Programs: By mapping conserved clusters of resistance genes, comparative genomics provides critical guidance for plant breeding. These insights support the use of marker-assisted selection and related techniques, enabling the efficient transfer of beneficial traits into new cultivars with enhanced disease resistance (Nishimura *et al.*, 2010). This approach, informed by the discovery of new and diverse R-gene architectures, allows breeders to develop plants with enhanced recognition capabilities, making them more resilient to a broader spectrum of pathogens.

5. Elucidating Host-Pathogen Interactions: Genome-wide comparisons allow for the detailed study of plant responses to pathogen attack. This includes the identification of signaling pathways, transcription factors, and molecular regulators that coordinate immune responses, offering a systems-level view of plant defense. For example, studies on different fungal pathogens show that necrotrophs use an extensive arsenal of degrading enzymes and toxins, while biotrophs have a reduced set, reflecting a strategy to keep

the host alive (Wang *et al.*, 2019). Understanding these contrasting strategies through comparative genomics is crucial for developing targeted control methods

6. Enabling Modern Gene Technology: Comparative genomics underpins biotechnological innovations such as genome editing. By pinpointing resistance genes with high precision, it enables targeted modification or introduction of traits, creating crops that are more resilient than those developed through conventional breeding alone. For example, the identification of novel, pathogen-specific genes in nematodes opens the door for using RNA interference (RNAi) to silence these genes, providing a highly specific and environmentally friendly control method. This approach is made possible by the precise, genome-wide data gathered through comparative studies (Grynberg *et al.*, 2020).

7. Revealing Pathogen Genomic Innovations: Beyond plants, comparative genomics sheds light on how pathogens evolve virulence and host specificity. It uncovers genetic changes that drive adaptation, reflecting the ongoing evolutionary “arms race” between host and pathogen. The analysis of plant-parasitic nematode genomes revealed that some of their unique genes were likely acquired through horizontal gene transfer (HGT) from bacteria and fungi, showing how pathogens can rapidly acquire new functions. Similarly, fungal pathogen studies have shown how gene gain and loss events, particularly in necrotrophs, reflect a high level of genomic plasticity that aids their adaptation to different host environments. Such knowledge informs strategies for building durable and sustainable resistance (Grynberg *et al.*, 2020).

Conclusion

Comparative genomics is a crucial tool for understanding and enhancing plant disease resistance, offering insights that bridge evolutionary history with modern agricultural needs. By comparing genomes across various species, this field has revealed that while the location of key resistance (R) genes, such as the *NBS-LRR* family, is often conserved, the specific pathogens they recognize can evolve rapidly. This dual nature of stability in genomic location and dynamism in function provides a roadmap for developing durable resistance strategies. The power of comparative genomics is evident in its ability to identify multi-stress responsive "super genes" and guide modern breeding efforts through techniques like marker-assisted selection and gene editing. Ultimately, this discipline transforms our fundamental understanding of plant immunity into practical, innovative solutions for creating more resilient and productive crops.

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Empowering Cotton Farmers through Digital Innovation: The Role of the Kapas Kisan App in MSP Procurement

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Introduction

Cotton is one of India's most important commercial crops, contributing substantially to rural livelihoods and the national economy. India is a global leader in cotton cultivation, with about 120.55 lakh hectares under the crop. The major producing states are Maharashtra, Gujarat, Telangana, Rajasthan, and Karnataka and they together account for over 80% of the national cotton acreage, reflecting its crucial role in the agricultural landscape.

To ensure that farmers receive a fair and remunerative price, the Government of India announces Minimum Support Price (MSP) for cotton every year. Traditionally, procurement at the Minimum Support Price (MSP) for cotton has been managed through physical registration and manual processes at procurement centres. While this mechanism aimed to ensure price protection, delays in operations and the involvement of intermediaries often limited the timely flow of benefits to farmers (Keller et al., 2024; Abhilasha & Janaiah, 2021).

Recognizing this gap, the Cotton Corporation of India (CCI) under Ministry of Agriculture and Farmers Welfare and Ministry of Textiles launched the Kapas Kisan App on 02.09.2025, marking a significant step toward digitalizing cotton procurement. This initiative is expected to bridge operational inefficiencies and strengthen the MSP ecosystem for cotton growers across the country.

Cotton Scenario in India and Telangana

Cotton is primarily cultivated during the Kharif season, with sowing starting from June and harvest extending from October onwards and gives good yields in black soils. India's cotton production system is characterized by a wide diversity of agro-climatic conditions, yield levels, and farming practices.

The following table provides the details of cotton cultivation in major producing states during 2024–25 season:

S.No.	State	Area (Lakh ha)	Production (Lakh Bales)	Yield (kg/ha)	Source (2024–25)
1	Maharashtra	40.86	89.09	370.66	Committee on Cotton Production and Consumption.
2	Gujarat	23.66	71.34	503.50	
3	Telangana	17.71	49.86	468.04	
4	Rajasthan	6.91	18.45	500.24	
5	M.P.	5.37	15.35	425.98	
	All India	112.76	294.25	443.00	

Source: Committee on Cotton Production and Consumption, 2024-25.

Highlights of Telangana Cotton (2024–25)

1. Total cotton area: 17.71 lakh ha
2. Total production: 49.86 lakh bales
3. MSP procurement: 40 lakh bales, valued at ₹14,800 crore
4. Beneficiaries: 8.5 lakh farmers

Telangana ranks third in India both in terms of acreage and production, underscoring its strategic importance in the country's cotton economy. Efficient MSP operations in such a state can create ripple effects in stabilizing farmer incomes nationally.

Digital Transformation through the Kapas Kisan App

The Kapas Kisan App represents a paradigm shift from conventional procurement systems to a digital, transparent, and farmer-centric model. By allowing farmers to register their produce online, book procurement slots, and receive MSP payments directly into their bank accounts, the app reduces dependency on middlemen and administrative delays.

More importantly, it integrates real-time data on arrivals and procurement volumes, enabling CCI and state agencies to plan logistics, manage capacity, and improve the timeliness of operations.

Objectives of the Kapas Kisan App

1. Digitization of the entire MSP procurement process for cotton.
2. Streamlining farmer registration and allocation of slots to reduce congestion at centers.
3. Ensuring timely payments through direct benefit transfer (DBT).
4. Enhancing transparency and accountability in cotton procurement.
5. Building farmer confidence in the procurement system through user-friendly technology.

Step-by-Step Procurement Process via the App

1. Registration – Farmers enroll using Aadhaar, mobile number, and land record details.
2. Crop Declaration – Enter crop variety, sown area, and expected kapas quantity.
3. Slot Allotment – Procurement centers schedule date and time for delivery.
4. Weighing & Quality Check – Cotton is weighed and tested for quality parameters.
5. Payment – MSP amount is transferred directly to the farmer's bank account.

This structured approach not only reduces waiting time but also ensures accurate record-keeping and better farmer experience at procurement centers.

Benefits to Farmers

1. Timely procurement and MSP payments.
2. Elimination of middlemen and distress sales.
3. Hassle-free digital registration and slot booking.
4. Reduced crowding and better queue management.
5. Transparent transactions and traceable records.
6. Increased confidence in government procurement mechanisms.

MSP for Cotton (₹ Per Quintal)

Commodity	Variety	2023–24	2024–25	Increase (₹)
Cotton	Medium Staple	6620	7121	501
Cotton	Long Staple	7020	7521	501

Source: Directorate of Economics and Statistics (India), 2024

The consistent increase in MSP reflects the government's policy to safeguard farmers against market volatility and encourage crop diversification towards high-value crops like cotton.

Implementation Challenges and Policy Response

Despite its potential, the transition to digital procurement poses several practical challenges:

- a. Limited digital literacy among small and marginal farmers.
- b. Poor or inconsistent internet connectivity in rural areas.
- c. Technical glitches such as server downtime during peak procurement periods.
- d. Difficulties with Aadhaar verification and document compliance.

To overcome these, the Cotton Corporation of India and state governments have initiated:

- a. On-ground training and awareness programmes for farmers.
- b. Establishment of help desks at procurement centers.
- c. Upgrading server infrastructure and app performance.
- d. Strengthening coordination between agencies for faster grievance redressal.

These measures aim to make the Kapas Kisan App not just a tool, but a farmer-friendly service ecosystem.

Conclusion

The Kapas Kisan App marks a transformative step in MSP procurement for cotton, aligning with the broader vision of Digital India and farmer empowerment. By bridging the gap between policy intent and field-level implementation, it improves transparency, ensures timely payments, and strengthens farmer trust in government mechanisms. If scaled effectively, this model can be extended to other MSP crops, thereby improving market access, reducing post-harvest stress, and stabilizing farm incomes. For a state like Telangana—where cotton is a dominant crop the app has the potential to reshape procurement operations and enhance farmer welfare at scale.

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Performance of Different Artificial Light Sources in Enhancing Vegetable Crop Growth

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Grow Lights

Grow lights are artificial light sources specifically engineered to provide the necessary light energy for plants to perform photosynthesis, especially in conditions where natural sunlight is limited or absent. They are essential tools in indoor farming, greenhouses, vertical farming systems and plant research laboratories, allowing plants to grow efficiently throughout the year regardless of outdoor weather or seasonal changes.

The three main types of lights are LED, HID (HPS/MH) and Fluorescent. Each type of grow light has its pros and cons, but when all is said and done, we believe LEDs are the best overall investment for producing high-quality crops for the best cost. As shown below, LEDs typically have a higher initial cost upfront, but you save on the long-term operating costs. However, direct-to-consumer model, we offer top-quality LEDs for nearly half the cost of competing LED lights. So, the time to recoup your initial investment in LEDs is much shorter (Zakurin *et al*, 2020).

HID is a kind of bulb that passes electricity through a gas-filled tube. HID remains a popular choice for novice growers, whether it is HPS or MH, because of their low setup cost.

Three types of HID grow lights are used in indoor growing – High-Pressure Sodium (HPS), Metal Halide (MH) and Ceramic Metal Halide CMH.

HPS

HPS emits light strongly at red and orange end of the light spectrum, which is more suited to plants' flowering stage.



MH

MH is often used in the vegetative phase of plants because it gives more blue light range of the spectrum.

CMH

Ceramic Metal Halide or also called Light Emitting Ceramic (LEC) uses a ceramic arc tube just like HPSs. CMH is probably a combination of HPS and MH, so CMH has a broader light spectrum range, making it a great single light solution.

However, though CMH is more efficient than regular MH lights, it does not give more lights in the red spectrum than HPS. As a result, CMH cannot beat HPS when it comes to the flowering stage of the plants and it is still not proven if using a single broader PAR light spectrum will be a more efficient solution in terms of cost, crop yields, convenience than a combination of different plants (Mills *et al*, 2016).

HID Grow Light Tips

You can use three kinds of lights (HPS MH and CMH) for a full growing phase from the beginning to the harvest, but it is not strongly recommended. Normally start with MH or CMH during the vegetative phase. Then move to HPS during the flowering stage. That would mean if you intend to use HID's, you should purchase one MH and one HPS bulb type separately because HPS igniter does not fit to MH and conversely. However, you can consider getting a conversion bulb, which let you run HPS bulbs on an MH ballast or an MH bulb on an HPS ballast.

1. Relatively cheap
2. Stable and quality yields have been proven over the past.
3. Easy to use and consistent models across suppliers. Unlike LEDs, you have to check what spectrum, the positioning and what model types suited for plants.
4. Require ballast and reflector.
5. Short life span.

Fluorescent

Like its name, a fluorescent bulb or tube uses fluorescent to give visible light. It works by passing electrodes positioned on both ends of the bulb. As the electric current moves, the mercury inside the bulb takes up energy and produces a short-wave light that causes a phosphor coating inside of the lamp to glow. Fluorescent lights do not emit as much light as HID's. so, they are often used for seed starting, rooting cuttings and early to mid-stage plant vegetative phase.

Two common types of fluorescent lights used for indoor plants are tube-style lights and compact fluorescent lights (CFL).

Tube-Style Fluorescent Light

There are many forms of tube-style fluorescent light forms, namely the T5, T8 and T12. Among them, the most popular and efficient for growing indoors is the T5.

The T5 for growing usually comes with multiple bulbs arranged parallel to each other in a panel. The T5 emits less power than HID's, so it's much cooler in temperature and can be kept closer to plants.

CFL (Compact Fluorescent Lamp)



CFLs are the short twisty bulbs, which are commonly seen in every house. When CFLs were invented, they replaced the old incandescent light bulbs because of their long-life expectancy and efficiency.

These are my sizes and colours of CFLs that can be used for both daily activities and for growing from 12 watts to as much as 250W.

1. Relatively cheap.
2. Running cool and can be placed near plants. Cons:
3. Not as strong for Flowering as HID's (HPS)

4. Short life span (around 10,000 hours of use)
5. Require ballast and reflector.

Fluorescent Grow Light Tips

Fluorescent lights are an efficient cost-saving solution for beginners and are great supplementary bulbs for experienced growers. They are an excellent option for young plants, clones and the vegetative growth phase of plants because the lights are not as strong as HPS or LED high-power lights.

So that means you use fluorescent bulbs for all grow phases if your set-ups are small. But if you want a better approach when plants come to the flowering phase, it's better to go with HPS or LED grow lights which bring much higher yields (Pratama *et al.*, 2020).

LED (Light Emitting Diode)



LED came to the market later compared to other lighting types. It was met with skepticism by home users and as well as growers initially. However, LEDs soon prove its worth by performing efficiently and displaying some discernible unique advantages that other grow light types cannot have. Led grow lights are in popular use nowadays either by hobby growers and commercial greenhouse farm. This is because LEDs are energy-efficient, don't give off much heat and don't require much maintenance. People can customize the LEDs to emit a specific light wavelength they want (Zareie *et al.*, 2020).

1. LEDs usually come with a built-in cooling system that helps regulate heat around plants, so no bother for ventilation and frequent checking for growers.
2. Little heating was given off. You can place the LEDs close to plants, which grants you great versatility.
3. Better lifespan. LEDs have an average of 50,000 hours of lighting that can last up to 15 years as compared to 10,000 hours of HPs.
4. High initial set-up expense. But in the long run, LEDs do not cost more because of its efficient performance.
5. LEDs need spaces from the plants. Even though the temperature is cool, plants can be burned with too much light.
6. Environment temperature vulnerability. This only happens to places where the temperature is very high (like processing mills). The diodes of LEDs lights will depend on the ambient surrounding temperature for its performance. Too hot and the LED module can burn out.

LED Lighting Technology Advancements

- 1. Increased Energy Efficiency:** The future of lighting in agriculture lies in even more energy-efficient LEDs. As LED technology advances, their energy consumption will continue to decrease while improving light output. This will make it possible for growers to reduce costs while increasing yields.
- 2. Customizable Spectrums:** One of the most significant developments is the ability to customize light spectra to meet the specific needs of plants at different growth stages. By using more sophisticated **smart LEDs** with adjustable spectra, growers can optimize the light for various phases such as seedling,

vegetative growth, and flowering. This precision in light spectrum can lead to more efficient growth and higher yields.

3. Integration of UV and Infrared Light: Future LEDs will likely include a broader spectrum, including UV (ultraviolet) and infrared light. UV light can help stimulate the production of antioxidants and secondary metabolites in vegetables, enhancing their nutritional value and resistance to pests. Infrared light could be used to enhance root growth and overall plant vigour.

Effect of Light on the Growth of Vegetables

Plant	Radiation source	Effect on plant physiology
Cabbage (<i>Brassica oleracea</i> var. <i>capitata</i> L.)	Red (660 nm) LEDs	Increased anthocyanin content
Baby leaf lettuce (<i>Lactuca sativa</i> L. cv. Red Cross)	Red (658 nm) LEDs	Phenolic concentration increased by 6%
Kale plants (<i>Brassica oleracea</i> L. cv. Winterbor)	Red (640 nm) LEDs (With cool-white light fluorescent lamp)	Lutein and chlorophyll a,b accumulation increased
Tomato (<i>Lycopersicon esculentum</i> L. cv. Momotaro Natsumi)	Red (660 nm) LEDs	Increased tomato yield
Cherry tomato Seedling	Blue LEDs with red and green LEDs, total PPF of 300 $\mu\text{mol m}^{-2} \text{S}^{-1}$.	Net photosynthesis and stomatal number per mm^2 increased.
Cucumber (<i>Cucumis sativus</i>) and tomato (<i>Lycopersicon esculentum</i>)	Blue (455 nm, 7-16 $\mu\text{mol m}^{-2} \text{S}^{-1}$) LEDs and HPS (400-520 $\mu\text{mol m}^{-2} \text{S}^{-1}$)	LED light with HPS increased total Biomass.
Spinach (<i>Spinacia oleracea</i>), Green onions (<i>Allium cepa</i>)	Red (638 nm) LEDs with HPS lamp (90 $\mu\text{mol m}^{-2} \text{S}^{-1}$)	Increased vitamin C content in spinach and green onions.
Transplant of cucumber 'Mandy F1'	Green (505 and 530 nm, 15 $\mu\text{mol m}^{-2} \text{S}^{-1}$) LEDs with HPS lam (90 $\mu\text{mol m}^{-2} \text{S}^{-1}$)	505 and 530 nm resulted in increased leaf area, fresh and dry weight.
Red lettuce 'Outeredgeous' (<i>Lactuca sativa</i> L.)	Red (640 nm, 270 $\mu\text{mol m}^{-2} \text{S}^{-1}$) LEDs with blue (440 nm, 30 $\mu\text{mol m}^{-2} \text{S}^{-1}$) LEDs	Anthocyanin content, antioxidant potential and total leaf area increased.

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Humus: The Cornerstone of Soil Fertility and Sustainable Agriculture

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Abstract

Soil fertility is the foundation of productive agriculture and among the various components that contribute to it, humus plays a central and irreplaceable role. Humus is the stable, dark and colloidal organic matter that results from the decomposition of plant and animal residues in the soil. It not only enhances soil structure, water retention and nutrient availability but also fosters a thriving microbial ecosystem essential for plant growth. The importance of humus extends beyond fertility-it improves soil aeration, prevents erosion, buffers pH and sequesters carbon, contributing to climate resilience. However, humus formation is a slow process and faces modern challenges such as intensive agriculture, deforestation, overuse of chemical fertilizers and declining organic matter inputs. Significance of humus in maintaining soil fertility, including its benefits, factors affecting its formation, limitations and management practices to enhance humus content for sustainable agricultural productivity, particularly under Indian conditions.

Keywords: Humus, Soil fertility, soil structure, nutrients availability.

Introduction

Healthy soil is the lifeblood of agriculture, and its fertility determines the productivity and sustainability of farming systems. Fertile soil is characterized by its ability to supply essential nutrients to plants, retain moisture and support biological activity. Among the multiple components that determine soil fertility-minerals, water, air and organic matter-humus stands as one of the most vital. Humus represents the final stage of decomposition of organic matter and plays a pivotal role in maintaining soil structure, fertility and long-term productivity. It acts as a reservoir of nutrients, improves soil physical properties and supports beneficial microorganisms essential for nutrient cycling. However, the modern shift toward intensive farming, reduced organic recycling and heavy reliance on chemical fertilizers has led to declining humus levels in soils worldwide, particularly in tropical regions like India.

Understanding the functions, benefits and challenges of humus management is critical for developing sustainable agricultural systems that ensure productivity without compromising soil health.

What is Humus?

Humus is the stable, amorphous, dark-colored organic material that forms in soil from the decomposition of plant and animal residues. It represents the most advanced stage of organic matter transformation, where the original biological materials are no longer recognizable.

Unlike fresh organic matter, humus is resistant to further decomposition and can persist in the soil for decades or even centuries. It is composed of complex carbon compounds, including humic acids, fulvic acids and humin -collectively known as humic substances. These compounds are critical in binding nutrients, improving soil structure and regulating microbial activity.

In short, humus serves as the heart of the soil ecosystem, connecting biological, chemical and physical components in a balanced cycle that supports plant life.

1. Formation of Humus: The process of humus formation, called humification, occurs through the decomposition and transformation of organic residues under the influence of microorganisms such as bacteria, fungi and actinomycetes. The stages include:

a. Decomposition of Organic Residues: Plant and animal materials undergo breakdown into simpler organic compounds through microbial action.

b. Transformation and Synthesis: Intermediate products like amino acids, sugars and lignin derivatives recombine chemically and biologically to form complex humic substances.

c. Stabilization: The final stable material-humus-is formed, which is resistant to further microbial attack.

The humification process depends on multiple factors, including the type of organic matter, soil texture, climate, microbial activity and management practices.

2. Composition and Characteristics of Humus: Humus is not a uniform material; it consists of several components:

a. Humic Acid: Dark brown to black, soluble in alkali but insoluble in acid. It helps bind soil particles and retain nutrients.

b. Fulvic Acid: Yellow to brown, soluble in both acid and alkali, more mobile in soil and helps in nutrient transport.

c. Humin acid: The most resistant fraction, insoluble in both acid and alkali, contributes to long-term carbon storage.

Physical and Chemical Properties:

- i. High cation exchange capacity (CEC) allowing it to hold and release essential nutrients like potassium, calcium and magnesium.
- ii. High water-holding capacity due to its colloidal nature.
- iii. Buffering capacity stabilizing soil pH.
- iv. Dark color helps warm soil quickly in cooler seasons.
- v. Biological stability resistant to microbial decomposition.

3. Role of Humus in Soil Fertility: Humus contributes to all aspects of soil fertility physical, chemical and biological.

a. Physical Fertility: Humus improves soil structure by binding soil particles into aggregates, enhancing aeration, root penetration and water infiltration. It also reduces compaction and erosion.

b. Chemical Fertility: Humus acts as a natural chelator, holding nutrients in an available form for plants. It buffers soil pH and increases cation exchange capacity, which enhances nutrient availability and prevents leaching.

c. Biological Fertility: Humus supports a diverse microbial community, including nitrogen-fixing bacteria, mycorrhizal fungi and decomposers. These organisms play key roles in nutrient cycling and disease suppression.

4. Benefits of Humus in Agricultural Systems: The benefits of humus in soil fertility and crop productivity are multifaceted:

a. Enhances Nutrient Availability: Humus stores and slowly releases essential nutrients such as nitrogen (N), phosphorus (P), sulphur (S) and micronutrients, making them available to plants over time.

b. Improves Soil Structure: The binding effect of humus creates granular structure, improving porosity and preventing crusting and compaction.

c. Increases Water Retention: Humus can hold up to 90% of its weight in water, which improves drought resistance and reduces irrigation needs.

d. Promotes Microbial Activity: It provides a habitat and energy source for beneficial microorganisms, which in turn promote decomposition and nutrient cycling.

e. Enhances Root Growth: By improving aeration and moisture balance, humus creates favourable conditions for deeper and healthier root systems.

f. Buffers Soil pH: Humus helps neutralize acidic or alkaline conditions, providing a stable environment for plant growth.

g. Reduces Nutrient Leaching: Humus holds cations (K^+ , Ca^{2+} , Mg^{2+}) and anions (NO_3^- , PO_4^{3-}), preventing their loss through percolation.

i. Prevents Soil Erosion: By improving structure and cohesion, humus minimizes runoff and soil loss.

j. Increases Carbon Sequestration: Humus acts as a stable carbon sink, mitigating greenhouse gas emissions and contributing to climate change adaptation.

k. Enhances Crop Yields: Soils rich in humus typically produce higher and more consistent yields, as plants experience better nutrition and reduced stress.

5. Mechanisms of Action: How Humus Works in Soil: Humus affects soil properties through various mechanisms:

a. Adsorption of Nutrients: The negative charges on humus molecules attract and hold positively charged ions (E.g., K^+ , Ca^{2+}).

b. Formation of Complexes: Humus forms organo-mineral complexes, stabilizing nutrients and reducing fixation (Especially phosphorus).

c. Microbial Interactions: Humus provides carbon sources for microorganisms that release plant-available nutrients during decomposition.

d. Improved Soil Porosity: The glue-like property of humus binds soil particles into aggregates that allow better aeration and infiltration.

6. Factors Influencing Humus Formation and Stability: Humus formation is influenced by several environmental and management factors:

a. Climate: Warm, humid climates accelerate organic matter decomposition, reducing humus accumulation, while cooler regions favour its buildup.

b. Soil Type: Clay soils protect organic matter from decomposition better than sandy soils due to higher aggregation and surface area.

c. Vegetation: Leafy, deep-rooted plants contribute more residues that promote humus formation compared to shallow-rooted crops.

d. Microbial Activity: Bacteria and fungi are key agents in humification; their population depends on soil temperature, moisture, and organic input.

e. Land Management: Practices such as organic manure addition, reduced tillage and crop rotation enhance humus formation.

f. Fertilizer Use: Excessive use of chemical fertilizers without organic amendments can reduce soil microbial diversity and hinder humus formation.

g. Irrigation and Drainage: Proper moisture levels favour decomposition and stabilization; waterlogging or drought impedes humification.

7. Limitations and Challenges Related to Humus Maintenance: Despite its importance, maintaining adequate humus levels poses several challenges:

a. Slow Formation Rate: Natural humus formation is gradual, often taking years to accumulate significant levels.

b. Rapid Decomposition in Tropics: High temperatures and microbial activity in tropical regions (like India) accelerate decomposition.

c. Decline of Organic Matter Inputs: Modern agriculture often removes crop residues or burns them, reducing organic inputs essential for humus formation.

d. Overuse of Chemical Fertilizers: Continuous use of synthetic fertilizers diminishes soil biota and reduces organic carbon levels.

e. Soil Erosion and Land Degradation: Loss of topsoil leads to depletion of humus-rich layers.

f. Urbanization and Deforestation: Conversion of agricultural lands to non-agricultural use reduces organic matter recycling.

g. Water and Climate Stress: Erratic rainfall, floods and droughts disrupt organic matter decomposition and stabilization.

8. Management Strategies to Enhance Humus in Soil: Building and maintaining humus levels require systematic management approaches integrating organic recycling, conservation and biological enhancement.

a. Addition of Organic Manures: Farmyard manure, compost and green manures are direct sources of humus-forming materials.

b. Crop Residue Management: Instead of burning residues, farmers should incorporate them into the soil to enhance organic matter.

c. Cover Cropping: Leguminous cover crops improve nitrogen content and provide biomass that decomposes into humus.

d. Reduced or Zero Tillage: Minimizing soil disturbance reduces decomposition rates and helps accumulate organic matter.

e. Integrated Nutrient Management (INM): Combining organic and inorganic fertilizers supports balanced nutrient cycling and humus stability.

f. Biochar Application: Biochar improves carbon sequestration, soil structure and microbial habitat, complementing humus formation.

g. Agroforestry and Organic Farming: Trees, shrubs and perennial vegetation continuously add organic residues to the soil.

h. Mulching: Organic mulch reduces evaporation, moderates temperature and adds humus upon decomposition.

i. Composting: Proper composting of waste materials accelerates humus-like material formation before field application.

j. Vermicomposting: Earthworms enhance humification by breaking down organic materials and improving nutrient availability.

9. Importance of Humus under Indian Agricultural Conditions: In India, where soils often suffer from low organic carbon (<0.5%), maintaining humus is essential for sustainable farming. The tropical climate promotes rapid organic matter breakdown, making continuous replenishment necessary.

a. Soil Health Restoration: Indian soils, particularly in rainfed and dryland areas, are degraded and need organic amendments to restore fertility.

b. Nutrient Efficiency: In regions with declining fertilizer response ratios, humus improves nutrient use efficiency and reduces input costs.

c. Water Management: Humus-rich soils hold more moisture, vital for drought-prone areas in central and western India.

d. Carbon Sequestration: Increasing humus supports India's commitment to climate-smart agriculture and carbon neutrality.

e. Smallholder Livelihoods: Building humus through low-cost organic resources aligns with resource-poor farmers' needs.

10. Future Perspectives and Research Needs: The growing concern about soil degradation demands focused research on humus management and enhancement strategies. Future directions include:

a. Advanced Carbon Monitoring: Using digital soil mapping and remote sensing to track humus dynamics.

b. Microbial and Enzymatic Studies: Understanding microbial communities that drive humification processes.

c. Climate-Specific Strategies: Developing region-specific models to manage humus under varying agroclimatic zones.

d. Integration with Climate Policy: Linking humus enhancement to carbon credit schemes and sustainable farming incentives.

e. Farmer Education: Promoting awareness and training on the benefits of organic matter recycling.

Conclusion

Humus is the soul of fertile soil. It binds together the physical, chemical and biological processes that sustain plant life and ensure agricultural productivity. Despite its slow formation, humus provides long-term benefits that far outweigh the efforts required to maintain it. In the face of declining soil health, intensive farming and climate change, integrating humus-building practices into agricultural systems is not merely beneficial-it is essential.

In Indian agriculture, where soil organic matter depletion threatens productivity, enhancing humus through organic recycling, green manuring, composting and reduced tillage can transform degraded lands into resilient, fertile ecosystems. Sustainable soil management centered on humus conservation will secure the future of farming, food security and environmental sustainability.

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Biochar: A Sustainable Soil Amendment for Climate-Resilient Agriculture in India

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Abstract

Biochar, a stable carbon-rich material produced from the pyrolysis of biomass, has emerged as a promising solution for enhancing soil fertility, sequestering carbon and mitigating climate change. Its potential in the Indian context is particularly significant, where soil degradation, low organic matter and erratic rainfall patterns challenge sustainable crop production. Biochar improves soil physical, chemical and biological properties, increases nutrient retention and enhances microbial activity. Moreover, it plays a crucial role in carbon sequestration, thereby reducing greenhouse gas emissions. The concept, production techniques, characteristics, soil interactions, benefits and challenges associated with biochar use in Indian agriculture. The integration of biochar into traditional and modern farming systems could be a transformative step toward achieving sustainable and climate-smart agriculture in India.

Keywords: Biochar, carbon sequestration, nutrient retention and microbial activity.

Introduction

India's agricultural system is under tremendous pressure due to rapid population growth, soil degradation and the increasing impacts of climate change. According to estimates, nearly 120 million hectares of land in India are degraded, with declining soil fertility and organic carbon content being the primary concerns. Continuous mono cropping, overuse of chemical fertilizers and poor residue management practices have further worsened soil health. In such a scenario, biochar offers a sustainable and eco-friendly solution. Biochar is a fine-grained, porous form of charcoal produced through the pyrolysis (Heating in absence or limited presence of oxygen) of organic materials such as crop residues, animal manure, wood chips or other biomass sources. When added to soil, it acts as a long-term carbon sink and improves soil structure, nutrient retention and microbial diversity.

The traditional Indian practice of using charcoal and ash in soils, known locally in some regions as “**Kala Mitti**” mirrors the ancient concept of biochar. However, the modern scientific understanding of biochar allows for more precise control over its properties and applications. Given India's vast agricultural residue potential estimated at 500-550 million tonnes annually the conversion of a portion of this biomass into biochar could serve as a dual solution for waste management and soil rejuvenation.

What is Biochar?

Biochar is a carbon-rich, porous solid obtained when biomass is thermos chemically converted under limited oxygen conditions. The process involves temperatures between 300°C and 700°C, depending on the desired properties.

Chemical Composition

Typical biochar consists of:

- Carbon (C): 60-90%
- Hydrogen (H): 1-4%
- Oxygen (O): 5-30%
- Ash (minerals): 2-15%

The C:H and C:O ratios are indicators of aromaticity and stability - higher ratios imply greater carbon stability in soil.

Types of Biochar Feedstock

Biochar can be produced from various biomass sources:

- 1. Agricultural residues:** Rice husk, sugarcane bagasse, cotton stalk, maize cobs, groundnut shells
- 2. Forestry waste:** Wood chips, sawdust
- 3. Animal waste:** Poultry litter, cow dung
- 4. Urban organic waste:** Food waste, sewage sludge (carefully treated)

Each feedstock produces biochar with unique physical and chemical characteristics.

Production of Biochar

Pyrolysis Process: The pyrolysis process involves thermal decomposition of biomass under oxygen-limited conditions. It can be classified into:

Sr. No	Type	Temperature	Residence Time	Major Products
1	Slow Pyrolysis	300-500 ^o C	Hours	Biochar (70%), Less char
2	Fast Pyrolysis	500-700 ^o C	Second	Bio-oil, gas and less char
3	Gasification	>700 ^o C	Short	Syngas, minimal biochar

For soil application, slow pyrolysis is preferred due to higher char yield and better stability.

Small-Scale Rural Units in India: In India, simple low-cost pyrolyzers such as drum kilns, pit kilns and top-lit updraft stoves are being promoted for village-level production.

Example: The Indian Institute of Soil Science (IISS), Bhopal and Central Institute of Agricultural Engineering (CIAE) have developed low-cost biochar reactors suitable for rural communities.

Properties of Biochar

The properties of biochar vary depending on:

1. Feedstock type
2. Pyrolysis temperature
3. Residence time
4. Cooling and storage conditions.

Physical Properties:

- a. Porous structure increases surface area (50-400 m²/g)
- b. High water-holding capacity
- c. Improves soil aeration and aggregation

Chemical Properties:

- a. High cation exchange capacity (CEC)
- b. Neutral to slightly alkaline pH (6.5-9.0)
- c. Contains nutrients such as K, Ca, Mg, P
- d. High carbon stability (Resistant to microbial decomposition)

Biological Properties:

- a. Supports beneficial microbes like rhizobacteria and mycorrhizae.
- b. Reduces harmful pathogens by adsorption or habitat competition.

Benefits of Biochar in Indian Agriculture

Biochar offers a wide range of agronomic, environmental and socio-economic benefits, especially under Indian soil and climate conditions.

1. Soil Fertility Enhancement:

- a. Increases soil organic carbon content, a key indicator of soil health.
- b. Improves CEC, allowing better nutrient retention (Especially nitrogen, potassium, calcium and magnesium).
- c. Enhances availability of phosphorus by reducing its fixation in acidic and alkaline soils.

2. Improved Water Retention: In arid and semi-arid regions like Rajasthan, Gujarat and Bundelkhand, biochar-amended soils exhibit 20-40% higher water-holding capacity, making crops more resilient to drought.

3. Enhanced Microbial Activity: Biochar provides microhabitats for soil microbes. Studies show higher microbial biomass and enzymatic activity, promoting nutrient cycling and plant growth.

4. Reduction in Fertilizer Requirement: By increasing nutrient-use efficiency, biochar reduces dependency on costly chemical fertilizers supporting low-input sustainable farming.

5. Carbon Sequestration: One of the most significant benefits is its long-term carbon sequestration potential. Biochar can lock carbon in the soil for hundreds to thousands of years, helping India meet its climate commitments under the Paris Agreement.

6. Waste Management: India generates massive quantities of crop residues (E.g., rice straw, sugarcane trash) that are often burned, leading to air pollution. Converting this biomass into biochar prevents residue burning and turns waste into a resource.

7. Mitigation of Greenhouse Gas Emissions: Biochar reduces N_2O and CH_4 emissions from agricultural soils by modifying microbial activity and improving aeration.

8. Improved Crop Yield: Field trials in India have demonstrated yield increases in rice, wheat, maize and vegetables ranging from 10-25% depending on soil and crop type.

Factors Influencing Biochar Efficiency

The performance of biochar in soil depends on several interrelated factors: Feedstock Type Different raw materials produce biochar with varying nutrient profiles.

1. Wood-based biochar: High carbon, low nutrients.

2. Manure-based biochar: Rich in nitrogen and phosphorus.

Pyrolysis Temperature:

a. Low temperature (300–400°C): High nutrient retention but less stable carbon.

b. High temperature (600–700°C): High carbon stability, lower nutrient content.

Soil Type:

a. In acidic soils, biochar raises pH and improves base saturation.

b. In alkaline soils, it may slightly reduce sodium toxicity.

c. In sandy soils, it improves water retention.

d. In clayey soils, it enhances porosity and drainage.

Application Rate: Optimum rates vary between 5 to 20 tonnes per hectare, depending on soil condition, crop type and biochar quality.

Combination with Organic and Inorganic Input: Maximum benefit is achieved when biochar is combined with farmyard manure (FYM), compost or bio-fertilizers promoting synergistic effects.

Reaction Mechanisms of Biochar in Soil

Physical Interactions: Biochar's porous structure improves soil aeration, bulk density and water-holding capacity. It acts as a "soil sponge," holding water and nutrients that are slowly released to plant roots.

Chemical Reactions:

a. Cation exchange: Negatively charged surfaces retain nutrients like NH_4^+ , K^+ and Ca^{2+} .

b. Adsorption: Biochar adsorbs organic and inorganic pollutants.

c. Buffering capacity: Helps maintain pH stability in acidic or alkaline soils.

Biological Reactions: Biochar stimulates beneficial microbial communities such as *Azospirillum*, *Rhizobium* and Mycorrhizal fungi. It also suppresses soil-borne pathogens by improving microbial balance.

Nutrient Cycling: Biochar interacts with soil minerals and organic matter, slowing down nutrient leaching and promoting gradual release especially of nitrogen and phosphorus.

Biochar Application Techniques

1. Broadcasting and Incorporation: Mixing biochar into the top 10-15 cm soil layer before sowing.

- 2. Band Placement:** Applying along crop rows to improve nutrient use.
- 3. Compost Integration:** Mixing biochar with compost during decomposition enhances compost quality.
- 4. Seedling Nursery Mix:** Using biochar as part of potting media for vegetables and nurseries.
- 5. Foliar or Liquid Biochar Extracts:** Emerging techniques using biochar leachate for plant growth promotion.

Challenges and Limitations

Despite its potential, several challenges hinder large-scale adoption:

1. High production cost of quality biochar.
2. Lack of awareness among farmers and extension agencies.
3. Limited research on region-specific biochar recommendations.
4. Unregulated market for biochar products.
5. Energy demand for pyrolysis units in rural settings.
6. Variability in feedstock and quality, leading to inconsistent results.

Environmental and Climate Change Implications

1. Biochar contributes to carbon-negative agriculture.
2. Reduces soil erosion and nutrient leaching, protecting groundwater.
3. Enhances biodiversity by supporting microbial habitats.
4. Reduces air pollution by avoiding residue burning.

According to global studies, applying biochar on just 10% of India's crop land could sequester up to 50-60 million tonnes of CO₂ annually.

Economic Feasibility in Indian Context

Economic analysis indicates that biochar application (10 t/ha) can yield a benefit-cost ratio (B:C) of 1.5-2.0, depending on crop type and local material availability.

When produced locally using agricultural residues, the cost of biochar production ranges between Rs. 5,000-Rs. 8,000 per tonne, which can be reduced further through community-level kilns.

The co-benefits such as waste management, carbon credits and increased yields make it a profitable long-term investment.

Integration with Natural Farming and Organic Agriculture

Biochar aligns perfectly with Bharatiya Prakritik Krishi Paddhati (BPKP) under Paramparagat Krishi Vikas Yojana (PKVY). Its use complements Jeevamrut, Ghanjeevamrut, and cow-based bio-inputs, enhancing microbial proliferation and soil vitality. Thus, biochar can become a critical component in India's natural farming revolution.

Future Prospects and Research Needs

- 1. Standardization:** Develop Indian standards for biochar quality (pH, CEC, PAH content, etc.).
- 2. Field Validation:** Multi-location trials across agro-climatic zones.
- 3. Integration Models:** Combine biochar with compost, biogas slurry, or nanofertilizers.
- 4. Policy Support:** Incentives for farmers using residue for biochar instead of burning.
- 5. Carbon Credit Mechanism:** Recognize biochar under carbon trading schemes.
- 6. Capacity Building:** Training farmers and entrepreneurs in biochar production and use.

Research institutions like ICAR, IISS, CFRI and IITs are already exploring advanced pyrolysis systems and biochar-blended fertilizers.

Conclusion

Biochar represents an innovative, nature-based solution for addressing India's agricultural and environmental challenges. By improving soil fertility, conserving water and locking atmospheric carbon into the soil, it offers a pathway toward climate-resilient and sustainable farming. For India, where millions of farmers depend on soil health for their livelihood, biochar provides a bridge between traditional ecological

wisdom and modern sustainable technology. Its adoption can transform degraded soils into fertile, productive lands, reduce greenhouse gas emissions and enhance food security. To realize its full potential, biochar must be mainstreamed into national agricultural policies, supported through research and extension and adopted by farmers with adequate training and incentives. In the long run, biochar is not just a soil amendment-it is a soil revolution for sustainable India.

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The Role of AI in Fisheries: A Boon or Ban

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Introduction

In recent years, the integration of Artificial Intelligence (AI) in the fisheries industry offers a transformative approach to data collection, analysis, and decision-making. AI-powered sensors and drones can gather vast amounts of data on fish populations, habitats, and fishing activities, providing insights into abundance, distribution, size, species, water temperature, salinity, pH, and other environmental factors. Machine learning algorithms can then analyse this data to identify patterns and trends, inform better fisheries management decisions, develop predictive models for fish stock assessments and forecasting, and enhance our understanding of the impacts of climate change on fisheries.

Furthermore, AI-powered systems can monitor fishing activities in real-time using satellite imaging, vessel tracking, underwater sensors, and cameras, enabling authorities to detect and prevent illegal fishing practices, monitor compliance with fisheries regulations, respond quickly to suspicious activity, and enforce penalties. This leads to a reduction in the risk of depletion of fish stocks and protection of the marine ecosystem.

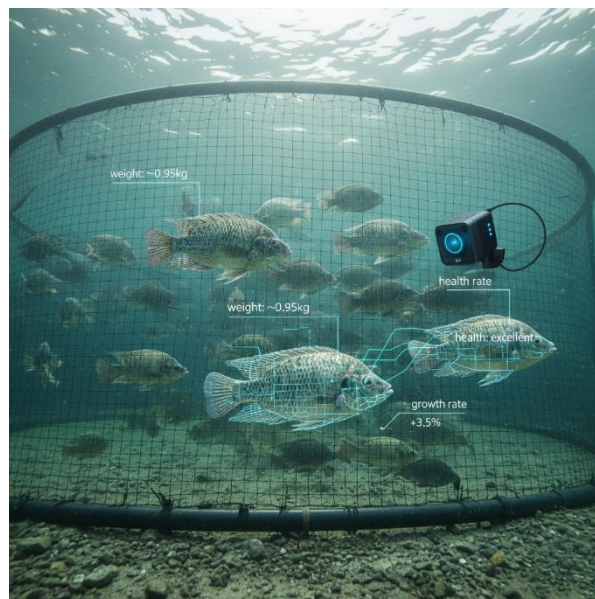


Figure 1: Advanced sensor technology and AI analytics optimizing modern fish farm operations

The Promise of AI in Fisheries

1. Enhanced Monitoring and Data Collection: One of the most significant contributions of AI to fisheries is in the realm of monitoring and data collection. Traditional methods of tracking fish populations and fishing activities have been labor-intensive and often inaccurate. AI-powered systems, including computer vision and machine learning algorithms, can analyze satellite imagery, sonar data, and video feeds from onboard cameras to provide real-time information on fish stocks, vessel movements, and fishing practices.

These technologies enable more accurate fish counting, species identification, and size estimation. For instance, AI can process underwater camera footage to identify and count fish with greater precision than human observers. This wealth of data helps fisheries managers make more informed decisions about quotas, fishing seasons, and protected areas.

2. Predictive Analytics for Sustainable Fishing: AI's ability to process vast amounts of data and identify patterns makes it an invaluable tool for predictive analytics in fisheries. By analyzing historical data on fish populations, ocean conditions, and climate patterns, AI models can forecast fish migration routes, optimal fishing locations, and potential changes in fish stocks due to environmental factors.

This predictive capability allows fishing fleets to operate more efficiently, reducing fuel consumption and minimizing bycatch. It also aids in the implementation of dynamic ocean management, where protected areas can be adjusted in real-time based on the movement of endangered species or sensitive habitats.

3. Improving Catch Quality and Reducing Waste: AI technologies are being employed to improve the quality of caught fish and reduce waste in the supply chain. Smart sensors and AI algorithms can monitor storage conditions on fishing vessels, ensuring optimal temperature and humidity levels to maintain fish freshness. In processing plants, AI-powered sorting systems can quickly grade fish based on quality, size, and species, improving efficiency and reducing human error.

Moreover, AI can help in predicting market demand and optimizing distribution routes, ensuring that fish reaches consumers in the best possible condition and reducing food waste.

4. Combating Illegal, Unreported, and Unregulated (IUU) Fishing: IUU fishing is a major threat to marine ecosystems and the sustainability of fisheries worldwide. AI is proving to be a powerful ally in the fight against these illegal practices. Machine learning algorithms can analyze vessel movement patterns to identify suspicious behaviour indicative of illegal fishing. Satellite imagery processed by AI can detect dark vessels (those with their tracking systems turned off) operating in restricted areas.

These technologies enhance the capabilities of enforcement agencies, allowing them to monitor vast ocean areas more effectively and target their limited resources on high-risk activities. AI is transforming the fisheries sector by providing innovative solutions to various challenges that are mentioned in the table below:

AI technology in the fisheries sector	Uses
Water Quality Management	AI systems monitor and analyze water quality parameters, ensuring optimal conditions for fish health and growth
Fish Health Monitoring	Computer vision and AI detect signs of disease or stress in fish populations, enabling early intervention and treatment.
Automated Sorting and Processing	AI-powered machines sort and process fish by species and size, improving efficiency and product quality.
Robotic Cleaning and Maintenance	AI-driven robots clean tanks and nets, reducing labor costs and maintaining optimal living conditions for fish.
Market Demand Forecasting	AI models analyze market trends and consumer behaviour to forecast demand, aiding in inventory management and pricing strategies.
Fish Population Monitoring	AI algorithms analyze data from SONAR, satellite imagery, and drones to monitor fish populations and their movements, aiding in sustainable management.
Predictive Analytics for Fish Migration	AI models predict fish migration patterns based on environmental data, helping fishermen optimize their efforts and reduce fuel consumption.
Sustainable Fishing Practices	AI systems provide accurate data on fish stocks and environmental conditions, to support sustainable fishing practices, reducing overfishing and promoting conservation.

A summary of key research findings related to Artificial Intelligence (AI) in aquaculture is mentioned in the table below:

Area of Research	Outcome	Reference
AI in aquaculture	Effectiveness in traceability, feeding, disease detection, growth prediction, environmental	Mustapha et al., 2021

	monitoring, market information, and others is key to increasing aquaculture productivity and sustainability.	
Mortality detection	Mortality alert is produced by AI techniques to supply information about the number of dead fish and the date/time of the death.	Bochkovski et al., 2020; Glenn, 2020
AI based fish production, management, and harvest	Camera programmed to get high resolution images which are manually annotated into live and dead objects and merged to generate datasets for statistical analysis.	Ranjan et al., 2023
Farm management	Data on fish length, body breadth, temperature, and frequency of feeding are used in fish condition management to estimate weight, oxygen consumption, and feeding.	Yu et al., 2022; Lin et al., 2022
Water quality detection	A mixture of a network of sensors and automated control mechanisms is adopted for continuous, real-time monitoring of critical water quality.	Jie et al., 2019; Mayormonte, 2024
Environment condition management	AI based temporal correlation of water quality data	Chen et al., 2022; Ahmadzadeh et al., 2022
AI based monitoring of fish growth	Accurate tracking for analysing fish growth performance is done	Chen et al., 2023
AI based disease detection	Covers periodical optical monitoring of the fishes in the farm, detecting the onset of any disease, with a minimum time lag.	Darapane ni et al., 2022
Intelligent feeding technique	To calculate the shrimp biomass and determine the appropriate feeding amount by reading the sensors in real time.	Chen et al., 2022
Intelligent feeding	Intelligent equipment can replace people, reduce labour intensity, reduce risk, and improve work efficiency.	Wu et al., 2022
Internet of Things (IoT) systems in aquaculture	Maintaining water quality and other parameters within the acceptable ranges.	Rastergari et al., 2023
Behaviour recognition	Cameras used for capturing diverse underwater conditions, including muddy, dark, and light conditions.	Christensen et al., 2018; Jalal et al., 2020

The Potential Drawbacks

1. Job Displacement and Economic Disruption: While AI brings numerous benefits to the fishing industry, it also raises concerns about job displacement. Automation of certain tasks, such as fish sorting and quality control, could lead to job losses in traditional fishing communities. There's a risk that the economic benefits of AI-enhanced fishing might concentrate in the hands of large, technologically advanced fishing operations, potentially marginalizing smaller, traditional fishers.

2. Data Privacy and Security Concerns: The implementation of AI in fisheries relies heavily on data collection, including sensitive information about fishing locations, vessel movements, and catch data. This raises important questions about data ownership, privacy, and security. There are concerns about how this data might be used by competitors or even by hostile entities to exploit fish stocks or gain economic advantages.

3. Overreliance on Technology: As AI systems become more integrated into fisheries management, there's a risk of overreliance on technology. Technical glitches, cyberattacks, or simply the limitations of AI models could lead to poor decision-making if not balanced with human expertise and traditional knowledge. There's also the danger of a "black box" problem, where the decisions made by AI algorithms

are not fully understood or explainable, potentially leading to a loss of transparency in fisheries management.

4. Ethical and Environmental Considerations: The use of AI to optimize fishing operations raises ethical questions about the relationship between humans and marine ecosystems. If AI significantly increases fishing efficiency, it could potentially lead to overfishing if not properly regulated. There's a delicate balance to be struck between using AI to support sustainable practices and using it to maximize short-term profits at the expense of long-term sustainability.

Conclusion: Navigating the Future

The role of AI in fisheries is neither an unequivocal boon nor an outright ban. Instead, it represents a powerful set of tools that, if wielded responsibly, can significantly contribute to the sustainability and efficiency of the fishing industry. The key lies in how we choose to implement and regulate these technologies.

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Epigenetic Regulation of Crop Physiology Implications for Crop Improvement

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Summary

Epigenetic mechanisms—including DNA methylation, histone modifications, non-coding RNAs, chromatin remodelers, and higher-order chromatin organization—constitute a heritable yet reversible layer of gene regulation that operates independently of DNA sequence changes. In plants, these mechanisms intricately regulate essential physiological processes such as growth, development, photosynthesis, nutrient uptake, reproduction, and responses to biotic and abiotic stresses. Through epigenetic modifications, plants fine-tune gene expression to adapt to fluctuating environmental conditions, thereby influencing traits like flowering time, seed development, and yield potential. Notably, some epigenetic states (termed *epialleles*) can be stably transmitted across generations or artificially manipulated through environmental or agronomic interventions, creating new avenues for heritable phenotypic variation without altering the genome sequence. This emerging concept, known as *epibreeding*, holds transformative potential for accelerating crop improvement and resilience under climate stress. The integration of epigenomics with genomics-assisted breeding, epigenome editing, and omics-enabled phenotyping promises to uncover novel regulatory networks that underpin crop productivity and stress adaptation. This review highlights: (1) the molecular underpinnings of plant epigenetic regulation; (2) the links between epigenetic reprogramming and physiological traits; (3) current and prospective applications in crop improvement; and (4) the challenges and opportunities of leveraging epigenetic variability in sustainable agriculture.

Introduction

Plant physiology and crop performance have traditionally been viewed through the lens of DNA sequence variation and environmental interactions. However, epigenetic regulation introduces an additional dimension of heritable variation without changes in underlying DNA sequence. As pointed out by Springer (2013) in a foundational review, epigenetic information plays central roles in developmental gene regulation, environmental responses and natural variation in gene expression — and thus holds potential for crop improvement strategies including favourable epigenetic states and novel epialleles. In more recent years, Kakoulidou et al. (2021) emphasized the significance of epigenetic adaptation in the context of climate change and crop breeding. This review synthesises mechanistic insights and physiological relevance, focusing particularly on crop species, and outlines how epigenetics could be incorporated into breeding and agronomy.

Core Epigenetic Mechanisms in Plants

1. DNA Methylation: In plants, cytosine methylation occurs in three sequence contexts: CG, CHG and CHH (H = A, T or C). Key methyltransferases include MET1 (maintenance of CG methylation), CMT3 (maintenance of CHG), and CMT2 (for CHH in heterochromatin) plus de novo methyltransferases like DRM2 through RNA-directed DNA methylation (RdDM) pathways. Demethylases such as ROS1, DME and DML2/3 remove methylation marks. DNA methylation typically represses transcription by limiting access of transcription factors or RNA polymerase to promoters, and silences transposons and repetitive elements thereby maintaining genome stability. The interplay between methylation and histone modifications (for example H3K9me2) is important for reinforcing stable repressive chromatin states.

2. Histone Modifications and Variants: Histone tails can receive post-translational modifications (PTMs) such as methylation (e.g., H3K4me3 for activation, H3K27me3 for repression), acetylation (generally associated with activation), phosphorylation, ubiquitination, and incorporation of histone variants (e.g., H2A.Z). These modifications influence chromatin accessibility, nucleosome stability and

transcriptional outcomes. Chromatin remodelers (such as SWI/SNF complexes) and histone variant deposition also modulate these processes and contribute to dynamic regulation of gene expression in response to developmental or environmental cues.

3. Small RNAs and Long Non-coding RNAs: Small interfering RNAs (siRNAs, ~21–24 nucleotides) and long non-coding RNAs (lncRNAs) play roles in guiding DNA methylation via RdDM in plants, in post-transcriptional gene silencing (PTGS) and modulating chromatin states. For example, in the RdDM pathway, siRNAs generated from transcripts of RNA Pol IV/Pol V guide DRM2-mediated methylation at homologous loci. These RNA-mediated pathways allow sequence-specific targeting of epigenetic modifications, enabling plants to respond to transposons, viruses and environmental stress.

4. Chromatin Remodelers and 3D Genome Architecture: Beyond local chromatin modifications, the three-dimensional folding of chromatin and higher-order genomic architecture influence which regulatory elements interact, and thus gene expression. ATP-dependent chromatin remodelers (e.g., DDM1 in plants) reposition nucleosomes and enable methyltransferases or transcription factors to access DNA. Emerging evidence suggests that in crops, chromatin compartmentalisation and loop formation can influence stress responses and trait expression, though mechanistic details remain less well developed compared to model species.

Epigenetic Control of Physiological Processes Relevant to Crops

1. Development and Yield Components: Epigenetic regulation plays a role in meristem activity, organ formation, seed development and fruit ripening. For example, methylome remodeling during fruit ripening in tomato influences expression of key transcription factors and metabolic genes, thereby affecting fruit quality and shelf-life. Such developmental epigenetic control means that epialleles (heritable epigenetic states) can influence yield components (e.g., grain number, size) or quality traits (e.g., nutrient composition, flavour).

2. Stress Responses, Priming and Memory: Plants under abiotic (drought, salinity, heat) and biotic (pathogen, pest) stress frequently undergo epigenetic changes: altered DNA methylation, histone marks or small RNA profiles at stress-responsive genes or transposons. Some of these changes may be transient (within the same generation), others may persist as “stress memory” across mitoses or even meiosis, influencing future responses (priming). For example, Abdulraheem et al. (2024) review recent evidence of how epigenetic regulation contributes to stress adaptation and mentions potential transgenerational inheritance of stress memory in plants. In crop species, stress-associated epigenetic variation has been correlated with improved recovery, altered developmental timing and yield stability under stress conditions.

3. Reproduction, Hybrid Vigour and Fertility: Epigenetic regulation influences flowering time, gametogenesis, imprinting, seed size and fertility. For example, RdDM and small RNAs are required for gamete methylation dynamics; misregulation may lead to seed abortion or hybrid incompatibilities. In hybrids, epigenetic divergence between parental genomes can contribute to heterosis (hybrid vigour) or epigenetic “shock”. Selection of favourable epigenetic states may help stabilise hybrid performance.

4. Root & Shoot Architecture, Nutrient Use Efficiency, and Physiology: Traits such as root length, lateral root formation, stomatal density, hormone signalling (auxin, ABA), nutrient uptake and water-use efficiency appear to be influenced by epigenetic regulation of underlying gene networks. Although causal evidence in major crops is still developing, methylation profiling in maize and rice shows tissue-specific epigenomic signatures correlated with growth zones and physiological outputs. Thus, epigenetics has potential relevance for resource-use efficiency traits that are central to crop productivity and sustainability.

How Epigenetics Can Be Used for Crop Improvement?

1. Natural and Induced Epialleles as Breeding Material: Naturally-occurring stable epialleles (for example, differential methylation states at gene loci) have been documented and correlated with agronomic traits. Breeders may be able to select for favourable epigenetic states if they are stable across generations and predictive of trait expression. Springer (2013) highlighted this potential: “because epigenetic information plays a role ... there is the potential for epigenetics to play a role in crop improvement strategies including the selection for favourable epigenetic states, creation of novel epialleles...”. It is also

possible to induce epimutations (via chemical demethylation, tissue culture or targeted suppression of methylation maintenance) to generate novel variation — albeit with variable stability and heritability.

2. Epi-markers and Integration into Selection Pipelines: Epigenetic variation (e.g., differentially methylated regions, DMRs) can serve as supplementary markers alongside SNPs and structural variants in genomic selection models. Some studies in maize and other crops indicate that methylation profiles can add predictive power for certain traits, independent of DNA polymorphisms. Kakoulidou et al. (2021) emphasise how epigenomic diversity may help predict plant performance under climate change. In practice, integrating epigenetic data into breeding requires cost-effective methylation profiling, stability of epigenetic markers across seasons, and models that account for epigenetic inheritance and environmental lability.

3. Epigenome Editing and Targeted Manipulation: Emerging tools based on dCas9 (dead Cas9) fused to methyltransferase or demethylase domains—or histone-modifier domains—offer locus-specific modulation of epigenetic marks without changing DNA sequence. While such technologies are more developed in models, they represent a precision route to create desired epialleles in crops. Epigenome editing can in principle allow activation or repression of key genes (e.g., for stress tolerance, developmental timing) without introducing foreign DNA; this may have regulatory and public-acceptability advantages.

4. Agronomic Practices: Priming, Memory and Epi-breeding: Agronomic interventions — e.g., controlled priming (mild stress exposure), grafting, in vitro culture regimes, seed treatments — may establish beneficial epigenetic states (stress memory) that improve subsequent performance. The concept of “epi-breeding” envisions using epigenetic variation or memory as part of crop improvement pipelines. Kakoulidou et al. (2021) present epigenetics as a toolbox for breeders in the era of climate change. However, practical deployment will depend on the reproducibility, stability and heritability of induced epigenetic states in field conditions.

Technical Approaches and Integration with ‘Omics’

Advances in bisulfite sequencing (for DNA methylation), ChIP-seq (for histone modifications), ATAC-seq (chromatin accessibility), smallRNA-seq and long-read sequencing enable high-resolution epigenome mapping. Integration with transcriptomics, metabolomics and phenomics is crucial for linking epigenetic state to physiological output. For example Abdulraheem et al. (2024) discuss how genome-wide profiling under stress has revealed potential epigenetic markers of adaptation. Single-cell/single-nucleus epigenomics and spatial epigenomics are emerging, which may help dissect cell-type and tissue-specific epigenetic regulation of physiology. The challenge is to translate such detailed mechanistic knowledge into breeding-usable data: stable markers, predictive models, cost-effective assays, and alignment with phenotypic evaluation.

Case Studies

1. Tomato (*Solanum lycopersicum*): Fruit ripening involves major changes in methylation at promoters of ripening-associated TFs and metabolic genes; epialleles influence metabolite accumulation and shelf-life (discussed in Kakoulidou et al., 2021).

2. Maize (*Zea mays*): Genome-wide methylation profiling shows natural DMRs associated with expression variation. For example, gene-body methylation variation correlates with expression levels and adaptation to environment.

3. Polyploid crops (e.g., wheat, Brassica): Epigenetic differentiation among homoeologous gene copies contributes to sub functionalisation and stress responses; manipulating epigenetic states in polyploids may help stabilise trait expression under variable conditions. Although specific examples remain limited, the principle is covered in reviews of epigenetics for crop improvement.

Limitations, Challenges and Open Questions

Despite the significant potential of epigenetic regulation for crop improvement, several limitations and challenges remain. The stability and predictability of epigenetic states are a major concern, as many modifications are reversible or labile across generations and environments, and heritable, stable epialleles are relatively rare and often influenced by underlying genetic variation. Establishing causality remains

difficult because much of the epigenomic data in crops is correlative; changes in DNA methylation or histone marks are associated with gene expression or phenotypes, but determining direct cause-effect relationships and deploying them in breeding is challenging. Species and tissue specificity also pose obstacles, as most mechanistic studies are conducted in *Arabidopsis*, whereas crop genomes are larger, more complex, polyploid, and highly repetitive, complicating mapping and interpretation of epigenetic regulation. Additionally, epigenome editing faces technical challenges including efficient delivery, off-target effects, long-term stability, and evolving regulatory frameworks. Integrating epigenetic data into breeding pipelines requires stable, heritable variation, high-throughput assays, cost-effectiveness, standardization, and predictive value across environments. Environmental influence further complicates trait control, as epigenetic states are responsive to environmental cues and may change with seasons or management practices. Finally, most epigenetic studies are performed under controlled laboratory conditions, limiting understanding of how mechanisms operate under complex field environments, which include variable stresses, soil types, microbiomes, and agronomic practices, highlighting a critical need for field-based validation and translational research.

Future Directions and Recommendations

Future research should focus on identifying robust epi-targets by systematically screening crop germplasm and induced epi-populations to discover loci with stable, heritable epialleles that influence key traits across diverse environments. Developing epi-aware breeding pipelines is essential, integrating epigenetic profiling, such as methylation arrays or cost-effective bisulfite assays, into selection strategies, genomic selection models, and marker-assisted breeding programs, particularly for traits affected by environmental variation or phenotypic plasticity. Translating epigenome editing to crops requires improving delivery systems, including viral vectors, nanoparticles, or RNPs, ensuring target specificity, enabling multiplexing of edits, and evaluating stability and off-target effects in field-relevant germplasm. Standardizing assays and establishing public databases linking epigenetic states—such as differentially methylated regions, histone modifications, and small RNAs—to phenotypes, environments, and management practices will facilitate data sharing and reproducibility. Field validation and modeling of manipulated epigenetic states or epi-priming treatments across multi-environment trials are needed to predict performance under climate change, resource limitations, and stress conditions. Exploration of agronomic epigenetics, including seed priming, controlled stress exposures, microbiome manipulation, and grafting, may offer practical approaches to modulate epigenetic states and enhance yield, quality, or resilience. Finally, addressing ethical, regulatory, and social aspects is critical to clarify the regulatory status of epigenetic interventions, ensure biosafety, and foster public acceptance through transparent risk and benefit assessments for epigenome-edited or epigenetically manipulated crops.

Conclusion

Epigenetic regulation adds a dynamic and context-sensitive layer to gene regulation, one that is particularly relevant to crop physiology under variable environments. While sequence variation remains the backbone of breeding, epigenetics offers complementary avenues — for fine-tuning responses, enhancing plasticity, stabilising traits under stress and exploring heritable variation beyond DNA sequence. When combined with modern genomics, phenomics and predictive modeling, epigenetics has the potential to expand the breeders' toolbox. However, to fully harness this potential, we must move from mechanistic understanding (largely in model species) to actionable application in major crops: identifying stable epialleles, developing cost-effective and high-throughput assays, integrating epigenetic data into breeding pipelines, and field-validating epigenetic interventions. In the coming years, as climate change increases pressure on cropping systems, epigenetics may become a key component in developing resilient, high-quality crops — bridging genotype, environment and management in a new dimension of plant improvement.

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Root Physiology and its Role in Crop Water and Nutrient Acquisition

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Summary

Root systems are the primary organ for plant water and nutrient acquisition and play a central role in determining crop productivity, resilience to abiotic stress, and resource-use efficiency. Root form and function — described by root system architecture (RSA), root anatomy, and physiological processes such as water transport and nutrient-uptake kinetics interact with the soil physical, chemical and biological environment to determine the spatiotemporal capture of water and nutrients. Manipulating root phenotypes (distinct, measurable root traits or “phenes”) through breeding or agronomy offers a powerful route to improve crop performance under both high- and low-input agriculture. This review synthesizes current understanding of root physiology and its role in crop water and nutrient acquisition, highlights key root traits and mechanisms, discusses rhizosphere interactions, and outlines opportunities and challenges for phenotyping and translation.

Introduction

Roots determine the volume of soil explored, the timescale over which moisture and nutrients are acquired, and the plant’s ability to withstand stress (drought, low nutrient availability, salinity). Root systems are plastic and respond dynamically to resource heterogeneity; this plasticity enables local proliferation into nutrient-rich patches and physiological adjustments (for example, changes in hydraulic conductivity and transporter expression) in response to changing water and nutrient supply (Holz et al., 2024). Given global challenges — water scarcity, rising fertilizer costs and the environmental impacts of over-fertilization — optimizing root systems is an essential component of sustainable intensification (Lynch, 2013; Lynch, 2019).

Conceptual Framework: Root Traits, Phenotypes and Functional Outcomes

1. Root system architecture (RSA) and phenotypes: RSA describes the spatial configuration of roots (primary root length, lateral branching pattern, root growth angles, depth distribution, root length density). A “phene” is a single trait element (e.g., root angle, root cortical aerenchyma, root hair length) that contributes to whole-plant function; combinations of phenotypes determine resource capture and metabolic cost (rhizoeconomics). Breeding for targeted phenotypes (ideotypes) is proposed as an effective way to increase acquisition of water and mobile nutrients (e.g., nitrate) or immobile nutrients (e.g., phosphorus) (Lynch, 2013; Lynch, 2019).

2. Rhizoeconomics: cost vs benefit: Root growth and maintenance consume carbon and respiratory energy. Traits that reduce metabolic cost per unit soil explored (for example, root cortical aerenchyma that reduces living cortical tissue) can increase the net soil volume explored per unit carbon invested. The “steep, cheap and deep” ideotype formalizes trade-offs by favoring steeper axial roots (deep exploration), cheaper construction (lower metabolic cost), and deeper exploration to access water and nitrate that have leached below the topsoil (Lynch, 2013; Lynch, 2019).

Water Acquisition: Mechanisms and Root Determinants

1. Pathways of water entry and transport: Water enters roots across the epidermis and root hairs, moves through apoplastic and cell-to-cell (symplastic) pathways and is transported axially in xylem to the shoot. Root hydraulic conductivity is governed by root anatomy (xylem vessel number and diameter), activity and regulation of aquaporins, suberization of exodermis and endodermis, and the relative contributions of apoplastic versus cell-to-cell fluxes. Plants dynamically regulate aquaporin abundance and

xylem development to modulate water uptake under soil drying or fluctuating transpiration demand (Holz et al., 2024).

2. Spatial distribution of roots and water capture: Deep, steeply angled roots access subsoil water and are advantageous under seasonal or terminal droughts and for capturing mobile nitrate that leaches downward; shallow, highly branched systems more effectively exploit transient surface water (e.g., light rains) and immobile nutrients in the topsoil. Thus, root angle, axial root elongation rates and lateral branching pattern shape the water-capture strategy of crops. Ideotype selection (e.g., “steep, cheap and deep”) has been proposed to improve crop water and nitrate acquisition in water-limited agroecosystems (Lynch, 2013).

3. Root responses to drying soils: hydraulics and plasticity: Under soil drying, plants typically reduce root hydraulic conductance, adjust aquaporin expression, increase suberization and change root growth patterns (for instance, reduced elongation in dry zones and compensatory proliferation in wetter microsites). Root plasticity — the ability to alter local growth and physiology in response to microsite conditions — permits maintenance of uptake when soil moisture is heterogeneously distributed and is an important determinant of whole-plant water relations (Holz et al., 2024).

Nutrient Acquisition: Diffusion, Mass Flow and Root Strategies

1. Modes of soil nutrient supply and root solutions: Nutrients differ in mobility: nitrate and sulfate move largely by mass flow with water, whereas phosphate, potassium and many micronutrients are diffusion-limited. Consequently, root strategies differ: for mobile nutrients, increasing the root length in soil volumes traversed by transpiration streams (deep roots, sustained uptake during transpiration) enhances capture; for diffusion-limited nutrients (notably phosphorus), increased root surface area near the soil (root hairs, dense lateral branching), exudation-driven mobilization and topsoil foraging are more effective (Lynch, 2019; Holz et al., 2024).

2. Root hairs, rhizosheath and exudation: Root hairs substantially increase absorptive surface area and promote rhizosheath formation, improving phosphorus uptake in many crops. Root exudates — organic acids, phosphatases and chelators — solubilize sparingly available phosphorus and mobilize micronutrients. Genotypic variation in hair length/density and exudation profiles means these are actionable targets for breeding or for agronomic manipulation (Lynch, 2019; Holz et al., 2024).

3. Anatomy and “cheap” phenotypes for nutrients: Anatomical traits such as root cortical aerenchyma reduce the volume of living cortical tissue, thereby lowering respiration cost per unit soil explored and improving acquisition of both nitrogen and phosphorus in low-fertility soils. Other anatomical traits — reduced cortical cell file number, larger stele or modified suberization patterns — also influence metabolic cost, nutrient uptake capacity and axial transport and are promising targets in breeding programs (Lynch, 2019).

Rhizosphere Interactions that Modify Acquisition Efficiency

1. Mycorrhizae and microbial mutualists: Arbuscular mycorrhizal fungi (AMF) extend absorptive networks beyond root depletion zones and frequently enhance phosphorus and some micronutrient uptake. Nitrogen-fixing rhizobia and associative diazotrophs provide plant-available nitrogen in legumes and, to a lesser extent, in cereals through associative interactions. Microbial communities also influence root morphology via hormonal signals (e.g., auxins) and contribute to nutrient cycling in the rhizosphere (Holz et al., 2024).

2. Root exudates and nutrient mobilization: Plants actively secrete organic acids, enzymes and siderophores that mobilize sparingly soluble nutrients and shape microbial communities. Exudation is genotype-dependent and responsive to nutrient status, making it an axis for selection to improve nutrient acquisition in challenging soils (Lynch, 2019; Holz et al., 2024).

3. Physical-chemical modification of the rhizosphere: Roots modify rhizosphere pH, redox potential and moisture microgradients; for example, localized acidification can increase phosphorus solubility. Rhizosheath formation and mucilage production alter soil hydraulic properties near roots and influence the coupling between water flow and nutrient transport (Holz et al., 2024).

Plasticity, Signaling and Integration Of Responses

Root growth and function are governed by integrated signaling networks that process local cues (soil moisture, local nutrient concentrations) and whole-plant status (carbon availability, transpiration demand). Hormones (auxin, cytokinin, abscisic acid), small peptides and long-distance nutrient signals coordinate root branching, elongation and senescence. Plastic allocation (e.g., preferential proliferation into nutrient-rich patches) is adaptive but involves trade-offs with carbon costs and potentially increased disease exposure. Understanding these signaling networks is crucial to predict genotype $\times$ environment responses and to design breeding targets that perform across realistic field conditions (Lynch, 2019; Holz et al., 2024).

Phenotyping and Breeding for Improved Root Systems

1. Phenotyping approaches: Phenotyping approaches include controlled environment platforms (rhizotrons, gel and transparent media, hydroponics) and non-destructive imaging (X-ray computed tomography, MRI) alongside scalable field methods (shovelomics, minirhizotrons, root coring) and image-analysis pipelines. Translating controlled-environment measures to field performance is challenging because root traits are strongly influenced by soil structure, biota and management; nonetheless, improved field-relevant proxies and remote sensing (for example, canopy water status correlated with rooting depth) help selection efforts (Holz et al., 2024).

2. Translating phenes to improved crops: Field trials and simulation modeling demonstrate that targeted phenes (deep axial roots and lower lateral branching for drought; dense shallow laterals and long root hairs for phosphorus) can increase yield or resource-use efficiency in specific environments. Breeding for root traits is most effective when supported by explicit ideotypes, multi-environment validation, and integration with genomic selection or marker-assisted approaches (Lynch, 2013; Lynch, 2019).

Agronomic Practices that Interact with Root Function

Management (tillage, residue retention, irrigation scheduling, fertilizer placement) strongly influences which root phenotypes are advantageous. No-till and residue retention tend to concentrate nutrients in the topsoil, favoring shallow foraging phenes, whereas deep irrigation or subsoil amelioration can increase the benefit of deep rooting. Microbiome management (bioinoculants, organic amendments) complements root traits by improving nutrient mobilization and plant health; therefore, coordinated breeding $\times$ management strategies are required for practical gains (Holz et al., 2024).

Challenges, Research Gaps and Future Directions

Root phenotyping for crop improvement still faces significant challenges and research gaps that define future directions. One of the central issues lies in the genotype $\times$ environment $\times$ management (G $\times$ E $\times$ M) complexity, as root trait performance is highly context-dependent, necessitating robust predictive models and multi-site field validation to identify phenes that perform consistently across diverse conditions (Lynch, 2019). A major bottleneck is linking laboratory studies to field performance, since many phenotypes characterized in controlled environments fail to translate directly to heterogeneous field soils, highlighting the need for realistic soil-based screening systems and advanced field phenotyping technologies (Holz et al., 2024). Another critical frontier is understanding the molecular control of beneficial root phenes—although genes and QTLs governing traits like root angle, root hair development, and aerenchyma formation have been identified, their manipulation without causing adverse pleiotropic effects remains challenging (Lynch, 2019). Moreover, integrating root phenotyping with microbiome research offers exciting potential; elucidating how plant genetics influences beneficial rhizosphere communities and breeding for synergistic root–microbiome interactions could enhance nutrient uptake and stress resilience (Holz et al., 2024). Finally, future breeding strategies must incorporate sustainability metrics, explicitly evaluating environmental outcomes such as reduced fertilizer requirements, enhanced water productivity, and lower greenhouse gas emissions alongside yield gains to ensure holistic agricultural progress (Lynch, 2013; Lynch, 2019).

Conclusion

Root systems offer a major leverage point for improving crop water and nutrient acquisition. Conceptual advances (root phenes and rhizoeconomics), progress in phenotyping and imaging, and growing understanding of rhizosphere biology permit targeted manipulation of root traits. To realize root potential for sustainable intensification, research and breeding must adopt integrated approaches that consider soil context, crop management, microbial partners and the trade-offs inherent in root construction and function. Strategic selection of root phenotypes (for example, “steep, cheap and deep” for water and nitrate; shallow, dense rooting and active exudation for phosphorus), combined with appropriate agronomy, can increase resource-use efficiency while maintaining or improving yield (Lynch, 2013; Lynch, 2019; Holz et al., 2024).

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Global Perspectives and Future Directions of E-Crop Systems in Agriculture 5.0

Article ID: 72298

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Abstract

Agriculture 5.0 represents the next revolution in global food production, integrating advanced digital technologies, artificial intelligence, robotics, and data analytics to ensure sustainable, efficient, and resilient farming systems. E-Crop Systems — or Electronic Crop Management Systems — serve as the digital backbone of Agriculture 5.0, connecting data from soil, crops, weather, and machinery to support intelligent decision-making. This article explores global perspectives, technological innovations, challenges, and future directions of E-Crop Systems within the framework of Agriculture 5.0.

Introduction

The world faces an urgent need to produce more food sustainably for a rapidly growing population projected to reach nearly 10 billion by 2050. Traditional farming systems, dependent on manual labor and empirical knowledge, are no longer sufficient to meet these global demands. In response, the agricultural sector has evolved from Agriculture 1.0 (manual) through Agriculture 4.0 (smart farming) and is now entering the era of Agriculture 5.0 — an intelligent, autonomous, and sustainable system.

At the core of Agriculture 5.0 lies the E-Crop System (Electronic Crop Management System) — a digital platform integrating sensors, drones, AI models, and cloud computing for precise, real-time crop monitoring and management. These systems enhance productivity, optimize input use, and ensure environmental sustainability through data-driven decision-making.

Globally, nations are increasingly adopting E-Crop technologies to modernize their agricultural sectors. Countries like Japan, the Netherlands, the USA, and Israel have pioneered smart farming innovations that integrate E-Crop systems with robotics, automation, and data intelligence, demonstrating measurable gains in yield and sustainability.

Global Perspectives on E-Crop Systems

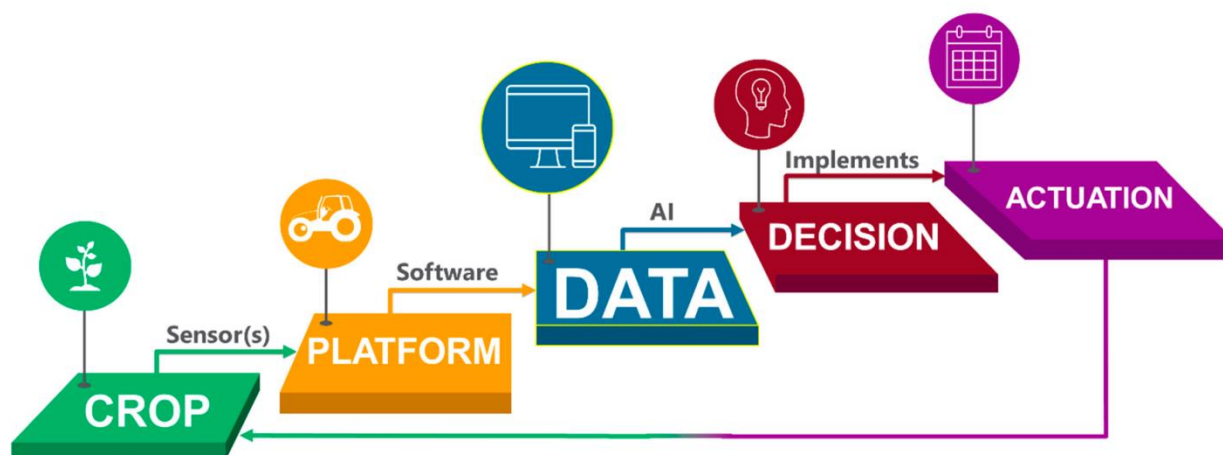
1. Developed Nations: Leading the Digital Agricultural Revolution: Developed countries have rapidly integrated E-Crop systems into commercial agriculture.

United States: The integration of IoT-based crop monitoring and AI-driven predictive analytics has revolutionized large-scale crop production. Companies like John Deere and Climate FieldView use E-Crop platforms to analyze satellite data, manage machinery, and provide field-level insights to farmers.

Japan: Leveraging robotics and precision sensors, Japan has created Smart Villages powered by E-Crop systems for remote monitoring and autonomous farming, addressing labor shortages and aging populations.

European Union: The EU's Digital Agriculture Strategy emphasizes data-driven, sustainable agriculture through projects like Smart Agri Hubs and IoF2020 (Internet of Food and Farm 2020), which focus on interoperability and data security across farm systems.

Netherlands: Known for its “high-tech greenhouse farming,” Dutch agriculture uses E-Crop tools that control microclimates, optimize nutrient supply, and achieve high yields with minimal resources.



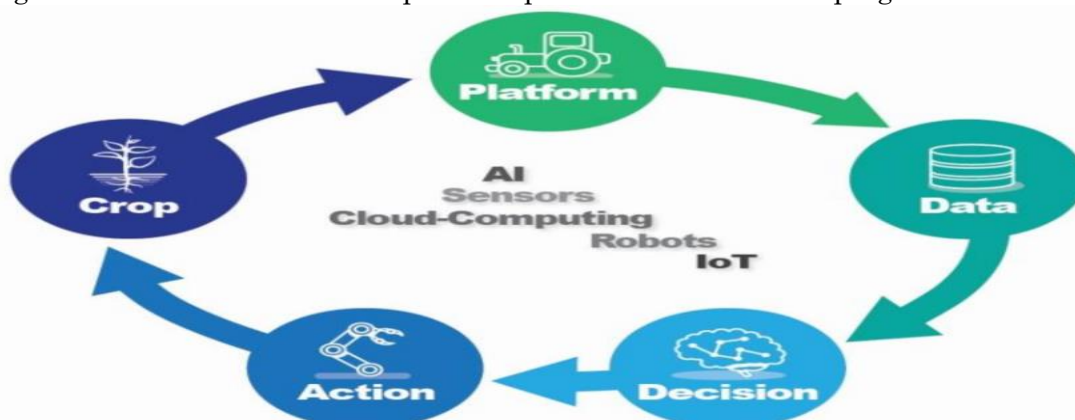
Source: <https://www.mdpi.com>

2. Developing Nations: Emerging Adoption and Challenges: In developing countries such as India, Brazil, Kenya, and Indonesia, E-Crop systems are being gradually introduced through government initiatives and private start-ups.

India: Under the Digital Agriculture Mission (2021–2025), E-Crop management platforms like Kisan e-Mitra and e-NAM are linking farmers with digital tools for crop planning, soil testing, and weather forecasting.

Brazil: Integrating E-Crop with satellite imagery has enabled large-scale monitoring of soybean and sugarcane crops, improving export competitiveness.

Africa: Initiatives like AgriTech Africa and Precision Agriculture for Development (PAD) are helping smallholders use mobile-based E-Crop tools to access agronomic advice and climate data. While adoption is promising, challenges such as poor internet connectivity, limited digital literacy, and high costs still constrain widespread implementation in developing economies.



Source: <https://www.researchgate.net>

Core Technologies Driving E-Crop Systems

E-Crop Systems function through the integration of multiple cutting-edge technologies that form the foundation of Agriculture 5.0:

1. Internet of Things (IoT) and Smart Sensors: IoT-based E-Crop systems utilize soil moisture sensors, nutrient sensors, and climate stations to collect real-time data. These sensors feed information to cloud-based systems, enabling precise irrigation scheduling, fertilizer application, and disease forecasting.

2. Artificial Intelligence (AI) and Machine Learning (ML): AI algorithms process large datasets to generate actionable insights. For instance, AI-powered crop models can detect pest outbreaks, estimate yields, and recommend optimal planting times. ML models continuously improve decision-making accuracy by learning from previous seasons.

3. Drones and Satellite Imaging: Unmanned aerial vehicles (UAVs) equipped with multispectral cameras monitor crop health, detect nutrient deficiencies, and map weed infestations. Combined with E-Crop dashboards, these images provide real-time visual analytics for targeted interventions.

4. Cloud Computing and Big Data Analytics: Cloud-based platforms enable farmers and researchers to store, share, and analyze massive amounts of agronomic data. Big data analytics support predictive modeling, enabling early warnings for droughts or pest infestations.

5. Blockchain for Traceability and Transparency: Blockchain-integrated E-Crop systems ensure food traceability from “farm to fork.” Consumers can verify the authenticity and sustainability of agricultural produce, while farmers benefit from transparent value chains and better market access.

Benefits and Impact of E-Crop Systems

E-Crop Systems bring significant advantages to modern agriculture by enhancing productivity, sustainability, and economic resilience. Through precision input management, they minimize wastage of fertilizers, pesticides, and water, leading to higher yields and profitability. These systems also promote climate-smart and sustainable farming by helping farmers adapt to unpredictable weather, monitor carbon emissions, and maintain soil health. By integrating real-time data such as weather forecasts, soil conditions, and pest alerts, E-Crop platforms enable effective decision-making and timely interventions, reducing crop losses. Economically, they empower farmers by providing access to digital marketplaces, price information, and government schemes, reducing reliance on intermediaries and ensuring fair profits. Moreover, the vast data collected through E-Crop systems supports research institutions and policymakers in developing evidence-based agricultural strategies, improving productivity and sustainability at regional and national scales. Thus, E-Crop Systems act as a bridge between technology, sustainability, and farmer empowerment in Agriculture 5.0.

Challenges and Limitations

Despite their potential, E-Crop Systems face several challenges. High technology costs limit smallholder adoption, while concerns over data privacy and security persist. The digital divide, caused by limited internet access and literacy, hampers rural integration. Additionally, interoperability issues between devices and inadequate policy support further restrict large-scale implementation, especially in developing nations.

Future Directions of E-Crop Systems in Agriculture 5.0

The future of E-Crop Systems lies in the convergence of intelligent automation, sustainable intensification, and inclusive innovation:

1. Integration of AI and Robotics: Next-generation E-Crop systems will employ autonomous robots and AI-based analytics to perform weeding, planting, and harvesting with minimal human intervention.

2. Predictive and Prescriptive Farming: Advanced algorithms will not only predict crop outcomes but also prescribe exact input doses and management actions for optimal yield and sustainability.

3. Climate-Adaptive and Regenerative E-Crop Platforms: Future E-Crop systems will integrate carbon accounting, soil biodiversity monitoring, and regenerative practices to restore ecosystem health.

4. Farmer-Centric Digital Ecosystems: Simplified mobile applications, voice-based advisory systems, and localized data models will make E-Crop systems accessible even to small and marginal farmers.

5. Global Collaboration and Policy Support: International organizations like the FAO, World Bank, and CGIAR will play a vital role in promoting data-sharing frameworks, capacity building, and funding mechanisms for digital agriculture.

Conclusion

E-Crop Systems represent the foundation of Agriculture 5.0, transforming global agriculture into a data-driven, intelligent, and sustainable enterprise. By merging AI, IoT, and cloud computing, these systems enhance efficiency, resilience, and inclusiveness. However, realizing their full potential requires addressing economic, infrastructural, and policy challenges. As the world advances toward a climate-smart and digital

future, E-Crop Systems will be the cornerstone of food security, sustainability, and technological transformation in agriculture.

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E-Crop Management Systems: Transforming Traditional Agriculture into Smart Farms

Article ID: 72299

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Abstract

The global agricultural landscape is rapidly evolving with the integration of digital technologies. E-Crop Management Systems (ECMS) represent a paradigm shift from conventional farming practices to data-driven, precise, and sustainable approaches. By integrating Internet of Things (IoT), artificial intelligence (AI), satellite imaging, drones, and data analytics, ECMS enable farmers to make informed decisions, enhance productivity, and ensure environmental sustainability. This article explores the concept, components, applications, benefits, challenges, and future prospects of E-Crop Management Systems, highlighting how they are revolutionizing modern agriculture into smart, efficient, and resilient farms.

Introduction

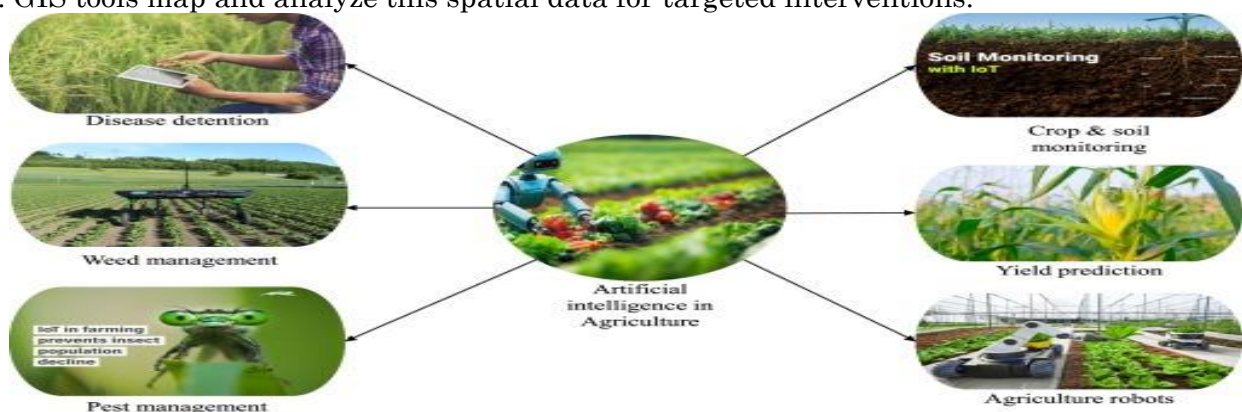
Traditional agriculture has long relied on farmers' experience, intuition, and manual observations. However, the increasing demand for food, the challenges of climate change, soil degradation, and the scarcity of natural resources have made conventional methods insufficient. The need for efficient resource management, real-time decision-making and sustainable practices has led to the emergence of E-Crop Management Systems (ECMS).

E-Crop Management Systems leverage digital tools and data analytics to monitor, analyze, and optimize all stages of crop production — from soil preparation and planting to irrigation, pest control, and harvesting. These systems combine hardware (sensors, drones, and devices) and software (mobile apps, AI models, and cloud platforms) to transform farms into intelligent, self-regulating ecosystems.

Concept and Components of E-Crop Management Systems

E-Crop Management Systems integrate multiple technologies into a unified platform that supports precision farming and real-time monitoring. The main components include:

- 1. Sensors and IoT Devices:** Soil moisture sensors, temperature sensors, nutrient detectors, and weather stations collect real-time data from the field. IoT (Internet of Things) devices transmit this data to cloud-based platforms for processing and analysis.
- 2. Geographic Information Systems (GIS) and Remote Sensing:** Satellite and drone-based remote sensing provide detailed information about crop health, soil condition, and vegetation indices (such as NDVI). GIS tools map and analyze this spatial data for targeted interventions.



Source: <https://www.sciencedirect.com>

3. Artificial Intelligence (AI) and Machine Learning (ML): AI and ML algorithms interpret large datasets to predict pest outbreaks, disease risks, and yield outcomes. These tools support decision-making by providing early warnings and recommendations.

4. Data Analytics and Cloud Computing: Cloud-based platforms store and analyze huge volumes of agricultural data. Data analytics transforms raw data into actionable insights for farmers, extension officers, and policymakers.

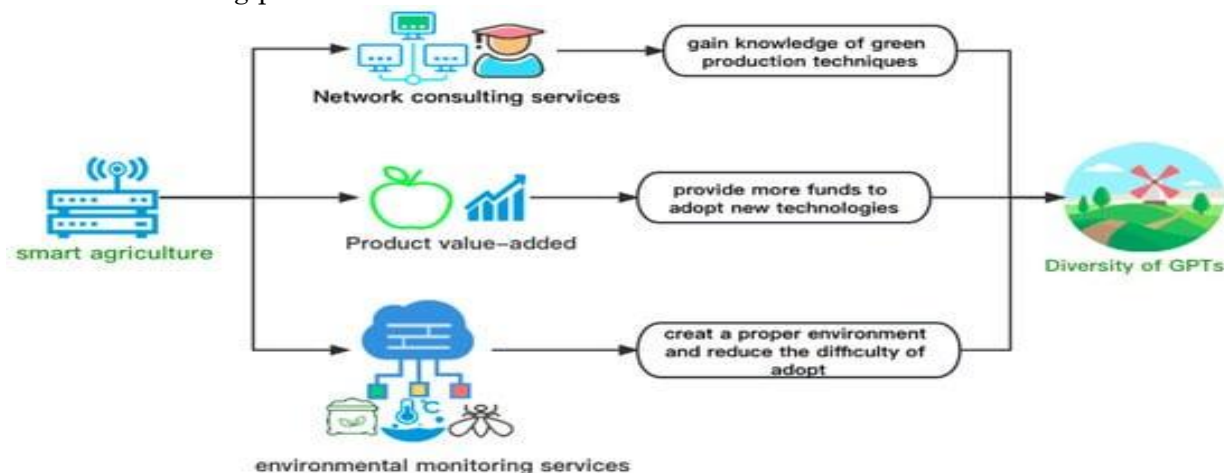
5. Mobile Applications and Farmer Dashboards: User-friendly mobile apps and dashboards allow farmers to access real-time information, receive alerts, and manage farm operations efficiently from anywhere.

Applications of E-Crop Management Systems

E-Crop Management Systems have a wide range of applications across different aspects of Agriculture. Some major applications include:

1. Precision Irrigation: IoT-enabled irrigation systems adjust water supply based on soil moisture levels, weather forecasts, and crop requirements, reducing water wastage and improving crop yield.

2. Nutrient and Fertilizer Management: By integrating soil nutrient data and crop growth models, ECMS guide farmers on the right type, quantity, and timing of fertilizer application, promoting balanced nutrition and minimizing pollution.



Source: <https://www.mdpi.com>

3. Pest and Disease Monitoring: AI-powered image recognition and remote sensing help in early detection of pest infestations and disease symptoms. This enables timely and precise pesticide use.

4. Yield Forecasting and Crop Planning: Using historical data, weather predictions, and AI modeling, ECMS forecast crop yields, helping farmers in crop selection, market planning, and risk management.

5. Post-Harvest Management: E-Crop platforms assist in logistics, supply chain tracking, and quality control. Blockchain integration enhances transparency and traceability in agri-produce marketing.

6. Climate and Risk Management: E-Crop systems integrate climate models and weather data to predict droughts, floods, and heat stress, enabling farmers to adopt adaptive measures for resilience.

Benefits of E-Crop Management Systems

E-Crop Management Systems (ECMS) offer significant economic, environmental, and social benefits, transforming traditional farming into a smart and sustainable enterprise. They enhance productivity by optimizing inputs and identifying issues early, resulting in higher yields. Precision resource use minimizes wastage of water, fertilizers, and pesticides, lowering costs and promoting sustainability. Automation reduces labor and operational expenses while supporting eco-friendly practices that protect soil and biodiversity. Data-driven insights enable informed decision-making, reducing climate and market risks. Furthermore, ECMS improve market access through digital traceability and product certification, boosting farmer income and consumer confidence.

Challenges in Implementing E-Crop Management Systems

Despite their transformative potential, several challenges hinder the large-scale adoption of E-Crop Management Systems:

- 1. High Initial Cost:** The cost of installing IoT sensors, drones, and cloud-based systems is often prohibitive for small and marginal farmers.
- 2. Lack of Digital Literacy:** Many farmers in developing countries lack the technical knowledge to operate digital tools and interpret data effectively.
- 3. Connectivity Issues:** Poor internet infrastructure in rural areas restricts real-time data transmission and limits system efficiency.
- 4. Data Security and Privacy:** Concerns over data ownership, misuse, and privacy need to be addressed through clear digital policies.
- 5. Institutional and Policy Barriers:** Absence of supportive government policies, subsidies, and extension frameworks hampers widespread implementation.

Case Studies and Global Examples

India: The government's Digital Agriculture Mission (2021–2025) promotes ECMS through AI-based crop monitoring, drone mapping, and farmer data integration.

Israel: Smart irrigation and fertigation systems use IoT and remote sensing to optimize water use in arid regions.

The Netherlands: Automated greenhouse systems integrate AI and robotics for precision control of crop environment and nutrition.

United States: Platforms like John Deere Operations Center and Climate FieldView provide real-time insights for large-scale farm management.

Future Prospects of E-Crop Management Systems

The future of ECMS lies in deeper integration of AI, robotics, blockchain, and 5G technology to create autonomous, interconnected farms. Smart contracts and traceable supply chains will ensure transparency and fair trade. Affordable sensors, open-data platforms, and digital literacy programs will further democratize access to these technologies. The collaboration between governments, research institutions, and agritech startups will accelerate the digital transformation of agriculture, making ECMS a cornerstone of climate-smart and sustainable food systems.

Conclusion

E-Crop Management Systems represent the future of agriculture, merging digital intelligence with traditional farming wisdom. They empower farmers to make informed, timely, and sustainable decisions that enhance productivity and profitability while safeguarding natural resources. As the world faces challenges of population growth and climate variability, ECMS provide a powerful tool to achieve food security, economic resilience, and environmental sustainability. The transition from traditional to smart farming through E-Crop technologies marks not just a technological advancement but a revolution toward sustainable agricultural transformation.

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Post- Harvest Handling of Cut Flowers

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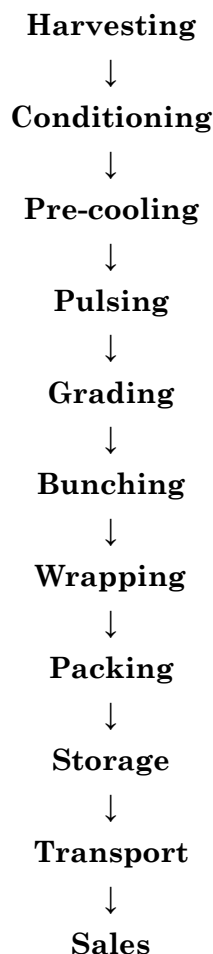
A 'flower' is an intricate organ composed of different morphological units including sepals, petals, androecium, gynoecium, stem and leaves. Cut flowers in general are highly perishable commodities and highly susceptible to huge post-harvest losses.

Most of the cut flowers complete their life cycle in two distinct phases. The first phase is of flower bud growth and development of the flower to full opening. The second stage is maturation, senescence and wilting. Post-harvest handling techniques of flowers are used to enhance cut flower longevity and to promote growth process in the 1st stage and retardation of metabolic processes of second stage.

Mode of Harvesting

1. Cut flowers should be cut with sharp tools and placed immediately in water or in a floral preservative solution.
2. The angle of cut must be slanting and smooth to absorb water freely through cut stems.
3. While cutting, the stem should not be crushed, which may lead to blockage of xylem vessels.

Post-Harvest Handling Chain of Cut Flowers



Conditioning of Cut Flowers

First step in conditioning or hardening is a simple process where the flowers are kept to stand loosely in a big container of water so the air circulates around the stems. The main purpose of this treatment is to restore turgidity of cut flowers after they have suffered from water stress during handling in the field, greenhouse or while transporting from greenhouse to post- harvest handling rooms.

Flowers can be conditioned in dark rooms so that their stomata will close, reducing the amount of water loss by transpiration.

Second step in conditioning is to place cut end of flower stems in floral preservative solutions.

Widely used floral preservative solutions

Citric acid (150- 400 ppm) + any one of germicide 8- Hydroxy Quinoline Citrate (200- 400 ppm) / 8- Hydroxy Quinoline Sulphate (200- 400 ppm) / Silver Nitrate (25 to 30 ppm) / Silver Thio Sulphate (25 to 30 ppm)

Pre-Cooling

Flowers have to pre-cool before storage and air lifting. Time between harvest and pre-cooling should be as short as possible. Forced air cooling is most effective in removing the field heat from flowers in a short period. Pre-cooling temperature suitable for flower crops vary from 1 to 4°C.

Pulsing

At this stage, a nutrient supplement like Sucrose (5- 10 %) is added to preservative solution which contain germicide. The absorption of chemical solutions containing sugar and germicides through the lower cut portion of flower stems is known as pulsing. This treatment should be performed under temperature of 20-25°C at light intensity of 2000 lux.

Grading

Grading is also done based on stem length, flower size, colour, quality, and also based on the standards recommended for each type of cut flower. According to these grades, prices are fixed in international markets.

Example: Grades in anthurium

Extra-large > 18cm spathe size

Large > 15-18cm spathe size

Medium > 12-15cm spathe size

Small > 9-12cm spathe size

Mini < 9cm spathe size

Bunching

Flowers should be bunched before wrapping/ packing and tying should be firm but not too tight. If flowers are too tightly crowded in storage, mould growth will be favoured.

Wrapping

Just before packing the flowers in boxes/ cartons, flowers are wrapped individually in thin polythene sleeves. Eg: Anthuriums are wrapped individually in thin polythene covers. Bud roses are wrapped in butter paper sheets or waxy sheets.

Packing

Packing is done to protect flowers from physical damage, water loss and external conditions during transporting. Packing can take many forms from flower cups, to sleeves, boxes, cartons, bulk bins, and special containers for flights. It is desirable to design a package which is specifically suitable to a particular flower under specific storage conditions. An ideal package should promote low respiration and low transpiration.

Cold Storage

Cold storage of cut flowers facilitates the adjustment of flower supply to distant markets based on demands. It makes possible to prolong the period of flower sales. Low temperature treatment during storage of cut flowers reduces the entire metabolism in the tissue, slows down the respiration, transpiration, ethylene production and activities of fungi and bacteria.

In general, temperate varieties of flowers like, Cymbidium, carnations, chrysanthemums are stored at 0–1°C. Sub-tropical flowers like, gladiolus, freesia, gerbera etc. are stored at 4–7°C. Tropical flowers like Anthurium, Vanda, Heliconia etc are stored at 7–10°C.

Transport

Flower should be transported in corrugated cardboard boxes. The flowers which are sensitive to ethylene, ethylene scrubbers containing KMnO_4 should be added to those boxes. Some of the flowers are like gladiolus and snapdragon are sensitive to geotropic bending, so these should be transported in upright position. Some of the flower crops show yellowing during transportation due to lack of light, therefore there should be a provision of light inside the transporting vehicle.

Some Treatments Used to Extend the Post-Harvest Life of Cut Flowers

Impregnation: The ends of stems can be impregnated with high concentration of Silver nitrate or Nickel chloride or Cobalt chloride solution for 10 minutes. This protects against the blockage of water vessel in stems by microbial growth and stems decay and greatly improves longevity of several flowers.

Chemicals used for impregnation of different cut flowers.

No.	Flowers	Chemical solutions
1	Gladiolus	AgNO_3 1000ppm for 10-15 min
2	Rose	NiCl_2 10 ppm for 20 min
3	Tuberose	AgNO_3 1000ppm for 10-15 min
4	Chrysanthemum	AgNO_3 1000-2000ppm for 10 min

Vase solutions: The cut flowers kept in the holding solutions or vase solutions should contain carbohydrates, germicides, growth regulators, ethylene inhibitors, mineral salts and organic acids for prolonging the life of cut flowers and improving quality of flowers.

Sustainable Intensification: Can We Grow More with Less?

Article ID: 72301

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Introduction

The global agricultural sector faces an unprecedented dual mandate: to sustainably raise food production for a projected world population of 9.7 billion by 2050, while simultaneously mitigating its environmental footprint, which includes a significant contribution to greenhouse gas emissions, biodiversity loss, and resource depletion (OECD-FAO, 2023-2032). The conventional approach of Extensive Intensification, expanding agricultural land or indiscriminately increasing external inputs like chemical fertilizers and irrigation, is no longer ecologically or economically viable. This necessity has brought the concept of Sustainable Intensification (SI) to the forefront of global policy and research agendas.

Sustainable Intensification is not merely about achieving higher yields; it is a philosophy that seeks to maximize output per unit of input while protecting or enhancing the natural capital (land, water, and biodiversity) upon which production depends (Amritha et al., 2025). It aims for "more output per unit input" rather than just a rise in yield (Kumar et al., 2025). This economic paradigm shift is central to achieving the United Nations Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger) and SDG 13 (Climate Action), by enhancing productivity, resilience, and resource efficiency (Amritha et al., 2025).

For India, a nation characterized by small and fragmented landholdings (averaging 1.08 hectares) and a rapidly depleting resource base, SI represents the crucial pathway to reconcile food security with long-term ecological stability. The Economic Survey 2024-25 has unequivocally highlighted that while the agriculture sector has witnessed consistent growth, averaging five per cent between FY17 and FY23, India's crop yields remain lower compared to other leading global producers, underscoring the urgent need for productivity improvements that do not strain resources further (Down To Earth, 2025).

Economic Theory and the Principle of Efficiency

The core economic justification for Sustainable Intensification lies in improving the marginal factor productivity of inputs. In traditional Green Revolution systems, a state of diminishing returns has been reached, where the marginal increase in yield from an additional unit of fertilizer or water is minimal, yet the environmental cost is high (Kumar et al., 2025). SI practices reverse this by shifting the production function outwards through technological and biological innovation.

1. The Economics of Resource Substitution and Water Productivity: In India, where agriculture consumes over 80% of freshwater, the economics of SI are most starkly visible in Water-Use Efficiency (WUE) (Das, 2025). Water-intensive crops like paddy and sugarcane, often supported by historically distorted price signals and subsidies, have led to unsustainable groundwater extraction, particularly in states like Punjab and Haryana (PIB Delhi, 2024; Das, 2025).

The push for micro-irrigation systems, such as drip and sprinkler, is an SI intervention with profound economic implications. Studies cited in the Economic Survey 2024-25 revealed that in Tamil Nadu, drip irrigation reduced water use by 39–55% and concurrently increased crop yields by 33–41% for horticultural crops (Farmers Rathna, 2025). Critically, this efficiency translated directly into substantial economic benefits for farmers, with profit margins increasing by 52.92% to 114.50% depending on the crop (Farmers Rathna, 2025). The government, under the *Pradhan Mantri Krishi Sinchai Yojana* and other schemes, aims to bring over 10 million hectares under micro-irrigation by 2025, saving billions of cubic meters of water annually and boosting farm income (Farmonaut, 2025).

2. Technological Intensification and Total Factor Productivity (TFP): The adoption of digital and precision agriculture technologies is transforming the economic measurement of *intensification*. Instead of inputting more, farmers are *managing* better, leading to a rise in Total Factor Productivity (TFP), output growth not accounted for by increases in traditional inputs (Kumar et al., 2025).

India-Specific Case Study: Precision and Conservation Agriculture (CA) Conservation Agriculture (CA), which involves minimal soil disturbance, permanent soil cover, and diversified crop rotations, is a key SI strategy. In the Indo-Gangetic Plains (IGP), particularly the rice-wheat systems that contribute over 80% of the nation's cereals (Kumar et al., 2023), CA practices have demonstrated significant yield and profitability gains. For instance, a study in the North-West IGP showed that a full CA permanent-bed soybean-wheat-summer moong cropping system increased system productivity by 15.55% in the second year compared to the conventional puddled transplanted rice-wheat practice. Furthermore, these systems concurrently recorded the highest Irrigation Water Productivity (IWP) and Benefit-Cost (B:C) ratio, making them an unequivocal economic and environmental win (Kumar et al., 2023).

Recent Data Trends (2025 Estimates): The push towards digitalization exemplifies this shift (Farmonaut, 2025):

a. Precision Farming Adoption: Estimated to rise from approximately 12% in 2020 to 35% by 2025 (Farmonaut, 2025).

b. Mobile App Usage by Farmers: Projected to increase from ~29% to 62% by 2025, facilitating real-time, AI-driven advisory services and instant market access (Farmonaut, 2025).

This integration of technology lowers transaction costs, reduces uncertainty, and enables more precise application of inputs, directly translating the 'more with less' ethos into on-farm profitability.

Crop Diversification and the New Green Revolution

A key SI strategy is to move away from the current cereal-centric food system, a legacy of the Green Revolution, towards diversified cropping patterns that prioritize resource conservation and nutritional security (Sampath et al., 2020). The Economic Survey 2024-25 explicitly calls for policy reforms to lower cereal overproduction and simultaneously boost the production of pulses and edible oils (Farmers Rathna, 2025).

Millets and Pulses: The shift towards millets (Shree Anna) and pulses is a prime example of SI. Pulses naturally fix nitrogen, reducing the need for synthetic fertilizers and thereby lowering the environmental footprint and greenhouse gas emissions (Sampath et al., 2020). Promoting these crops, through instruments like increased Minimum Support Price (MSP) for nutri-cereals, addresses the nation's nutrient imbalance, enhances soil health, and serves as a climate adaptation strategy (Down To Earth, 2025).

Challenges and Policy Implications

While the economic rationale for SI is compelling, its widespread adoption faces significant institutional and socio-economic hurdles in India.

Institutional and Socio-Economic Barriers

1. Fragmented Land Holdings: The average farm size of 1.08 hectares makes it difficult to implement scale-dependent technologies like mechanized precision farming and conservation agriculture uniformly (Das, 2025).

2. Knowledge and Awareness Gaps: Farmers often lack the necessary technical knowledge and long-term financial foresight to switch from established, input-heavy practices that guarantee short-term yields, to sustainable practices that require higher initial management skills (Das, 2025; Katya et al., 2025).

3. Credit and Risk: Marginalized farmers, already vulnerable to crop losses, are often reluctant to assume the risk associated with experimenting with new, intensified methods due to limited access to formal credit and secure land tenure (Roth et al., 2023).

Policy Road Map for SI Adoption

To overcome these barriers, policy interventions must be multifaceted and farmer-centric:

1. Shift from Input to Outcome Subsidies: The policy framework must transition from direct input subsidies (e.g., cheap fertilizer/electricity) to crop-neutral incentive structures that reward farmers for positive environmental and resource-use outcomes (PIB Delhi, 2024). This could include Direct Benefit Transfers for certified adoption of SI practices (e.g., conservation tillage, diversified rotation).

2. Strengthening Extension Services: Agricultural extension institutions must be revamped to disseminate targeted, reliable information on SI practices like the System of Crop Intensification (SCI) and Integrated Nutrient Management (INM) (T Katya et al., 2025; Farmonaut, 2025). The focus must be on practical demonstrations that establish the long-term profitability (high B:C ratio) of SI systems.

3. Investments in Rural Infrastructure: Addressing post-harvest losses, which account for around 16% of agricultural produce, is critical (Das, 2025). Investments in modern storage, transportation, and processing infrastructure (aligned with schemes like SAMPADA Yojana) will ensure that the 'more' produced through SI reaches the market efficiently, securing a fair return for the farmer and incentivizing adoption.

Conclusion

Sustainable Intensification is not a choice; it is an economic and ecological imperative for India's agricultural future. The transition from an input-intensive, yield-focused model to an efficiency-driven, TFP-centric system is essential for meeting both global demand and local resource constraints.

Economic insights from recent data (2023–2025) clearly demonstrate that SI practices, from micro-irrigation systems boosting profit margins by over 100% to Conservation Agriculture increasing system productivity by 15%, offer a win-win pathway: higher and more stable farm incomes alongside enhanced ecological stewardship. The commitment to SI, supported by smart, crop-neutral policies and digital technology adoption (projected at 35% for precision farming by 2025), will unlock significant rural growth potential and secure India's position as a sustainable global agri-power. By embracing SI, India can ensure that agricultural productivity is an engine for not just national food security, but for resilient and prosperous rural livelihoods, truly growing "more with less."

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Influence of Biochar on Soil Health

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Summary

Soil health refers to a soil's ability to continue to act as an essential living ecosystem within land-use boundaries by understanding that it includes biological elements that are critical to ecosystem functions. These functions may also help to preserve soil biological productivity, protect the environment's air and water quality, and promote the health of plants, animals, and humans. The application of biochar in agricultural production systems is one viable option to improve soil quality.

Introduction

The word "soil quality" first appeared in the literature in the early 1990s, and the soil science society of America's Ad Hoc Committee on soil quality approved the first official use of the term. Soil quality is described as a reference soil's ability to work within natural or controlled ecosystem boundaries to support plant and animal productivity, as well as maintain or improve the quality of water and air along with supporting human health and habitation. Soil quality refers to soil functioning, while soil health refers to the soil as a finite, nonrenewable, and dynamic living resource.

What is Soil Health?

The words "soil health" and "soil quality" are becoming more widely used around the world. Soil quality is characterized as a soil's ability to work within the ecosystem and land-use boundaries to maintain productivity, maintain environmental quality, and promote plant and animal health." In general, the terms "soil health" and "soil quality" are considered interchangeable. Inherent soil quality refers to the aspects of soil quality relating to a soil's natural composition and properties influenced by elements and processes of soil formation, in the absence of human impacts," according to the definition. Dynamic soil quality, on the other hand, refers to soil properties that change over time as a result of soil use and management.

Healthy Functioning Soils

1. Produce food, fuel, fiber, and medicinal products.
2. Store, filter, and release water.
3. Detoxification of harmful chemicals.
4. Store and cycle carbon.
5. Store and cycle nutrients internally.
6. Maintain biodiversity and habitat.

Recognizing Attributes of a Healthy Soil

1. Good soil tilth.
2. Sufficient depth.
3. Sufficient supply of nutrients.
4. Highly populated by beneficial organisms.
5. Short of plant pathogens and insect pests.
6. Free of allelochemicals.
7. Resistant to degradation.

How to Evaluate Soil Health?

1. Indicators: soil health indicators are functions and qualities that can be measured to monitor changes in the soil, that give clues about how well the soil can function.

2. Types of indicators:

- Physical indicators.
- Chemical indicators.
- Biological indicators.

Physical indicators	Chemical indicators	Biological indicators
Texture	pH	Soil organic carbon
Bulk density	Base saturation	Soil microbial biomass
Aggregation	Total nutrient	Nitrogen mineralization
Pore size distribution	Plant available nutrient	Soil flora
Available water capacity	Cation exchange capacity	Enzymatic activity
Infiltration rate	Calcium carbonate	Soil respiration rate
	Electrical conductivity	Earthworm

Biochar

Biochar is the carbon-rich solid product left over after biomass (plant organic matter) is heated to temperatures between 300°C and 700°C in the absence of oxygen and the process is known as pyrolysis.

Modes of Production

Sl. No.	Modes	Conditions	Yields (%)		
			Liquid	Char	Gas
1	Slow pyrolysis	Low temperature, long resident time	30	35	35
2	Fast pyrolysis	High temperature, short resident time	75	12	13
3	Gasification	High temperature, long resident time	5	10	85

Effect of Biochar on Physical Properties

Biochar is a low-density substance that improves water infiltration, root penetration, and soil aeration and also increases soil aggregate stability. The micro-aggregate component of the soil has the highest biochar content, while the macro-aggregates have lower content.

Through encapsulation of the organic fractions, micro-aggregates play an important role in reducing biochar decomposition. As biochar is broken down into humic acid, it may increase aggregation. However, aggregation can only play a minor role in reducing the biochar's decomposition rate, with its inherent recalcitrance playing a stronger effect.

Impact of Biochar on Chemical Properties

Biochar serves as a source of energy as well as a soil amendment. Due to its polycyclic aromatic carbon structure, black carbon (analogous to biochar) is very stable and resistant to physical and microbial breakdown, encouraging it to remain in soil due to the presence of crystalline morphology, the proportion of which may alter with pyrolysis temperature.

Biochar-enriched soils have high fertility and biochar helps to reduce climate change by lowering greenhouse gas emissions from agricultural soils (Verma *et al.* 2021). Biochar increases the ability of soils to maintain nutrients and plant usable water and decreases the leaching of nutrients and agricultural chemicals due to its high surface area and high surface charge density.

Influence of Biochar on Soil Microorganisms

The pH of soil amended with biochar is more suitable for the growth of microbes, especially fungal hyphae. Biochar is known to enhance the fertility of soils and carbon sequestration, but relatively little information is currently available about its effect on the soil microbial community, a component of terrestrial ecosystems that plays a key role in nutrient cycling. Microbial populations can be especially higher in soil rich in black carbon, thus the interaction between biochar as a soil amendment plays a vital role in soil biota.

Impact on Mycorrhizal Fungi and Biological Nitrogen Fixation

Biochar soil amelioration in degraded landscapes has the potential to increase grassland plant production, enrich soil microbial populations, and stimulate arbuscular mycorrhizal persistence. Biochar addition to soil increases in root colonization of arbuscular mycorrhiza fungi (AMF). Bio-char enhances biological N fixation (BNF) amendments in soil. This is mainly due to the:

1. Availability of nitrogen (N) in the soil is lower due to the high C/N ratio of the biochar, resulting in N immobilization.
2. Higher availability of nutrients other than N and the pH are higher
3. Biochar enhances mycorrhizal infection.

A combination of factors related to nutrient availability in soil and stimulation of plant-microbe interactions are most likely to be responsible for the improved BNF.

Biochar in Sequestering Soil Carbon

Soil carbon sequestration (SOC) is the process of raising the concentration of carbon in the soil by changing land use and implementing prescribed agricultural management practices. Another significant SOC sequestration technique is the use of manure and other organic amendments and the development of charcoal and the use of biochar as a fertilizer. Biochar is a component of the oldest C pool found in soil and deep-sea sediments, suggesting that black carbon may be a major global carbon sink. It is proposed that by using this approach to "tie up" carbon, existing global carbon emissions could be reduced by 10 percent.

Biochar in Remediation of Soil

Chars, charcoals, biochar, soots, and graphite are all examples of black carbon, which is thermally modified, partially charred to an extremely concentrated form of organic carbon. It functions as a recalcitrant pool, influencing hydrophobic organic chemicals (HOCs) mobility, extractability, and bioavailability in the soil, as well as helping in stabilizing and restoring soil organic matter (Li *et al.*, 2020). The soil remediation with biochar improves cation exchange capacity, nutrient binding, and subsequent control of nutrient run-off, reduces nitrogen leaching, improves soil water-holding capacity, neutralizes soil acidity, and provides a microorganism-friendly environment.

Conclusion

It is required to develop low-cost biochar kilns to make the technology affordable to small and marginal farmers. Further inter-disciplinary and location-specific research has to be taken up for studying the long-term impact of biochar application on soil physical properties, nutrient availability, soil microbial activities, carbon sequestration potential, crop productivity, and greenhouse gas mitigation.

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Impact of Custom Hiring Centers on Mandya Farmers, Karnataka

Article ID: 72303

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Introduction

Indian agriculture is gradually moving away from reliance on human and animal power and toward mechanical power because of rising animal maintenance costs and a growing labor shortage. Furthermore, using mechanical power not only makes agricultural activities more efficient and timely, but it also directly affects crop output. Thus, implementing farm mechanization is quite necessary. Agriculture Department the Government of Karnataka has decided to establish Custom Hiring Service Centres (CHSC's) at hobli-level, with an objective to assist the small and marginal farmers to provide machineries at their door steps. Mandya district in Karnataka has witnessed a significant transformation in agricultural practices with the introduction of Custom Hiring Centers (CHCs). These centers have emerged as a boon for farmers, providing them with access to modern farm machinery and equipment at affordable rates.

Traditionally, farmers in Mandya have faced numerous challenges, including labor shortages, high operational costs, and limited access to modern farm equipment. These issues have hindered their ability to cultivate and harvest crops efficiently, leading to reduced productivity and income. CHCs have addressed these challenges by providing farmers with a range of farm machinery and equipment, including tractors, harvesters, and planters, on a rental basis. This has enabled farmers to access modern technology without having to bear the high costs of purchasing and maintaining the equipment.

The present study addressed the performance of custom hiring centers, its impact and the constraints faced by the farmers in utilizing custom hiring services in Mandya district, Karnataka with the following major objectives.

Objectives

To study the socio-economic characteristics of farmers; To examine the extent of utilization and gap between requirement and availability of farm machineries from custom hiring centers; To analyze the change in farm income due to use of services of custom hiring centers; To identify the constraints in utilization of facility of custom hiring center by the farmers.

Coverage & Intervention

This research concentrated on Mandya district (Figure 1), a major rice-producing area reliant on extensive farm machinery. Five custom hiring centers, located in Basaralu, Athguru, Akkihebbala, Chinnakurli, and Arakere, were selected for the study. A sample of 150 paddy-growing farmers, comprising 75 beneficiaries and 75 non-beneficiaries of custom hiring services, was chosen. Primary data was collected through a pre-tested interview schedule and survey method during the Kharif season of 2023-24. Secondary data was gathered from the records of selected custom hiring centers. The collected data was analyzed using statistical techniques, including measures of central tendency and percentages, to examine the characteristics of beneficiary and non-beneficiary farmers, utilization of farm machinery, and the economic impact of custom hiring services.



Figure 1: Resource map of blocks in Mandya district

Findings & Recommendation

Key findings of the study are 100% of farmers mechanized their paddy cultivation operations, including land preparation, puddling, threshing, and transportation. 92% of farmers adopted the transplanting method for sowing, while 46.67% relied on manual labor for harvesting. Mechanical harvesters, such as reapers (29.33%) and combine harvesters (24%), were also used. 62.67% of beneficiary farmers used tractors for threshing, either owned or hired from CHSCs or private lenders. The study highlighted a shortage of tractors and farm machinery, including: MB plough: 66.67%; Cultivator: 61.76%; Rotavator: 58%; Transplanter: 75%; Combine harvester: 100% shortage. The beneficiary farmers had: 5.56% lower cost of cultivation; 9.61% higher productivity; 15.78% lower cost of production. The incremental cost-benefit ratio of using CHSC services was 3.62, indicating economic viability. The break-even point for tractors was 408.57 hours per year.



Plate 1: Data collection at CHSC, Mandya district

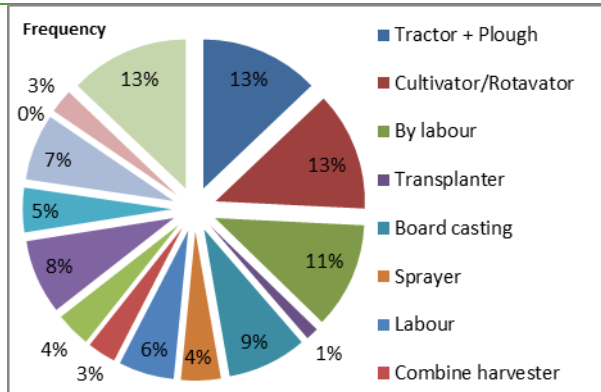


Figure 1: Utilization of farm machinery from CHSC by farmers

Conclusion

Custom Hiring Service Centers helped to alleviate labor issues for most farmers by providing custom hiring services. Custom Hiring Centers have revolutionized agricultural practices in Mandya district, empowering farmers with access to modern farm machinery and equipment. As the success of CHCs continues to grow, it is likely that more farmers will benefit from this initiative, leading to improved productivity, reduced costs, and enhanced livelihoods. The study revealed that custom hiring services significantly enhanced paddy cultivation operations, with 100% of farmers mechanizing their processes. Beneficiary farmers experienced a 5.56% reduction in cultivation costs, 9.61% increase in productivity, and 15.78% decrease in production costs. The incremental cost-benefit ratio of 3.62 indicated economic viability, making custom hiring services a valuable resource for farmers.

Allelopathic Effects of Wheat Residues on Subsequent Crops

Article ID: 72304

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Abstract

Allelopathy, a biological phenomenon by which plants release chemical compounds that influence the growth and development of neighboring plants, plays a significant role in crop rotation systems. Wheat (*Triticum aestivum* L.) residues are known to release allelochemicals that can affect germination, root elongation, and overall growth of subsequent crops. While these effects can be beneficial for weed suppression, they can also negatively influence the performance of sensitive crops in the following season. This article reviews the chemical nature of wheat allelochemicals, their mechanisms of action, environmental factors affecting allelopathic intensity, and management strategies to mitigate negative impacts on crop productivity.

Introduction

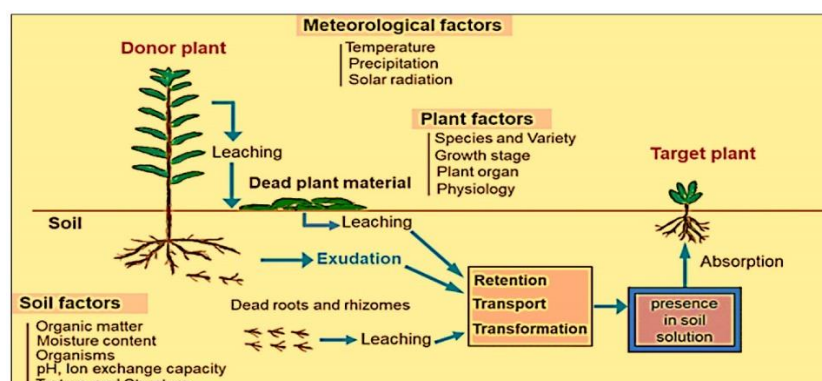
Wheat is one of the most widely grown cereal crops globally, serving as a staple food for more than one-third of the world's population. In many crop rotations, wheat is followed by crops like maize, rice, pulses, or oilseeds. However, the residues of wheat left in the field after harvest often influence the germination and growth of subsequent crops. This phenomenon, known as allelopathy, refers to the chemical interactions between plants through secondary metabolites called allelochemicals.

Wheat residues can either suppress or stimulate the growth of subsequent crops depending on the type and concentration of allelochemicals released, environmental conditions, and the decomposition stage of residues. Understanding these allelopathic effects is crucial for improving crop rotation design, residue management, and sustainable agricultural practices.

Concept of Allelopathy in Wheat

Allelopathy in wheat involves the release of specific biochemical compounds that influence plant-plant interactions. These compounds are produced in various plant parts including roots, leaves, stems, and seeds, and are released into the soil through leaching, root exudation, volatilization, or decomposition of residues.

1. Definition and Mechanism: According to Rice (1984), allelopathy is defined as the direct or indirect harmful or beneficial effect of one plant on another through the production of chemical compounds that escape into the environment. In wheat, these allelochemicals may alter the physiological and biochemical processes of neighboring plants, affecting seed germination, enzyme activity, nutrient uptake, and hormonal balance.



Source: <https://www.frontiersin.org/journals/plant-science>

2. Sources of Allelochemicals in Wheat:

The major sources of allelochemicals in wheat residues include: Phenolic acids: Such as p-hydroxybenzoic acid, vanillic acid, ferulic acid, syringic acid, and p-coumaric acid.

Hydroxamic acids: Particularly 2,4-dihydroxy-1,4-benzoxazin-3-one (DIBOA) and 2-benzoxazolinone (BOA), known for their strong inhibitory effects on weed and crop growth.

Flavonoids and alkaloids: Present in smaller quantities but may contribute synergistically to allelopathic activity.

These compounds are water-soluble and can enter the soil environment, influencing subsequent crops either by inhibiting germination or altering microbial activity.

Effects of Wheat Residues on Subsequent Crops

1. Impact on Germination and Seedling Growth: Studies have shown that wheat residue extracts can inhibit germination and reduce radicle and plumule length in sensitive crops such as chickpea, lentil, mustard, and maize. The inhibition is primarily attributed to the presence of phenolic acids, which interfere with cell division and elongation in germinating seeds.

For example:

- a. Chickpea germination may decrease by up to 30–40% under heavy wheat residue incorporation.
- b. Maize and sunflower show delayed emergence when grown after wheat under conservation tillage conditions.
- c. Rice seedlings exhibit reduced vigor when transplanted soon after wheat harvest in wheat–rice cropping systems.

2. Influence on Soil Microbial Activity: Wheat residues also influence soil microbial composition and enzyme activity. Some allelochemicals suppress beneficial soil microbes like Rhizobium and Azotobacter, while stimulating fungal populations. This imbalance can reduce nitrogen fixation and nutrient mineralization, indirectly affecting the following crop.

3. Weed Suppression: Interestingly, the allelopathic potential of wheat residues can be harnessed for weed control. Wheat-derived compounds inhibit the germination of weeds like Phalaris minor, Chenopodium album, and Amaranthus retroflexus. In conservation agriculture systems, retaining wheat residues as mulch helps suppress weed emergence, reducing the need for herbicides.

4. Crop-Specific Sensitivity:

- a. Different crops respond variably to wheat residues.
- b. Highly sensitive crops: Lentil, mustard, chickpea, pigeon pea.
- c. Moderately sensitive crops: Maize, rice, cotton.
- d. Less sensitive crops: Sorghum, pearl millet, and barley.

The degree of sensitivity depends on the crop species, variety, and environmental factors such as temperature, moisture, and soil pH.

Factors Influencing Allelopathic Effects

1. Residue Amount and Incorporation Depth: High residue loads (more than 4–6 tons/ha) incorporated into the soil can intensify allelopathic effects. Surface retention of residues causes slower decomposition and prolonged chemical release, whereas deep incorporation accelerates decomposition, diluting the allelochemical concentration.

2. Soil and Environmental Conditions: Temperature, moisture, and microbial activity strongly influence the degradation and persistence of allelochemicals. Warm and moist conditions favor rapid decomposition and detoxification, while cold or dry conditions prolong the inhibitory effects.

3. Crop Rotation and Tillage Practices: Continuous wheat cultivation or short rotation intervals increase the accumulation of allelochemicals. Conservation tillage systems with residue retention often exhibit more pronounced allelopathic effects compared to conventional plowing, where residues are removed or deeply buried.

Management Strategies to Mitigate Negative Effects

1. Residue Decomposition Period: Allowing sufficient time (20–30 days) between wheat residue incorporation and sowing of the next crop helps minimize allelopathic inhibition. This interval allows microbial degradation and detoxification of harmful compounds.

2. Use of Decomposers and Bio-inoculants: Application of microbial decomposers like *Trichoderma harzianum*, *Bacillus subtilis*, and *Aspergillus niger* accelerates residue breakdown and reduces allelochemical persistence.

3. Crop Selection and Rotation Planning: Including non-sensitive crops like sorghum or maize in rotation after wheat can reduce the buildup of allelochemicals. Rotations with legumes should be managed carefully, ensuring adequate residue decomposition before planting.

4. Irrigation and Soil Management: Irrigation after residue incorporation helps leach soluble phenolic compounds deeper into the soil profile, lowering their concentration near the germinating seeds.

5. Integration with Conservation Agriculture: In conservation agriculture, strategic management of wheat residues through partial retention, mixing with organic amendments, or biochar application can balance the benefits of weed suppression with minimal harm to subsequent crops.

Conclusion

Wheat residues exhibit significant allelopathic potential, influencing both beneficial and harmful aspects of crop production systems. While these residues play a positive role in weed suppression and soil moisture conservation, they can also negatively affect germination and early growth of sensitive crops. Therefore, understanding the biochemical mechanisms, environmental influences, and crop-specific sensitivities is essential for effective management. Integrating residue management with microbial inoculants, suitable crop rotations, and proper decomposition intervals can mitigate adverse effects and enhance the sustainability of wheat-based cropping systems.

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E-Crop for Sustainable Intensification and Climate-Resilient Agriculture

Article ID: 72305

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Abstract

The increasing pressure of climate change, land degradation, and population growth necessitates innovative and data-driven agricultural practices. E-Crop—an emerging digital platform integrating satellite imaging, IoT sensors, artificial intelligence (AI), and mobile-based applications—offers transformative potential for sustainable intensification and climate-resilient agriculture. This article explores the concept of E-Crop, its technological components, implementation strategies, and its role in optimizing resource use, enhancing productivity, and ensuring environmental sustainability. The discussion highlights how E-Crop systems can strengthen farmers' adaptive capacity, promote precision agriculture, and support decision-making for climate-smart farming systems.

Introduction

Agriculture, the backbone of the global economy, faces unprecedented challenges due to rapid climate variability, declining soil fertility, and growing food demand. To ensure food security by 2050, global agricultural productivity must increase by nearly 60%, but with minimal environmental footprint. Sustainable intensification—producing more food from the same land while reducing negative environmental impacts—is the way forward.

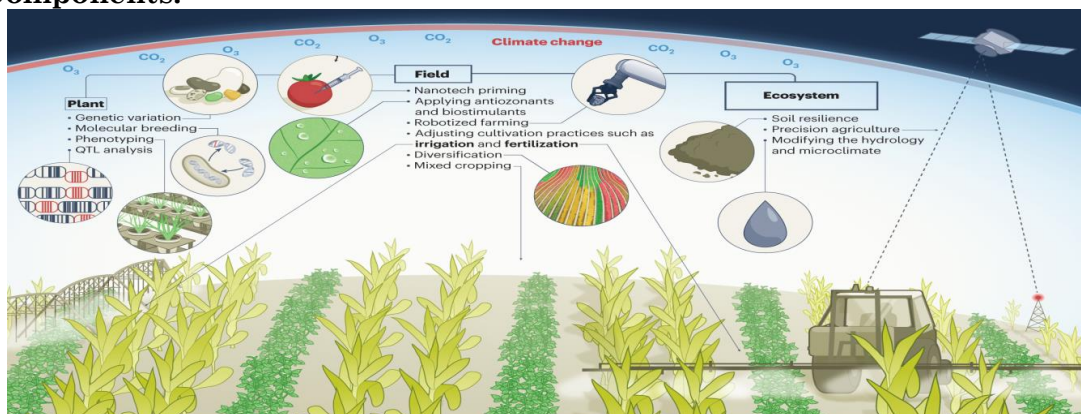
In this context, E-Crop has emerged as a revolutionary digital innovation designed to modernize agricultural management. It enables real-time monitoring, data-based decision-making, and precision resource utilization. By connecting farmers, researchers, and policymakers through a unified platform, E-Crop can transform traditional agriculture into a more climate-resilient and sustainable system.

Concept and Components of E-Crop

1. Definition: E-Crop refers to an electronic crop management platform that integrates digital technologies such as Geographic Information Systems (GIS), Remote Sensing (RS), Artificial Intelligence (AI), Internet of Things (IoT), and Machine Learning (ML) to collect, process, and analyze field data for informed decision-making in agriculture.

It enables farm-level digital records, real-time crop health assessment, predictive analytics, and advisory services for farmers through mobile applications and dashboards.

2. Core Components:



Source: <https://www.nature.com>

Remote Sensing and GIS: Provide high-resolution satellite imagery for crop identification, growth monitoring, and yield estimation.

IoT-Based Sensors: Measure soil moisture, temperature, pH, and nutrient status to optimize irrigation and fertilization.

Artificial Intelligence (AI) and Machine Learning (ML): Predict pest outbreaks, weather anomalies, and yield potential through data analysis.

Cloud Computing and Big Data Analytics: Store and process vast agricultural datasets for real-time access and decision support.

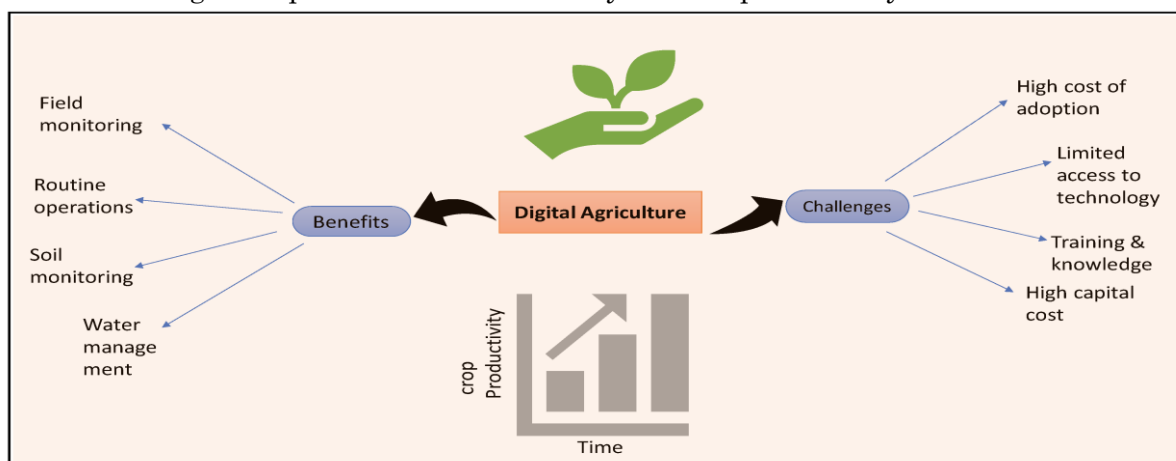
Mobile and Web Applications: Deliver localized advisories, weather forecasts, and crop management tips directly to farmers.

Blockchain and Data Security: Ensure transparency in input supply, traceability in production, and credibility in agri-marketing.

Role of E-Crop in Sustainable Intensification

Sustainable intensification (SI) aims to increase productivity without compromising natural resources. E-Crop supports SI through precision input management, resource optimization, and knowledge-based decision-making.

1. Precision Agriculture and Input Efficiency: E-Crop tools provide site-specific nutrient and water management. For instance, satellite-derived NDVI (Normalized Difference Vegetation Index) maps help identify crop stress areas, enabling targeted fertilizer application and efficient irrigation scheduling. This not only reduces wastage of inputs but also enhances yield and profitability.



Source: <https://www.mdpi.com/>

2. Soil Health and Nutrient Management: Through IoT soil sensors and predictive AI algorithms, E-Crop platforms monitor soil organic matter, pH, and nutrient status. They recommend balanced fertilizer doses, promoting integrated nutrient management (INM) and minimizing soil degradation.

3. Integrated Pest and Disease Management: AI-based image recognition helps detect early pest or disease infestations, allowing timely interventions. By reducing unnecessary pesticide use, E-Crop ensures ecological balance and prevents pest resistance buildup.

4. Water Resource Optimization: E-Crop integrates weather forecasts with soil moisture sensors to design smart irrigation systems, optimizing water use in drought-prone regions. Farmers receive real-time alerts for irrigation timing, improving water productivity and conserving groundwater resources.

E-Crop for Climate-Resilient Agriculture

1. Climate Risk Assessment: Climate variability directly impacts crop growth, pest dynamics, and yield stability. E-Crop uses AI-based climate models and remote sensing data to assess regional risks such as drought, flood, or heat stress. These insights enable proactive adaptation measures.

2. Early Warning Systems: E-Crop platforms can integrate local weather station data and satellite monitoring to provide early warnings for extreme events like heavy rainfall, frost, or pest outbreaks. Farmers can adjust planting dates, choose resilient varieties, or implement protective measures accordingly.

3. Carbon Footprint Reduction: By optimizing fertilizer and pesticide use, E-Crop helps reduce greenhouse gas (GHG) emissions from agriculture. Precision nutrient management minimizes nitrous oxide emissions, while residue management modules promote carbon sequestration practices such as conservation tillage and cover cropping.

4. Crop Diversification and Resilience: E-Crop advisory systems suggest crop diversification based on soil and climate suitability. For example, replacing high water-demand crops with millets or pulses in semi-arid zones enhances both resilience and nutritional security.

Implementation and Case Studies

1. India's E-Crop Platform: The Government of India has developed E-Crop as part of the Digital Agriculture Mission to digitally register crops, monitor fields through satellite data, and support policy formulation. The platform connects farmers, input suppliers, and government agencies for transparent record-keeping and subsidy management.

2. Farmer Benefits:

- a. Improved yield through precision management.
- b. Reduced production costs due to optimized input use.
- c. Access to localized advisories and market linkages.
- d. Reduced vulnerability to climate shocks through early warnings.

Challenges and Future Prospects

1. Challenges:

- a. **Data Gaps and Connectivity:** Rural areas often lack internet access and reliable data infrastructure.
- b. **Cost and Technological Awareness:** Small and marginal farmers may find digital tools costly or complex.
- c. **Data Privacy and Ownership:** Protection of farmers' data is critical to avoid misuse by private entities.
- d. **Interoperability Issues:** Integration of data from multiple sources and agencies remains a technical challenge.

2. Future Prospects:

- a. **AI-Driven Decision Support Systems:** Advanced machine learning models will offer crop-specific real-time advice.
- b. **Integration with Drones:** Drones for aerial imaging and pesticide application can be linked to E-Crop for field-level precision.
- c. **Climate-Smart Policy Integration:** Governments can use E-Crop data for insurance schemes, disaster relief, and subsidy targeting.
- d. **Public-Private Partnerships:** Collaboration between research institutes, agri-tech startups, and extension agencies can accelerate E-Crop adoption.

Conclusion

E-Crop represents a paradigm shift in agricultural management, enabling data-driven, resource-efficient, and climate-resilient farming systems. By linking technological innovation with field-level applications, it strengthens farmers' adaptive capacity and promotes sustainable intensification. For developing countries like India, integrating E-Crop within national agricultural frameworks can improve productivity, environmental sustainability, and food security. Future efforts should focus on capacity building, digital literacy, and policy support to make E-Crop accessible and affordable for all farmers.

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Prospects and Challenges of Organic Farming in India

Article ID: 72306

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Introduction

India is bestowed with lot of potential to produce all varieties of organic products due to its various agro climatic conditions. India ranks 5th in terms of world's organic agricultural land and 1st in terms of total number of producers (FIBL, 2020). As on 31st March 2022 total area under organic certification process (registered under National Programme for Organic Production) is 9119865.91 ha and produced around 3430735.65 MT of certified organic products. And the total volume of exports during was 460320.40 MT showed an export realization of INR 5249.32 Cr. (771.96 million USD). Among different states, Madhya Pradesh is the largest producer followed by Maharashtra.

Prospects of Organic Farming

1. Consumer acceptance
2. Environmentally friendly
3. Higher biodiversity
4. Better soil.

Challenges of Organic Farming

1. Lack of awareness
2. Output marketing problems
3. Lack of quality standards for bio-manures
4. Shortage of biomass
5. Inability to meet export demand
6. Inadequate supporting infrastructure
7. High input costs
8. Marketing problems of organic inputs
9. Vested interests
10. Lack of financial support
11. Low yields.

Research Studies

Oyesola *et al.* (2012) conducted study on awareness and level of involvement of farmers in organic farming across two vegetation zones of Ekiti state, Nigeria. The study revealed that majority (78.70%) of the respondents considered labour and laborious nature of organic farming as a severe problem. Unavailability of materials for organic manure was considered by majority (45.00%) of the respondents as a problem not severe. majority (73.70%) of the respondents agreed that weed problem was indeed a severe problem in organic farming. majority (56.90%) of the respondents opined that difficulty in application of organic manure was a major problem. majority of the respondents considered problems such as disease transmission through organic manure (66.90%) and unpleasant odour of certain organic manure (76.90%) as severe problems in organic farming. majority (70.60%) of the respondents stated that time consumption was a severe problems in organic farming.

Rifat *et al.* (2019) conducted a study on constraints faced by organic farming practicing farmers in Hill region of Uttarakhand, India. The study revealed that the economic constraints were ranked first (mean score of 2.36 out of maximum possible score of 3) followed by severity of marketing constraints (2.11),

technological constraints (1.91), infrastructural constraints (1.81) and situational/environmental constraints (1.56).

Ghanghas *et al.* (2021) undertook a study on prospects and constraints experienced in organic farming by farmers. They reported that environment friendly and improvement in soil health were perceived bright aspects occupied 1st rank, followed by organic products are safe, healthy and nutritious, enhance the employment opportunities and reduce dependence on external inputs for farming ranked 2nd, demand of products is increasing due to high health and nutrition awareness among people ranked 3rd, helps in conservation natural resources and biodiversity ranked 4th and produce fetches high price resulting in higher income occupied 5th rank. Whereas least bright or not bright prospects perceived by farmers were such as promotion of agro-based industries ranked 11th followed by it provides leverage to organic production of dairy, poultry, fishery etc. other allied fields of farming rank 10th and higher yields after conversion rank 9th. While remaining aspects were perceived to be somewhat bright by organic farmers.

Conclusion

In India, the growth of organic farming is relatively slower despite the fact that it is the best solution to the environmental problems such as climate change, health and sustainability issues that India is facing today due to conventional farming. Put the prospects here.....In hill regions, small farm holders face a number of constraints in practicing organic farming. The major constraints faced by them were economic and marketing including initial low price for the organic produce, lack of specialized market, initial yield loss and high transportation cost. These constraints need to be overcome by appropriate interventions. Extension services of the state should be strong and information on different aspects of organic farming should be provided to the farmers.

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Government Schemes for the Development of Agribusiness

Article ID: 72307

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Introduction

Agribusiness refers to the integration of agriculture and business principles to create a more efficient and profitable agricultural sector. The development of agribusiness involves various factors that contribute to its growth and evolution. These factors include technological advancements, policy reforms, market integration, infrastructure development, and capacity building.

Agribusiness includes all the activities within the agricultural food and natural resource industry involved in the production of food and fibre. (Goldberg and Davis,1957). The term was used first time by Davis and Goldberg in 1957, it represents Wholesale and retail sector, Processing Sector, Product Marketing Sectors and Resource Supply Sector.

Examples: Agri Chemicals Companies, Veterinary Supply Companies, Livestock Supply Companies, Biotechnology Firms, etc.

Scope of Agribusiness in Indian Economy

It is a critical sector of the economy for the country's long-term and inclusive economic growth. The sector employs 49.6% of the workforce, which is often seasonal, under-employed and underpaid, and accounts for ~17% of India's GDP

1. Agro industries are considered an extended arm of agriculture but in India they have not received as much attention as agriculture. While agriculture contributes about 17% of GDP of India, the value of added by processing industry is only 8 % of total production. In India only 2% of horticulture products are processed and more than only 30% is wasted due to lack of storage & processing facilities.
2. The global market is enormous from sugar, cotton, tea & processed foods sauce jelly & honey. The market meat spices and fruits is equally large. Only with mass production aided by modern technology & intensive marketing can the domestic market as well as export market be exported to the fullest extent
3. The size of food market is Rs. 3,50,000 crores. An average Indians spends around 53% of income on food. The domestic market for processed foods is not only huge but is growing fast in tandem with the country.
4. Agro based industries help in processing agri. Products are field crop, tree crops, livestock, fisheries & convert them to edible & other usable forms.
5. The raw materials & commodities product and marketed in India are wide range –paddy, wheat, rice, maize, sugarcane, potato, fruits, coffee, medicinal plants & honey. All these commodities are processed & consumed in huge quantities within the country & also exported. The domestic market for these items is growing at fast pace.
6. For Indians women, cooking is the way of life & also a matter of pride, different for urban women & particularly employed women. It is therefore important for food processing industries to create value addition in all processed food products to convenience the majority of women folk.
7. Dairy products have enormous potential. Country has made tremendous strides in last 20 years in production & processing of milk produced is processed.

Agriculture business has got tremendous scope as it covers not only a wide range of activities but also a multifarious magnitude of activities.

Challenges of Agribusiness Sector

1. Poor marketing and finance facilities.
2. Lack of infrastructure.
3. Trained personnel.
4. Out-dated technology.
5. Poor management.

List of Government Schemes for the Development of Agribusiness in India

1. Kisan credit card scheme
2. Agri-clinic Agri-business center scheme
3. Interest subvention scheme
4. Market intervention scheme
5. Agri-market infrastructure fund scheme
6. Integrated scheme for Agricultural Marketing
7. National Livestock Mission
8. Pradhan Mantri MUDRA Yojana
9. Pradhan Mantri Fasal Bima Yojana
10. PM- AASHA (Annadata Aay Sanrakshan Abhiyan)
11. PM- KISAN Yojana
13. PM- Formalization of Micro-food processing Enterprises scheme
14. Agriculture Infrastructure fund scheme
15. Animal Husbandry Infrastructure Development fund scheme.

Conclusion

Government schemes for the development of agribusiness play a vital role in fostering growth, sustainability, and innovation in the agricultural sector. These schemes aim to address the challenges faced by farmers, enhance productivity, promote entrepreneurship, value-addition and focusing on the welfare of marginalized communities, including small farmers, women, and rural youth and ensure food security. By providing financial support, technical assistance, and access to modern technologies, the government encourages the adoption of best practices and the development of agribusiness enterprises. This enables them to increase their productivity, reduce post-harvest losses, and improve the overall efficiency of their operations. These schemes have the potential to drive the agribusiness sector towards greater productivity, resilience and sustainability, ensuring food security and economic prosperity for generations to come.

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An Overview of Plant Based Meat Industry in India

Article ID: 72308

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Introduction

Plant-based foods are those that are devoid of animal origin ingredients whether in the processing or as part of the final product. These plant-based alternatives are foods and beverages made with vegetables, grains, nuts, millets, legumes, fungi or algae.

Plant-based meat alternative (PBMA) is a food product made from vegan ingredients and eaten as a replacement for meat. PBMA must imitate the qualities of specific types of meat, such as mouthfeel, flavour, appearance and chemical characteristics. These PBMA are also known as meat analogue, fake meat, vegan meat, mock meat, imitation meat or vegetarian meat.

History

1. Tofu is a meat alternative made from soybeans, was invented in China by the Han dynasty (206-220AD) The tofu was popularly known as "small mutton".
2. John Harvey Kellogg developed meat replacements variously from nuts, grains and soya, start in the year 1877, such as Nuttose and Protose.
3. Tofurky a plant -based turkey alternative was created in the US during 1980s.
4. In April 2019, Burger King partnered with Impossible Foods to launch the plant-based Impossible Whopper, Global scenario of PBMA.

Global Scenario of PBMA

The global meat substitutes market is estimated to be valued at USD 1.89 billion in 2021. It is projected to reach USD 4.04 billion by 2027, recording a CAGR of 13.5 per cent during the forecast period. USA and Europe are the major consumers of PBM.

Indian Scenario of PBMA

According to a report published by Global News Wire, India's meat substitute market is estimated to advance at a CAGR of 7.48 per cent during the forecast period of 2021–26, reaching US\$ 47.57 million by 2026. The market is largely driven by rising health concerns, coupled with an increase in awareness of different diseases caused by a deficiency in proteins. Over the next few years, growth in the number of vegetarians will continue to fuel the market. According to the United States Department of Agriculture (USDA) industry report, India seems to be a nascent market for plant-based meat substitutes. India has emerged as the largest consumer base in the world, with a massive scale of urbanization and transition in income groups. As per a survey conducted by the University of Bath and the Good Food Institute in 2019, 63 per cent of Indians were either very or extremely likely to buy plant-based meat daily.

Opportunities

1. Select consumer groups are willing to spend more on innovative, trendy, and high-quality healthy foods.
2. Greater concern for the environment and sustainability is fuelling "value-based" purchases.
3. Growing focus on nutrition and fitness is increasing demand for healthy food products.
4. Rising demand for frozen, ready-to-eat, and ready-to-cook products.
5. Consumers moving away from cereals toward more protein-rich diets.
6. Plant-based meats are seen as trendy, aspirational, and a status symbol in urban areas.
7. Fast-paced and busy lifestyles with limited time available for cooking and meal preparation.

Challenges

1. Price-sensitive market
2. Fragmented and long supply chain resulting in food wastage, and inadequate transportation for perishable items.
3. Lack of awareness towards plant-based meat products.
4. Lack of acceptance of processed food products as consumers tend to prefer fresh foods.

Major Players of Plant Based Meat Industry

International Level:

- a. Beyond Meat.
- b. Maple Leaf
- c. Impossible Meat.
- d. Quorn.

National Level:

- a. Good Dot
- b. Imagine Meat
- c. Blue Tribe
- d. Wakao.

Conclusion

PBMAs are emerging foods with delicious content and excel in the taste in the coming years by retaining maximum nutrition. Health-promoting food ingredients will offer a good substitute for meat consumption in terms of environmental, health, and ethical issues. The transition from animal to plant-based protein is an effective approach to tackle the impending food crisis and promote minimally processed PBMA. The consumption of protein-rich PBMA food shifts attention from the unsustainable meat industry, which generates huge waste, cause pollution, makes animal susceptible to diseases, and mitigates climate change.

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Turkey Berry (*Solanum torvum*): A Hidden Strength Beneath the Brinjal Plant

Article ID: 72309

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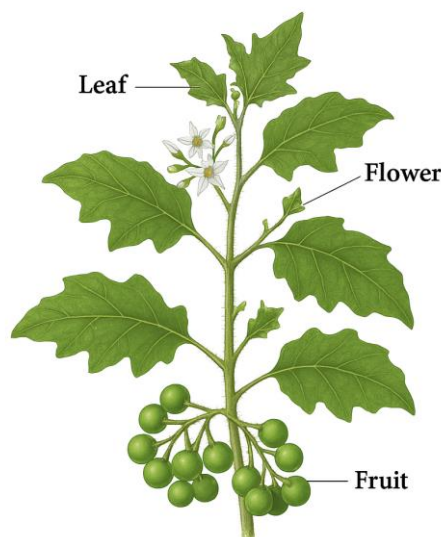
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Introduction

The last few years have seen a rise in the concept of what some call the "hidden helpers" of horticulture plants, which play a quiet, behind-the-scenes role in supporting the big crop stars in ways that are not necessarily apparent. Turkey Berry (*Solanum torvum* Swartz), also known as **pea eggplant**, **devil's fig**, or **pendejera**, is one of the unsung heroes of the food forest. This is a common, very hardy perennial shrub in the family Solanaceae used as a vegetable and rootstock for brinjal (eggplant).

Although we are most familiar with the small green fruits of the plant, which are used in many Asian and African dishes, the plant's true strength lies underground in its robust, disease-resistant root system. *Solanum torvum*, as the rootstock of brinjal, also copes with various soil-borne problems and utilises them to extend the lifespan of the brinjal plants. This dual significance as a horticultural economic plant and a nutritional food makes it an increasingly relevant crop for sustainable vegetable production in the tropics.



Turkey Berry
Solanum torvum

Botanical Features and Growth Habit

Solanum torvum is a spiny, bushy, erect and perennial plant with 2–3 m heights. The foliage consists of large, ovate, rough-textured leaves adorned with short spines along the midrib. The plant bears clusters of small, white, star-shaped flowers, which develop into pea-sized, green berries that turn yellow upon maturity. One of the biggest strengths of the grass is its deep, fibrous root system, which helps the plant thrive in drought-prone, poor soils, and disease-prone conditions. It acclimatises better to tropical and subtropical climates, and retains yield even in degenerated soils where other solanaceous crops do not. Its ability to adapt to various soil types and climates, along with its high disease tolerance, makes it a prospective rootstock for brinjal.

Global Distribution and Cultivation

S. torvum is a native of Central and South America, but it has disseminated naturally to the entire Asia, Africa, and some countries of the Caribbean. It is now a plentiful modern-day species, primarily found in India, Sri Lanka, Thailand, the Philippines, Indonesia, Malaysia, Ghana, and Nigeria, either as a planted species or a native one.

In India, it is primarily distributed in the southern and eastern states, including Tamil Nadu, Karnataka, Kerala, and Andhra Pradesh, as well as the northeastern states (Arunachal Pradesh, Assam, Mizoram, Manipur and Meghalaya), where farmers cultivate it in backyard gardens or nurseries. It performs best in warm, humid climates and well-drained, sandy loam soils, but can also withstand semi-arid environments. Fodder beet grows so well with so little care that it can be considered a robust element of low-input farming systems.

Global and Indian Culinary Uses

Turkey Berry: A traditional cuisine favourite, it may have a slightly bitter taste, but it is popular amongst many cuisines. Widespread in the tropics, it is cooked, fried, pickled, or dried for future use.

1. In **Thailand**, the small berries are used in *kaeng tai pla* and *green curry* dishes for their texture and mild bitterness.
2. It is used whole as a flavouring vegetable in soups and stews in **Ghana and Nigeria**, and to “clean the blood”.
3. In **Sri Lanka**, *sundakkai* is sun-dried and used in rice items and some medical preparations.
4. In the **South of India**, especially in **Tamil Nadu and Kerala**, Turkey Berry curry, also known as *sundakkai vathal kuzhambu*, is a staple that can stimulate your appetite and digestion.

The increasing acceptance of functional vegetable components has contributed to their incorporation into modern health-conscious and immunity-focused diets. Dried Turkey Berry is now available in stores in powdered form for daily consumption.

Nutritional and Medicinal Importance

Turkey Berry is popular as a functional food due to its rich nutrient content. These tiny green fruits are edible and are rich in minerals and bioactive compounds, according to Rahman *et al.* (2020). Fruits of *S. torvum* are rich sources of iron, calcium, phosphorus, and dietary fibre as well as the bioactive compounds antioxidants, flavonoids, and phenolic compounds. Those ingredients yield a handful of health benefits:

1. Sustains haemoglobin and fights against iron-deficiency anaemia.
2. This helps in controlling sugar and cholesterol, thus helpful in diabetes and hypertension.
3. Promotes digestion and liver with mild bitter and detoxification benefits.
4. It also has anti-inflammatory and anti-microbial properties, as well as an antiulcer effect
5. It serves as a natural remedy for exhaustion and overall frailty.

Medicinally, extracts from the fruit, leaves, and roots are utilised in Ayurveda, Siddha, and African traditional medicine for treating cough, fever, asthma, and stomach diseases. The plant also contains **solasodine**, a steroid alkaloid with industrial applications in the synthesis of cortisone and contraceptive steroids (Akoto *et al.*, 2015).

Importance as a Rootstock for Brinjal

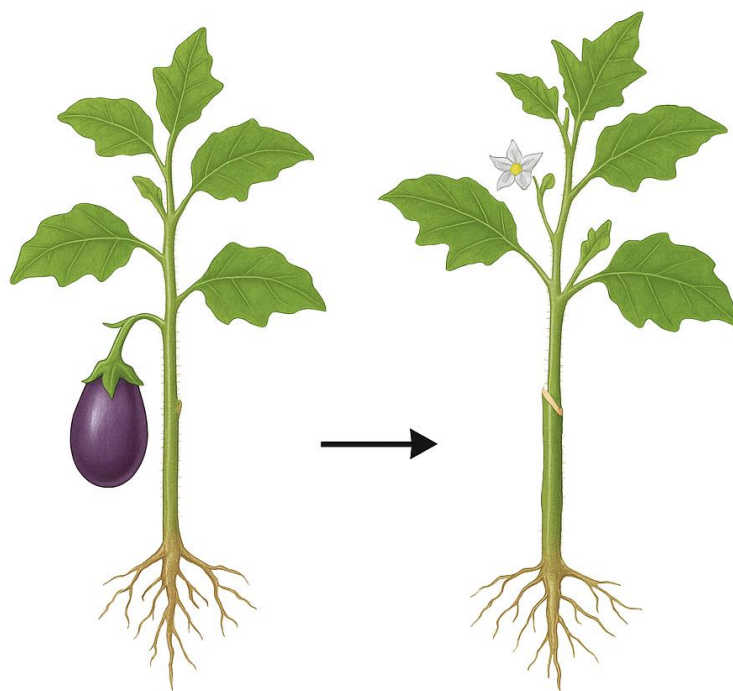
However, one of the most incredible uses of *Solanum torvum* in horticulture is brinjal's (*Solanum melongena* L.) rootstock. As a shallow-rooted crop, brinjal is prone to many diseases, including Fusarium wilt, bacterial wilt (*Ralstonia solanacearum*), and root-knot nematodes (*Meloidogyne spp.*) all factors which lead to lower yield and shorter crop life.

Brinjal plants thrive and produce more fruits over a longer season (2 years) when grafted on *S. torvum*. Grafted brinjal has gained popularity due to its early fruiting advantage, and studies at the Tamil Nadu level demonstrate a yield benefit of 30–40% over non-grafted ones (TNAU Bulletin, 2022). At IIHR, grafted brinjal has shown an increase in yield of 30–40% over non-grafted brinjal.

Therefore, Turkey Berry becomes a two-way plant, which benefits both sustainable horticulture and human health.

Cleft grafting, also known as tube grafting, is commonly used, and its success rate is often more than 90%. Practical experiences by farmers indicate reduced wilting incidents, improved root vigour, and better fruit quality. Furthermore, *S. torvum* rootstock enhances the crop's tolerance to salinity, drought, and temperature stresses, allowing farmers to grow brinjal continuously on the same land without lengthy crop rotations.

Grafting of Brinjal on *S. torvum* Rootstock



Grafted brinjal seedlings on *S. torvum* rootstock are produced commercially by most private nurseries and supplied to the farmers in many parts of the country, particularly in Tamil Nadu and Karnataka. Not only can it ensure a greater margin, but it will also help eliminate the need for chemical pesticides, which is precisely what sustainable and eco-friendly vegetable cultivation is all about.

Table 1. Comparison of Grafted vs Non-Grafted Brinjal Performance on *Solanum torvum* Rootstock:

Parameter	Non-Grafted Brinjal	Grafted on <i>S. torvum</i>	% Improvement	Remarks
Plant vigour	Moderate	High	+35%	vigour
Yield (t/ha)	22–25	30–35	+30–40%	yield

Incidence of bacterial wilt	60–70%	<10%	Strong resistance
Crop duration	6–8 months	16–20 months	Extended by 1 year
Root-knot nematode infection	Severe	Mild to negligible	Excellent tolerance
Pesticide requirement	High	Moderate to low	40% reduction

Source: TNAU Horticulture Bulletin (2022); Singh & Pandey (2018); Rao & Bhatt (2021).

Propagation and Cultivation Practices

Seeds of Turkey Berry germinate rapidly (2–3 weeks) under warm, moist conditions, making this species easy **to propagate from seed**. At physiological maturity, the fruit is harvested and the seeds are extracted, cleaned, and dried before sowing.

It is raised in polybags or nursery beds and transplanted at a height of 10–12 cm. Seedlings are kept at 45–60 days of age and uniformity for use as rootstock before grafting. They prefer a sunny location with well-drained soil, but are also acceptable in marginal areas. Weed and use light pruning to shape plants and promote fruit production. *S. torvum*, once established, needs little maintenance other than watering during extended dry periods.

Under the given circumstances, the shrub can survive for several years, providing both dessert and rootstock for future generations.

Future Prospects and Research Needs

Due to the increased realization of sustainable production of vegetables, this open cross-pollinated crop species has a huge scope of research and commercial exploitation.

Key Future Areas Include

1. Identifying new rootstock lines with superior compatibility and stress resistance.
2. Molecular identification of genes responsible for resistance against diseases.
3. Fast multiplication of elite rootstock material using micropropagation techniques
4. Understanding its phytochemicals for the nutraceutical and pharmaceutical sectors
5. Extension and demonstration of vegetable grafting technology to farmers.

Moreover, the inclusion of Turkey Berry production in organic and mixed farming systems will contribute to ecological sustainability and could provide more stable income for smallholders. This aligns with the concept of climate-smart agriculture, which is often characterised by low-input and pest-resistant practices.

Conclusion

The humble Turkey Berry, which has been treated as a wild weed or a home-garden plant, is gradually gaining affection in the hearts of farmers and consumers as a friend. As a hardy rootstock for brinjal and a source of edible fruits, it is indeed a vegetable **"hidden strength"**.

The use of *Solanum torvum* in grafting, coupled with its application as a food and medicine, could offer a sustainable solution to combat soil degradation and malnutrition through improved crop productivity, enhanced soil health, and improved human nutrition. As research funding continues to increase and more people learn about this small green berry, it could become a crucial aspect of sustainable olericulture in India and globally.

Did You Know?

Turkey berry (*Solanum torvum*) fruits contain **solasodine**, a natural **steroidal alkaloid** used in the **pharmaceutical industry** to manufacture **cortisone**, **steroid hormones**, and **certain contraceptive medicines**.

Besides its medicinal role, solasodine also contributes to the plant's **natural resistance to pests**, making *S. torvum* a valuable component in sustainable horticulture.

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E-Crop 3.0: Integrating AI, IoT, and Blockchain for Digital Farming Transformation

Article ID: 72310

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Abstract

The growing demand for sustainable and efficient agricultural systems has paved the way for the digital transformation of farming. E-Crop 3.0 represents the next generation of smart agriculture, combining the power of Artificial Intelligence (AI), the Internet of Things (IoT), and Blockchain technology. This integration ensures precise monitoring, data-driven decision-making, transparency, and traceability across the agricultural value chain. This article explores the concept, components, and applications of E-Crop 3.0, highlighting how these technologies collectively reshape modern farming for higher productivity, sustainability, and profitability.

Introduction

Agriculture, the backbone of many economies, is facing unprecedented challenges—ranging from climate change and soil degradation to water scarcity and rising input costs. To address these issues, digital farming technologies have emerged as transformative tools.

E-Crop 3.0 is an advanced framework that integrates AI, IoT, and Blockchain into a unified platform to enable data-driven, transparent, and adaptive agriculture. While E-Crop 1.0 focused on mechanization and E-Crop 2.0 emphasized precision farming, E-Crop 3.0 moves toward intelligent, connected, and trusted ecosystems.

This new paradigm empowers farmers to make informed decisions, enhances supply chain efficiency, and supports sustainable resource management. The combination of AI-driven analytics, IoT-enabled sensing, and Blockchain-based traceability forms the foundation of this digital revolution.

Core Technologies of E-Crop 3.0

1. Artificial Intelligence (AI): AI serves as the analytical core of E-Crop 3.0. By processing large volumes of farm data, AI algorithms identify patterns and provide actionable insights.

Applications include:

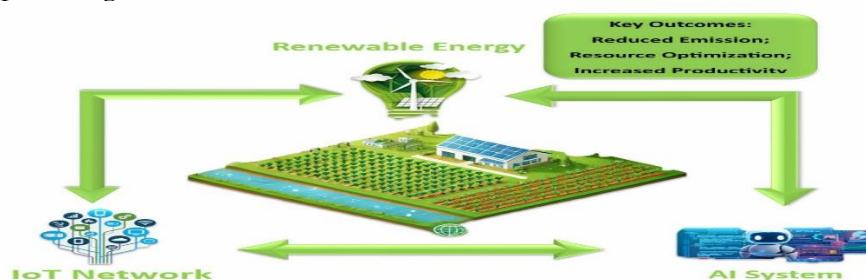
Predictive Analytics: Forecasting crop yields, pest outbreaks, and irrigation needs.

Image Recognition: Using drone and satellite imagery to detect diseases, nutrient deficiencies, and weed infestations.

Decision Support Systems (DSS): AI models guide farmers on optimal sowing dates, fertilizer schedules, and pest management.

Automation: Enabling autonomous tractors, drones, and robotic harvesters for precision field operations.

Through machine learning, AI continuously improves its predictions, ensuring higher efficiency and sustainability in crop management.



Source: <https://www.mdpi.com>

2. Internet of Things (IoT): IoT forms the sensory and communication backbone of E-Crop 3.0. Smart sensors collect real-time data from soil, water, air, and crops, which is transmitted to cloud-based systems for analysis.

IoT applications in E-Crop 3.0 include: Smart Irrigation: Soil moisture and weather sensors regulate water use automatically, reducing wastage.

- Soil Health Monitoring:** IoT devices measure pH, salinity, and nutrient levels for timely interventions.
- Livestock and Greenhouse Management:** Wearable and environmental sensors monitor temperature, humidity, and animal health.
- Supply Chain Tracking:** RFID and GPS-enabled devices ensure transparent product movement from farm to market.
- IoT ensures continuous connectivity and real-time decision-making across agricultural systems.



Source: <https://www.sciencedirect.com>

2.3 Blockchain Technology: Blockchain introduces trust and transparency to agriculture by providing an immutable ledger for recording every transaction or data point.

Benefits include:

- Traceability:** Consumers can verify the origin and production practices of food products.
- Smart Contracts:** Automate payments and logistics once specific conditions are met (e.g., delivery confirmation).
- Data Security:** Ensures that farm and supply chain data are tamper-proof.
- Fair Trade and Certification:** Blockchain helps verify organic or sustainable certifications, improving farmers' market credibility.

Integration Framework of E-Crop 3.0

- E-Crop 3.0 integrates AI, IoT, and Blockchain through a unified digital ecosystem.
- Data Collection (IoT Layer):** Sensors and drones collect multi-source data such as soil moisture, temperature, crop health, and weather conditions.
- Data Processing (AI Layer):** AI algorithms analyze the data for predictions and recommendations.
- Data Validation (Blockchain Layer):** Processed data and transactions are recorded securely, ensuring transparency.
- Decision and Action:** Farmers receive real-time insights through mobile apps or dashboards, enabling precision operations.
- Feedback Loop:** The system continuously learns and updates its models to improve future performance.

Applications and Case Studies

1. Smart Crop Monitoring: AI and IoT sensors detect early signs of disease or stress. For example, NDVI (Normalized Difference Vegetation Index) imaging from drones, combined with AI analytics, enables early intervention—reducing losses by up to 30%.

2. Precision Irrigation and Fertilization: IoT sensors and AI algorithms calculate the exact water and nutrient requirements, leading to improved input-use efficiency. In India, startups like Fasal and Crop In are pioneering these precision systems.

3. Blockchain-Based Supply Chains: Blockchain-enabled traceability systems allow consumers to scan QR codes to verify the source and quality of produce. Such systems are already in use for coffee, rice, and organic vegetables in several countries.

4. Climate-Smart Decision Support: AI models integrate satellite data and weather forecasts to recommend climate-resilient crop choices and management practices. This helps farmers adapt to changing environmental conditions.

Advantages of E-Crop 3.0

Aspect Impact:

- Productivity- AI-guided decision-making enhances yields through precision operations.
- Sustainability- IoT-enabled monitoring reduces input waste and environmental impact.
- Transparency- Blockchain ensures traceability and consumer trust.
- Profitability- Optimized resource use lowers costs and improves market access.
- Resilience- AI-based predictive systems help farmers mitigate risks from pests, droughts, and market fluctuations.

Challenges and Limitations

Despite its potential, E-Crop 3.0 faces several challenges:

- 1. High Initial Cost:** Investment in sensors, connectivity, and blockchain infrastructure is expensive.
- 2. Digital Divide:** Smallholders often lack technical literacy or internet access.
- 3. Data Privacy:** Managing ownership and sharing of farm data remains a concern.
- 4. Interoperability:** Integration between different platforms and devices requires standardization.

To overcome these, governments and private sectors must collaborate on training, infrastructure, and policy development.

Future Prospects

The future of E-Crop 3.0 lies in combining AI-driven robotics, edge computing, and 6G communication technologies for real-time precision and automation. Integration with satellite-based remote sensing and digital twins will further enhance decision accuracy. Additionally, the use of genomic data, climate models, and carbon accounting tools within E-Crop 3.0 will promote sustainable and climate-resilient farming systems.

Conclusion

E-Crop 3.0 represents a paradigm shift in modern agriculture. By merging Artificial Intelligence, IoT, and Blockchain, it offers a comprehensive approach to achieve data-driven, transparent, and sustainable farming. The integration of these technologies enables farmers to optimize inputs, increase productivity, and build trust within the food system.

As global agriculture moves toward digital ecosystems, E-Crop 3.0 will play a crucial role in achieving the goals of smart, sustainable, and equitable food production—ensuring food security for the future generations.

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Use of Trees in the Gardens

Article ID: 72311

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Trees

Trees can be classified into two groups namely, shade (or foliage) and ornamental trees and flowering trees. The line of demarcation between the two groups may sometimes get blurred. In the first group, only those trees are included which are planted for their showy ornamental foliage or for shade and which are either nonflowering (e.g., Cone bearing gymnosperms) or bear inconspicuous flowers. In the second group are included trees bearing showy and ornamental flowers.

Trees can be used in gardens as specimen, avenue plantation, wind break and screening of less pleasing sites and offer privacy. They provide shade and shelter and also reduce heat during hot summer.

Shade and Ornamental Trees Tress

Botanical name	Family	Common name	Particulars
<i>Albizzia lebbek</i>	Leguminosae	Vahai, Siris tree, Lebbek tree, Womans tongue tree	Deciduous, fast growing and spreading tree with thin feathery foliage. Resistant to drought.
<i>Alstonia scholaris</i>	Apocynaceae	Devil's tree	Elegant tree with whorled branches. Produces drumstick like fruits during summer
<i>Anthocephalus cadamba</i>	Rubiaceae	Kadamba	Tall tree with spreading crown and drooping branches. Flowers are ball like.
<i>Azadirachta indica</i>	Meliaceae	Vembu	Medium sized ever green tree with foliage light green, serrated leave. Recommended as a avenue tree for high ways.
<i>Callophyllum inophyllum</i>	Guttiferaceae	Alexandrian laurel, Dilo oil tree	Greek 'Kalos' meaning beautiful and 'phyllon' means leaf and 'inophyllum' means with strongly nerved leaves. The tree is more attractive for its large and shining leaves.
<i>Casuarina equisetifolia</i>	Casuarinaceae	Beef wood, she oak tree.	Suitable for growing in dry and hot tracts and is quick growing.
<i>Dalbergia sissoo</i>	Leguminosae	Sissoo tree.	Plant can stand drought as well as submerged conditions for a fairly long duration.
<i>Eucalyptus spp.</i>	Myrtaceae	Blue gum tree	It draws enormous amount of water from the soil. Grown as wind break at a spacing of 5 - 8 m.
<i>Ficus bengalensis</i>	Moraceae.	Banyan	Huge tree with aerial roots originating from the branches strike into the soil and gives a columnar support to the immense head of foliage.

<i>Ficus benjamina</i>	Moraceae	Java fig tree, Golden fig.	Evergreen tree with drooping branches. The globose fruits when ripe are very ornamental.
<i>Ficus elastica</i>	Moraceae	Indian Rubber Tree	Quick growing often reaching 15 to 60 m height, smooth shining leaves. Young leaves remain enclosed in a pinkish stipule giving the plant an ornamental look.
<i>Filicium decipiens</i>	Sapindaceae	Fern leaved tree.	Ornamental tree with attractive foliage.
<i>Grevillea robusta</i>	Proteaceae	Silver oak	Evergreen tree with finely divided fern like leaves, the under surface of which is silvery downy.

Fruit Trees for Avenues

Botanical name and family	Family	Common name	Characters
<i>Averrhoa carambola</i>	Oxalidaceae	Carambola tree	Medium sized tree and very ornamental
<i>Eugenia jambolana</i>	Myrtaceae	Jambolan	Tall and spreading tree and propagated through seeds
<i>Mangifera indica</i>	Anacardiaceae	Aam	
<i>Phyllanthus emblica</i>	Euphorbiaceae	Amla	Ornamental tree suitable road side planting
<i>Tamarindus indica</i>	Leguminosae	Tamarind	Large tree suitable for road side planting.

Flowering Trees

Botanical name and family	Family & Common name	Flower colour and flowering time	Characters
<i>Amherstia nobilis</i>	Leguminosae (Queen of flowering trees)	Vermilion coloured raceme with yellow flowers (February – May)	Medium sized spreading tree and young leaves remain folded with purplish coppery hue
<i>Bauhinia purpurea</i>	Leguminosae (Purple bauhinia or geranium tree)	Rosy purple or lilac or deep pink (November)	Medium sized evergreen tree with clawed or pointed flowers which are large and showy
<i>Callistemon lanceolatus</i>	Myrtaceae (Bottle brush tree)	Brilliant Crimson Scarlet (April May and Aug – Sep)	A small tree with narrow lanceolate leaves and weeping branches, propagated from seeds or layers
<i>Cassia fistula</i>	Leguminosae (Sarakonnai or Golden shower)	Bright yellow flower (February – May)	Medium size beautiful tree with long pendulous racemes.
<i>Erythrina indica</i>	Leguminosae (Kalyan Murungai or Indian coral tree)	Scarlet red flowers (March-May)	Propagated by cuttings seed and
<i>Delonix regia</i>	Leguminosae Gul Mohar	Orange flowers (April-May) scarlet	Raised from seed

<i>Lagerstroemia flosreginae</i> (Syn. <i>L. speciosa</i>)	Lythraceae Pride of India	Mauve flowers (April – May) coloured	A large deciduous tree, easily propagated from seeds
<i>Michelia champaca</i>	Leguminosae Shembagam	Light yellow whitish and red flowers (April - May and Sept - October)	Seedling takes three years to bloom
<i>Melia azedarach</i>	Meliaceae Persian Lilac	Lilac flower (March – May)	Deciduous 15 to 20 feet height, bipinnate leaves small heliotropic scented lilac flowers in large panicle
<i>Mellingtonia hortensis</i>	Bignoniaceae Indian cork tree or tree jasmine	Fragrant pure with jasmine like flowers (June – Nov)	A tall stately rapid growing tree, propagated from seed or by sucker
<i>Parkia biglandulosa</i>	Leguminosae Badminton ball tree	White flower (April – May)	Pretty foliage, pinnate leaves, small white flowers with long peduncle, propagation from seed
<i>Peltophorum ferrugineum</i>	Leguminaceae Copper shield	Pale yellow colour (April – May)	Quick growing tree, Fine graceful feather foliage, pinnate leaves, raised from seed
<i>Plumeria alba</i>	Apocynaceae Pagoda tree or temple tree	White colour Throughout the year	Handsome trees with architectural shapes and fragrant flowers. Evergreen species gives waxy white flowers throughout the year
<i>Plumeria rubra</i>	Apocynaceae Pagoda tree or temple tree	Red colour Throughout the year	Handsome trees with architectural shapes and fragrant flowers. Evergreen species gives waxy red flowers throughout the year
<i>Spathodea campanulata</i>	Bignoniaceae Indian Tulip	Orange, Scarlet flowers (June – July)	Leaves are glossy and bright green raised from seed
<i>Tabebuia rosea</i>	Bignoniaceae	Pale mauve coloured flowers	Good avenue tree
<i>Tabebuia avalandi</i>	Bignoniaceae	Mauve flowers (November - January)	Umbrella shaped tree and a good specimen tree for gardens

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Microbial Biostimulants: Feeding Plants through Microbes

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Microbial biostimulants are beneficial microorganisms that enhance plant nutrition through biological processes rather than direct chemical supplementation. These living allies improve nutrient use efficiency, reduce fertilizer requirements by 20-30%, and enhance crop resilience to environmental stress. By restoring damaged soil microbiomes and providing sustainable alternatives to chemical inputs, microbial biostimulants represent a shift toward precision biological agriculture that maintains productivity while protecting environmental health.

Microbial Biostimulants

Microbial biostimulants are living microorganisms that enhance plant nutrition and growth by improving nutrient availability, uptake, and utilization. Unlike traditional fertilizers that directly supply nutrients, these beneficial microbes work symbiotically with plants to optimize nutrient cycling and accessibility through biological processes.

Why are Microbial Biostimulants Important for Agriculture?

- 1. Food Security Challenge:** With the global population expected to reach nearly 10 billion by 2050, microbial biostimulants offer a sustainable approach to enhance crop yields while improving nutrient quality and food security.
- 2. Declining Soil Health:** Intensive use of chemical fertilizers and pesticides has severely damaged natural soil microbiomes, leading to poor soil fertility. Microbial biostimulants help restore beneficial microbial populations that rebuild soil health and support long-term agricultural productivity.
- 3. Climate Stress Adaptation:** As climate change intensifies, crops face increasing drought, salinity, and temperature stress. Microbial biostimulants enhance plant resilience by helping crops adapt and survive under harsh environmental conditions.
- 4. Sustainable Agriculture Need:** Heavy reliance on costly chemical inputs has contributed to environmental pollution and biodiversity loss. Microbial biostimulants provide eco-friendly alternatives that naturally boost plant growth while reducing chemical dependency.

How do Microbial Biostimulants Work?

1. Hormonal Regulation: Microbial biostimulants influence plant hormone levels by modulating the endogenous hormonal balance through the biosynthesis or degradation of specific hormones. By fine-tuning this hormonal cross-talk, they create a synchronized growth and defense response in plants, ensuring optimal development and enhanced resilience under various environmental conditions.

a. Abscissic acid (ABA): ABA reduces water loss by controlling stomata. They modulate endogenous hormonal balance through biosynthesis or degradation of specific hormones. This quick response minimizes dehydration and helps plants sustain photosynthetic activity even under water stress.

b. Indole-3-acetic acid (IAA): IAA regulates root elongation and branching. They produce IAA that stimulates root hair proliferation and lateral root formation, increasing soil exploration. Such well-branched roots enhance nutrient uptake and improve anchorage in soil ecosystems.

c. ACC deaminase: This hormone lowers ethylene, reducing stress damage. This enzyme degrades ACC, the ethylene precursor, preventing premature senescence and growth inhibition under stress. Plants treated with ACC deaminase-producing bacteria often show better recovery after drought or flooding.

d. Jasmonic acid (JA) & Salicylic acid (SA): These hormones strengthen stress tolerance and disease resistance. Microbial biostimulants trigger JA/SA signaling pathways, inducing systemic resistance against pathogens. These pathways act like a plants immune memory, preparing it to combat future stress more efficiently.

Together, these hormones create a balance that supports better growth under both normal and stressful conditions. This hormonal homeostasis helps plants maintain metabolic stability and adaptability.

2. Balancing Oxidative Stress: Under stress, plants generate reactive oxygen species (ROS), which damage cells. Excess ROS oxidize lipids, proteins, and nucleic acids, impairing cellular function. Microbial biostimulants-inoculated plants show:

a. Antioxidant enzymes: Microbial biostimulants enhance the activity of antioxidant enzymes such as catalase, peroxidase, and superoxide dismutase, which play a crucial role in neutralizing reactive oxygen species (ROS) by converting them into less harmful molecules like water and oxygen. This biochemical priming enables plants to mount a faster and more effective response to oxidative stress when it arises.

b. Osmolytes production: They also promote the accumulation of osmolytes such as proline and glycine-betaine by stimulating their biosynthetic pathways. These osmolytes help stabilize cellular proteins and membranes under stress conditions while maintaining turgor pressure, thereby keeping leaves hydrated and physiologically active even in adverse environments.

As a result of this balanced biochemical response, oxidative damage is minimized, cell membrane integrity is preserved, and photosynthetic efficiency remains stable. Collectively, these effects manifest as healthier foliage, sustained growth, and improved biomass accumulation under challenging environmental conditions.

3. Water Use Efficiency and Photosynthesis: Microbial Biostimulants help plants manage water better by altering root architecture and aquaporin regulation to optimize water uptake. Such improved hydraulic conductivity allows plants to survive longer under limited water availability.

a. Microbial biostimulants improve leaf water status and regulate stomatal conductance, ensuring efficient gas exchange with minimal water loss. This balance supports steady photosynthesis while conserving internal moisture.

b. Enhancing photosynthetic activity, even during drought or salinity stress. They boost chloroplast function and carbon fixation under stress, enhancing CO₂ assimilation and energy production for better growth and stress adaptation.

c. AMFs improve root water flow through regulation of aquaporin genes. Arbuscular mycorrhizal fungi (AMFs) enhance root water transport by modulating aquaporin expression. Their hyphae act as microchannels, allowing plants to access water from deeper or drier soil layers.

d. Microbial biostimulants also help preserve chlorophyll, ensuring effective photosynthesis. By maintaining nitrogen and magnesium levels, they reduce chlorophyll degradation, sustaining light capture and photosynthetic efficiency under stress.

4. Nutrient Use Efficiency (NUE): Microbial biostimulants enhance uptake of essential nutrients (K, Ca, Mg, Zn, Fe, Mn, and Cu). They secrete chelating compounds and enzymes that mobilize bound nutrients in the rhizosphere. This process transforms the root zone into a more nutrient-accessible environment for plants. They also help exclude harmful ions like sodium. Mechanisms include:

a. AMF hyphae expanding the root absorption zone: Arbuscular mycorrhizal fungi extend fine hyphae into soil micropores beyond the root's reach, greatly improving nutrient foraging efficiency. Their widespread network not only enhances nutrient uptake but also contributes to better soil aggregation and stability.

b. PGPR secretion of organic acids to solubilize phosphorus and potassium: Plant growth-promoting rhizobacteria (PGPR) release organic acids that lower rhizospheric pH, converting insoluble minerals into available nutrient forms. This process unlocks essential elements like phosphorus and potassium, increasing their accessibility for plant absorption.

c. Nitrogen-fixers (*Rhizobium*, *Azospirillum*) converting atmospheric N₂ into ammonia: Symbiotic and associative nitrogen-fixing bacteria transform atmospheric nitrogen into ammonia, which plants assimilate into amino acids and proteins. This natural process reduces reliance on chemical fertilizers and enhances long-term soil fertility.

d. Siderophore production making iron available for plant use: Microbial siderophores chelate ferric ions (Fe³⁺), making them readily available for microbial and plant uptake. Simultaneously, they limit pathogen access to iron, thus supporting both plant nutrition and natural disease resistance.

Major Microbial Biostimulant Groups

Plant Growth-Promoting Rhizobacteria (PGPR):

a. *Bacillus* species: Phosphate solubilization, biocontrol. They produce organic acids and lipopeptides that dissolve insoluble phosphates and inhibit soil-borne pathogens, improving nutrient availability and root health.

b. *Pseudomonas* species: Disease suppression, growth promotion. These bacteria release antibiotics and siderophores that outcompete harmful microbes while secreting growth-promoting compounds like IAA and gibberellins.

c. *Azotobacter* species: Nitrogen fixation, phytohormone production. Free-living *Azotobacter* converts atmospheric nitrogen into plant-usable forms and synthesizes vitamins and auxins that stimulate seed germination and root growth.

Mycorrhizal Fungi:

a. *Glomus* species: Phosphorus uptake enhancement. Their extensive hyphal networks increase the root's absorptive surface area, mobilizing phosphorus and other micronutrients from soil particles.

b. *Rhizophagus* species: Stress tolerance improvement. By enhancing water absorption and antioxidant activity, these fungi help plants withstand drought, salinity, and other environmental stresses.

Nitrogen-Fixing Bacteria:

a. *Rhizobium* species: Legume-specific symbiotic nitrogen fixation. They form root nodules in legumes where they fix atmospheric nitrogen, enriching the soil naturally and reducing the need for chemical fertilizers.

b. *Azospirillum* species: Associative nitrogen fixation in cereals. These bacteria colonize the rhizosphere of cereals and grasses, improving nitrogen availability while releasing plant hormones that stimulate root branching.

Endophytic Microorganisms: Beneficial microbes that colonize internal plant tissues without causing disease, providing systemic plant protection and growth enhancement. They act as invisible allies within the plant, boosting resistance to pathogens, promoting nutrient assimilation, and enhancing stress resilience through biochemical signalling.

Benefits of Microbial Biostimulants

Agricultural Benefits:

a. Improved Nutrient Use Efficiency: Microbial biostimulants boost root activity and nutrient mobilization, enabling plants to absorb more from the same fertilizer input. Enhanced NUE can reduce fertilizer requirements by 20-30%, improving both productivity and sustainability.

b. Enhanced Crop Yields: By promoting balanced nutrient uptake and hormone regulation, microbial biostimulants strengthen plant growth and reproductive efficiency. This results in higher yields and improved harvest quality.

c. Stress Resilience: Beneficial microbes enhance plant tolerance to drought, salinity, and temperature extremes by activating stress-responsive genes and stimulating osmoprotectant synthesis. This helps plants sustain vital functions even under harsh conditions.

d. Disease Suppression: Through competitive exclusion and production of antimicrobial compounds, microbial biostimulants protect roots from pathogens. They colonize rhizosphere niches and form a natural bio-shield, reducing disease incidence and promoting healthier plants.

Environmental Benefits:

a. Reduced Chemical Inputs: Microbial biostimulants decrease the need for synthetic fertilizers and pesticides, fostering more sustainable farming practices. This eco-friendly shift lowers greenhouse gas emissions and prevents long-term accumulation of chemical residues in the soil.

b. Soil Health Restoration: By rebuilding beneficial microbial communities, biostimulants revitalize soil ecosystems and enhance their biological activity. This improvement leads to better soil structure, aeration, and nutrient cycling, ultimately restoring soil vitality.

c. Water Quality Protection: Enhanced nutrient retention and root absorption reduce nutrient leaching and runoff, protecting groundwater and nearby water bodies from contamination. This minimizes eutrophication and supports cleaner aquatic ecosystems.

d. Biodiversity Conservation: Microbial biostimulants encourage rich and diverse soil life, supporting the coexistence of bacteria, fungi, and soil fauna. Such biodiversity strengthens ecosystem resilience and maintains the natural balance of agroecosystems.

Economic Benefits:

a. Cost Reduction: Microbial biostimulants cut input costs by reducing fertilizer and pesticide use. Farmers maintain or even increase yields with fewer chemical inputs.

b. Improved Crop Quality: Enhanced nutritional content and market value. Microbial interactions boost the accumulation of essential vitamins, minerals, and antioxidants, improving crop taste and shelf life.

c. Long-term Productivity: Continuous application improves soil fertility and microbial activity, creating resilient and self-sustaining soils over time.

d. Risk Mitigation: Reduced crop failure under stress conditions. Microbes act as biological insurance, ensuring stable yields even when weather or environmental factors fluctuate unpredictably.

Future Perspectives:

a. Precision Agriculture Integration: Combining microbial biostimulants with digital farming technologies for targeted application

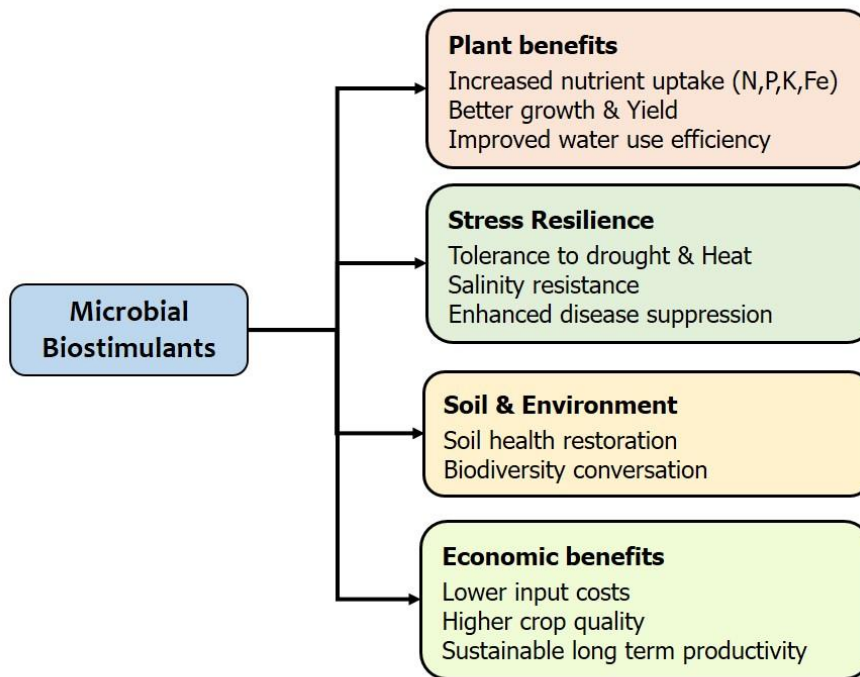
b. Multi-functional Consortia: Development of microbial communities that provide multiple benefits simultaneously

c. Genomic Enhancement: Using molecular tools to improve microbial performance and survival

d. Bioengineered Solutions: Creating synthetic microbial communities (SynComs) designed for specific agricultural applications.

Conclusion

Microbial biostimulants represent a paradigm shift toward biological agriculture, where beneficial microorganisms serve as natural partners in plant nutrition and growth. By harnessing the power of plant-microbe interactions, these biostimulants offer sustainable solutions to modern agricultural challenges. They provide a pathway to reduce chemical dependency while maintaining productivity, supporting both environmental health and food security. As our understanding of soil microbiology advances, microbial biostimulants will become increasingly important tools for feeding the world sustainably through the invisible allies beneath our feet.



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Recycling Packaging Materials

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Abstract

The environmental impact of food packaging waste is a major concern worldwide, driving efforts to adopt sustainable solutions such as the green circular economy. Recycling packaging materials plays a vital role in this shift, helping to reduce waste and conserve natural resources. However, the recycling process faces significant challenges, particularly regarding the quality and safety of the recycled materials.

Packaging materials are currently considered an important source of environmental waste because of their great volume. Although for materials like glass, aluminum, and paperboard recycling has been rather extensively practiced, it proved to be a much more arduous task for polymeric materials because of their great variety and the coexistence/mixing of various polymers either as blends or as copolymers. Therefore, constructive approach to recycling would consist of reviewing its current status worldwide to make a comprehensive presentation of the current trends and the state of art techniques for plastic disposal, sorting, and recycling. Although mechanical, feedstock, and chemical recycling of polymers are thoroughly analyzed within the frame of this review, other alternatives such as landfill, incineration, pyrolysis, reuse and recovery, and composting are also presented and commented.

The choice of recycling method often depends on the type of plastic involved. Materials such as HDPE (High-Density Polyethylene), PET (Polyethylene Terephthalate), and PP (Polypropylene) are generally suitable for both mechanical and chemical recycling. In contrast, plastics like PVC (Polyvinyl Chloride) and PS (Polystyrene) are more difficult to recycle mechanically because of their lower molecular weight and complex composition, frequently resulting in their down cycling into lower-value products.

Keywords: Recycled packaging; Waste Safety; Concerns migration Analysis quality assessment techniques; Green economy.

Introduction

Packaging has become ubiquitous in modern industrial and consumer economies, serving essential roles in protection, transportation, presentation, and shelf life extension. However, this convenience comes at substantial environmental cost. Globally, plastic waste generation more than doubled from 156 million tons in 2000 to 353 million tones by 2019. Of that total, about 40% originates from packaging materials, especially those with short lifespan.

Yet despite this large share of waste, recycling remains limited. In 2019, only 9% of plastic waste was successfully recycled, while nearly 50% went into sanitary landfills, about 19% was incinerated, and the rest was mismanaged (dumped, burned, or leaked into the environment). Meanwhile, packaging waste in regions such as the European Union has continued to grow: In 2022 the EU generated 83.4 million tones of packaging waste, with per-capita generation rising to about 186.5 kg per person in that year.

The gap between potential and actual recycling raises questions of efficiency and efficacy: materials exist, regulatory frameworks are increasingly pressing, and markets are demanding sustainable solutions, yet only a small proportion of packaging waste is being redirected from landfill or incineration into new material cycles. For example, while around 300 million tones of plastic packaging waste are generated each year globally, estimates suggest only 14% is collected for recycling.

Recycling packaging materials thus emerges not only as an environmental imperative—offering reductions in raw material extraction, energy consumption, and greenhouse gas emissions—but also as an economic and policy challenge. It involves material science (design for recyclability), logistics (collection and sorting), regulation (extended producer responsibility, mandates), and consumer behaviour. This article examines the current scope of packaging waste, the benefits and limitations of recycling, and strategies for improving uptake and impact in the transition toward a circular economy.

Recycling

According to Waite, “recycling is a very broad term referring to the conversion of waste into a useful material.” While recycling is second in priority waste management options, it has gained ground in many European and American countries as an essential ingredient for the reduction of wastes that must be land filled. Over the last decade, the emphasis on the part of municipal solid waste management has been on recycling due to the introduction of waste management hierarchy. Recycling is relatively an old method with a well-recorded history.

According to NSWA (National Solid Waste Management Association), recycling consists of five basic steps
Collection and sorting of recyclable materials from the waste stream.

Raw material reclamation by special treatment, so that they could replace virgin materials in manufacturing operations.

Marketing of the recycling materials.

Market establishment for recycled materials.

Public involvement in the recycling programs operations.

Types of Recyclable Packaging Materials

Recyclable packaging materials can be broadly categorized into plastics, paper and cardboard, metals, and glass. Each type presents unique properties, recycling processes, and challenges.

Material Type	Examples	Recycling Methods	Challenges
Plastics	PET bottles, HDPE jugs, PP containers, LDPE films	Mechanical recycling, chemical recycling (for PET and mixed plastics)	Contamination, mixed polymers, degradation of mechanical properties, sorting difficulties
Paper & Cardboard	Corrugated boxes, cartons, paper bags	Pulping, de-inking, re-forming into new paper products	Laminated or coated materials, waxed surfaces, ink residues
Metals	Aluminum cans, steel tins	Melting and re-casting	Contamination, separation of alloys, collection efficiency
Glass	Bottles, jars	Cleaning, crushing (cullet), remelting	Color sorting, contamination, heavy transport, breakage during collection

Case Study 1: Coca-Cola’s Transition to 100% Recyclable PET Bottles: A notable example of recyclable packaging implementation is The Coca-Cola Company’s initiative to produce bottles made entirely from recycled PET (rPET). In 2021, Coca-Cola introduced its first 100% rPET bottles (excluding caps and labels) in several markets, including the United States and parts of Europe. The initiative aimed to reduce the company’s carbon footprint by approximately 25% per bottle compared to bottles made from virgin plastic (Coca-Cola, 2021).

This move represented a major shift toward a closed-loop recycling system, where used PET bottles are collected, cleaned, and reprocessed into new bottles of equivalent quality. To achieve this, Coca-Cola partnered with local recycling facilities and organizations such as PET Recycling Company (PETCO) to enhance collection rates and ensure material traceability. The project also addressed quality concerns by employing advanced mechanical recycling and decontamination processes that meet stringent food-contact safety standards established by the U.S. Food and Drug Administration (FDA) and the European Food Safety Authority (EFSA).

The Coca-Cola case illustrates that large-scale implementation of recyclable packaging is both technically feasible and environmentally beneficial, provided that collection infrastructure, consumer participation, and regulatory compliance are effectively managed.

Case Study 2: Nestlé’s Transition to Recyclable Paper-Based Packaging: Nestlé, one of the world’s largest food and beverage companies, has undertaken significant steps to replace plastic packaging with recyclable paper-based alternatives as part of its global sustainability strategy. The company’s initiative

aligns with its commitment to ensuring that 100% of its packaging is recyclable or reusable by 2025 (Nestlé, 2020).

A prominent example of this transition is the introduction of paper-based packaging for its Yes! snack bars and Smarties confectionery products, which were among the first confectionery items from a major global brand to be packaged in recyclable paper instead of plastic. The Smarties paper packaging, launched in 2021, marked Nestlé's complete shift of the Smarties brand portfolio to paper packaging across 56 countries—a move expected to eliminate over 400 million plastic units annually (Nestlé, 2021).

The newly developed paper packaging is produced from sustainably sourced, FSC-certified paper and is fully recyclable through existing paper waste streams. The material was designed to provide adequate barrier protection against moisture and oxygen, ensuring product safety and shelf stability without relying on plastic laminates. Achieving this required substantial investment in research and development, as well as modifications to production lines to accommodate paper-based wrapping materials.

From a technical and environmental standpoint, Nestlé's innovation demonstrates how design-for-recycling (DfR) principles can be successfully implemented in large-scale food packaging. Moreover, it addresses consumer expectations for environmentally responsible products while complying with evolving regulatory frameworks such as the European Green Deal and the EU Packaging and Packaging Waste Directive.

The Nestlé case exemplifies how material innovation, corporate sustainability goals, and regulatory alignment can converge to reduce plastic dependency and promote circular economy practices in the food sector. It also highlights that effective recyclable packaging solutions require systemic collaboration—from material scientists and suppliers to policymakers and consumers—to ensure end-of-life recovery and recycling efficiency.

Comparative Discussion: Strategies for Advancing Recyclable Packaging

The case studies of Coca-Cola and Nestlé exemplify two distinct yet complementary approaches to enhancing the recyclability and sustainability of packaging within the food and beverage industry. While both corporations share the overarching objective of reducing plastic waste and promoting circular economy principles, their strategies diverge in terms of material focus, technological pathways, and system integration.

Coca-Cola's initiative centers on the closed-loop mechanical recycling of existing plastic packaging materials, specifically polyethylene terephthalate (PET). By introducing bottles made from 100% recycled PET (rPET), the company seeks to demonstrate that high-quality recycled plastics can meet the same functional and safety requirements as virgin materials. This approach leverages well-established recycling infrastructure and polymer recovery technologies to retain material value within the production cycle. However, its success depends heavily on efficient collection systems, consumer participation, and contamination control in the recycling stream (Coca-Cola, 2021). Thus, Coca-Cola's model emphasizes system optimization and technological refinement within existing material categories.

In contrast, Nestlé's strategy represents a material substitution approach, focusing on innovation in packaging design through the adoption of recyclable paper-based alternatives. By replacing multi-layer plastic films with sustainably sourced paper, Nestlé aims to eliminate plastic use altogether in certain product categories. This approach mitigates dependency on fossil-based polymers and enhances recyclability through the widespread accessibility of paper recycling systems (Nestlé, 2021). Nevertheless, the development of functional paper packaging capable of providing comparable barrier properties to plastics poses significant technical challenges. Nestlé's investments in material science and production adaptation reflect an effort to balance product integrity, sustainability, and consumer acceptance.

Comparatively, Coca-Cola's model demonstrates how polymer circularity can be achieved through technological advancement and effective waste management, whereas Nestlé illustrates how material innovation can drive transformative change in packaging sustainability. Both pathways contribute to global sustainability objectives, yet they highlight different priorities within the circular economy framework: Coca-Cola focuses on closing existing material loops, while Nestlé pioneers the transition toward renewable and easily recyclable materials. Together, these initiatives underscore that achieving a sustainable packaging future will require a diverse portfolio of solutions—combining improved recycling

technologies, alternative materials, and supportive policy mechanisms to ensure long-term environmental and economic viability.

Technologies Used

Recycling packaging materials involves a range of technologies that differ based on the type of material being processed, as each has unique physical and chemical properties.

Plastic Packaging: For plastic packaging, several technologies are employed depending on the type and quality of the plastic. The most common method is mechanical recycling, where plastics such as PET bottles, HDPE containers, and polypropylene (PP) are collected, sorted, washed, shredded, and remelted into pellets for reuse. More advanced processes include chemical recycling, which breaks down plastics into their original monomers using heat, solvents, or catalysts to produce virgin-quality materials. Pyrolysis and gasification are also used for mixed or contaminated plastics; these thermal processes convert plastics into synthetic oil, gas, or syngas, which can be used as energy sources or raw materials for new plastics. Additionally, solvent-based purification technologies can selectively dissolve and recover pure polymers from complex plastic mixtures or multilayer films.

Paper and Cardboard Packaging: In the case of paper and cardboard, recycling technologies are well established. The process generally begins with pulping and screening, where water and mechanical agitation separate the fibers from inks, adhesives, and coatings. De-inking is commonly used for printed materials, employing air bubbles to lift ink particles away from the fiber slurry. Some facilities also apply enzymatic treatments to remove stubborn adhesives and improve fiber recovery. For composite materials such as paper-plastic laminates (e.g., Tetra Pak cartons), hydro-pulping is used to separate paper fibers from plastic and aluminum layers, allowing partial recovery of valuable components.

Glass Packaging: Glass packaging is infinitely recyclable without losing quality. The recycling process involves cleaning, crushing, and melting glass to form cullet, which serves as feedstock for new glass products. Modern plants use optical sorting systems equipped with near-infrared and color sensors to separate glass by color and remove impurities. In some cases, low-quality or mixed glass is repurposed into foamed glass, an insulating material made by heating crushed glass with foaming agents.

Metal packaging: Metal packaging, including aluminum cans and steel tins, is also highly recyclable and energy-efficient to process. Magnetic separation is used to extract ferrous metals like steel, while eddy current separation recovers non-ferrous metals such as aluminum. The collected metals are then remelted and refined into ingots or sheets that can be used to make new packaging. In certain applications, electrolytic recovery techniques are employed to extract pure metals from coated or mixed metal packaging materials.

Composite and Multilayer Packaging: Recycling composite and multilayer packaging presents a greater challenge because these materials combine layers of paper, plastic, and aluminum. To handle such complexity, technologies such as delamination, which uses heat, solvents, or mechanical friction to separate the layers, are being developed. Hydrothermal treatment is another method that uses pressurized hot water to dissolve adhesives and separate material layers efficiently. When separation is not feasible, advanced pyrolysis can convert the mixed materials into fuel or chemical feedstocks.

Emerging technologies are also transforming the recycling sector. AI-powered optical sorting systems use machine learning and advanced sensors to improve the precision of material identification in mixed waste streams. Enzymatic recycling offers a biological route to break down plastics like PET and PLA into reusable monomers. Meanwhile, microwave pyrolysis enables faster and more energy-efficient conversion of plastics into oil, and bioleaching (or biometallurgy) uses microorganisms to extract metals from coated or electronic packaging waste.

Together, these diverse recycling technologies enable the recovery and reuse of materials from various types of packaging, reducing landfill waste and conserving resources. However, continuous innovation is essential to improve efficiency, handle complex packaging materials, and create a more circular packaging economy.

Conclusion

In conclusion, recycling packaging materials plays a vital role in promoting environmental sustainability, conserving natural resources, and reducing pollution caused by waste disposal. As packaging continues to evolve with new materials and designs, recycling technologies must also advance to meet these challenges. Traditional methods like mechanical recycling and pulping remain essential for common materials such as plastics and paper, while emerging innovations such as chemical recycling, enzymatic processing, and AI-based sorting are paving the way for more efficient and comprehensive recovery systems. By integrating these technologies and encouraging responsible consumer participation, industries and communities can move closer to achieving a circular economy—one where packaging materials are continuously reused, waste is minimized, and the impact on the environment is significantly reduced.

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Custom Hiring Centres for Farm Women Skill, Livelihood and Income Enhancement

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Abstract

Custom Hiring Centres (CHCs) have emerged as a transformative model for empowering rural farm women by enhancing access to mechanization, skill development, and income generation. The CHC model, implemented through women's self-help groups (SHGs), provides affordable access to farm machinery on a rental basis, thereby reducing drudgery, ensuring timely operations, and improving productivity. The ICAR-Central Institute for Women in Agriculture (ICAR-CIWA), under the Odisha Integrated Irrigation Project for Climate Resilient Agriculture (OIIPCRA), established CHCs in seven Minor Irrigation Projects across 20 villages of Keonjhar district. These centres, equipped with women-friendly tools for irrigation, harvesting, threshing, and value addition, have enabled women to undertake both on-farm and off-farm enterprises. Capacity-building programmes have strengthened their technical, managerial, and entrepreneurial competencies, contributing to enhanced income and socio-economic empowerment. By integrating mechanization, value addition, and climate-smart practices, CHCs have become catalysts for sustainable rural development and gender-inclusive growth.

Introduction

Agriculture in rural India is at a transformative stage where mechanization, value addition, and entrepreneurship are becoming essential for sustainability and income enhancement. However, small and marginal farmers particularly farm women often face barriers to accessing modern farm machinery due to high costs, fragmented landholdings, and limited technical knowledge. In this context, Custom Hiring Centres (CHCs) have emerged as an innovative, inclusive model to bridge the gap between technology and resource-poor women farmers. By facilitating access to farm machinery and equipment on a rental basis, Custom Hiring Centres not only enhance agricultural productivity but also create new opportunities for women's empowerment and rural entrepreneurship.

Enhancing Access to Mechanization

In traditional farming systems, rural women perform several labour-intensive tasks such as transplanting, weeding, harvesting, threshing, and post-harvest handling. These operations are physically demanding and time-consuming. The establishment of Custom Hiring Centres, especially those managed by all-women groups, has significantly reduced the drudgery associated with manual operations. Through CHCs, women farmers can rent tractors, power tillers, transplanters, weeders, and threshers at affordable rates. This access to mechanization ensures timely field operations, better crop management, and efficient use of inputs such as seeds, fertilizers, and water. Moreover, the shared model of machinery use reduces individual investment costs, making mechanization viable for small and marginal farmers particularly.

Promoting Women's Entrepreneurship

A key dimension of the CHC model is its potential to foster women-led enterprises in agriculture. When women's self-help groups (SHGs) or community-based organizations (CBOs) are trained and entrusted with the management of Custom Hiring Centres, they gain not only financial benefits but also confidence, leadership, and decision-making power. Managing a CHC involves activities such as scheduling machinery rentals, maintaining records, ensuring maintenance, and coordinating with farmers — all of which enhance managerial and entrepreneurial skills. These women entrepreneurs serve as role models for others,

breaking social barriers and redefining gender roles in rural communities. The income generated through the CHCs further contributes to household welfare, education, and improved living standards.

Beyond cultivation, mechanization in processing and value addition offers another layer of empowerment for rural women. Post-harvest machinery such as threshers, cleaners, graders, dehullers, pulverizers, and oil extractors can be introduced in women-managed processing units. These units transform raw produce into marketable value-added products — for example, millets into flour, ragi into different products or pulses into cleaned and packed dal. This not only enhances the shelf life and market value of farm produce but also provides women with avenues for off-farm income generation. Mechanization in value addition reduces manual drudgery, ensures quality consistency, and strengthens linkages with local markets, cooperatives, and agri-startups.

Sustainability and Resource Efficiency: The CHC mechanism contributes to the sustainability of agriculture by encouraging efficient use of resources and climate-resilient practices. Mechanized equipment like zero-till drills, land levelers, and drum seeders help conserve soil moisture, reduce greenhouse gas emissions, and promote precision farming. Women's participation in operating and managing such technologies builds their capacity in climate-smart agriculture and enhances their role in sustainable resource management. Additionally, the shared-use model of machinery minimizes idle capacity and promotes collective ownership, reducing the carbon footprint associated with individual machinery ownership.

Economic growth and Rural Development: Empowering rural women through CHCs and mechanized processing units leads to multiplier effects in the rural economy. Increased farm efficiency, higher productivity, and reduced input costs directly contribute to improved household incomes. The additional employment generated through machinery operation, repair services, transport, and processing also stimulates local economic activity. Women-led CHCs can further integrate with digital platforms for machinery booking, agri-advisory, and financial management, strengthening their business models. Over time, these centres evolve into hubs of agricultural innovation and rural entrepreneurship, supporting the government's vision of *"Doubling Farmers' Income"* and *"Atmanirbhar Bharat."*

ICAR-Central Institute for Women in Agriculture

Bhubaneswar (ICAR-CIWA) has done such an effort through Odisha Integrated Irrigation Project for Climate Resilient Agriculture (OIIPCR) Project is demonstrating women-friendly Climate Smart Agriculture Technologies and practices in 7 Minor Irrigation Projects (MIPs) covering 20 villages of Keonjhar district, Odisha. In these villages Income generation opportunities through community-managed Custom Hiring Centres (CHCs) are providing economic independence and empowerment for women. Across these 7 MIPs (Table 1), CHCs have been established where farm women, through their SHGs, benefit from mechanized facilities for primary and secondary cleaning, processing, and post-harvest management of farm produce.

Each CHC is equipped with women-friendly tools such as belt drive water pumps for efficient irrigation, power-operated maize shellers and paddy threshers for quick harvesting and grain separation, and power weeders for timely intercultural operations reducing drudgery. Groundnut decorticators, hand winnowers, and seed treatment drums support improved processing, grading, and seed quality management, while solar dryers ensure hygienic drying and value addition of pulses and oilseeds using renewable energy (Table 2). Together, these machines not only enhance productivity and reduce manual labor but also enable women to undertake value-added enterprises within their own communities. The integration of technology, economic feasibility, and gender equality has helped build resilient agricultural systems capable of withstanding climate challenges while fostering rural entrepreneurship and sustainable economic growth.

Conclusion

The integration of Custom Hiring Centres and mechanization for processing and value addition represents a transformative approach to empower rural women in agriculture. By reducing drudgery, improving productivity, and enhancing value chains, these interventions pave the way for inclusive and sustainable agricultural growth. When women are at the forefront of managing such initiatives, they not only uplift themselves but also inspire entire communities towards progress. Thus, CHCs are not merely centres for

machinery distribution—they are engines of empowerment, sustainability, and economic resilience for India's rural women.

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Sacred Fruits: Their Role in Religion and Traditions

Article ID: 72315

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Introduction

Fruits have long held a sacred status in religious and cultural traditions across the world. They are more than just sources of nourishment; they symbolize life, purity, prosperity, and divine blessings. From ancient myths to modern rituals, sacred fruits continue to play a role in spiritual practices, offerings, and festivals. Across different civilizations, fruits have been revered as gifts from the gods, embodying the essence of divine energy and the interconnectedness of life. Whether used in sacred ceremonies, symbolizing moral virtues, or serving as metaphors in religious texts, fruits have been an integral part of human spiritual evolution.

Many ancient scriptures and mythologies mention specific fruits as having supernatural or divine significance. These fruits are often believed to possess magical or healing properties, reinforcing their role in sacred traditions. Their significance is not only tied to their nutritional value but also to their association with divine figures, historical religious events, and their ability to convey deeper spiritual meanings. From the Garden of Eden to the holy lands of India and the Middle East, fruits have played a pivotal role in shaping religious customs and traditions.

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The Fig: A Symbol of Enlightenment

The fig tree has deep religious significance in many cultures. In Buddhism, Siddhartha Gautama attained enlightenment under the Bodhi tree, a species of fig known as *Ficus religiosa*. The Bodhi tree is considered the most sacred tree in Buddhist traditions, and its presence in monasteries and temples symbolizes wisdom, inner peace, and the path to Nirvana. In Christianity, the fig is mentioned in the Bible as a symbol of knowledge and abundance. Jesus is said to have cursed a barren fig tree to illustrate the importance of spiritual fruitfulness. In Hinduism, the sacred Peepal tree (*Ficus religiosa*) is considered the abode of gods, and sitting under its shade is believed to bring wisdom and good fortune. Additionally, in ancient Egypt, figs were believed to be the favorite fruit of the goddess Hathor and were often placed in tombs for the deceased to enjoy in the afterlife. The fig tree is also significant in Islamic traditions, where it is mentioned in the Quran as a symbol of sustenance and divine favor. Because of its deep roots and wide branches, it is often seen as a representation of knowledge, wisdom, and the connection between heaven and earth. The fruit itself is highly nutritious, rich in fiber, antioxidants, and essential vitamins, making it both physically and spiritually nourishing.



The Pomegranate: A Fruit of Fertility and Eternal Life

The pomegranate is revered in multiple religions for its vibrant red color, numerous seeds, and health-giving properties. In ancient Greek mythology, it was associated with the cycle of life and death, as Persephone, the goddess of the underworld, was bound to return to Hades for part of the year after consuming pomegranate seeds. In Hinduism, it symbolizes prosperity, fertility, and abundance, and it is often offered in prayers and rituals. The pomegranate is believed to be an auspicious fruit, bringing blessings of wealth and success. In Christianity and Judaism, the pomegranate represents righteousness and divine promise, as it is believed to contain 613 seeds, corresponding to the 613 commandments of the Torah. The fruit also appears in Christian iconography as a symbol of resurrection and eternal life. In Islamic culture, the pomegranate is mentioned in the Quran as a fruit from paradise, signifying health and divine blessings. In Persian traditions, the pomegranate is a symbol of rebirth and eternal life. It is also a part of many cultural ceremonies and feasts, including Yalda Night, where it is eaten as a way to celebrate the renewal of light and life. Nutritionally, pomegranates are packed with antioxidants, vitamins, and minerals, making them beneficial for heart health, immunity, and overall well-being.



The Banana: A Sacred Offering

The banana is considered a sacred fruit in Hinduism, where the entire plant, including its leaves, trunk, and flowers, is used in religious ceremonies. The banana plant itself is often worshipped, and its leaves are

used as serving plates during feasts and offerings. In South Indian temples, bananas are commonly offered to deities as a symbol of purity, nourishment, and devotion. In Buddhist traditions, bananas are associated with simplicity and detachment from materialism, as they provide quick nourishment and require minimal effort to consume. The banana tree is also associated with Lord Vishnu and Goddess Lakshmi, symbolizing abundance and marital happiness. In many parts of Southeast Asia, banana trees are planted near homes and temples, as they are believed to bring good luck, ward off negative energies, and promote fertility. The banana plant is unique because it produces fruit multiple times before dying, symbolizing the cycle of birth, death, and rebirth. In various folk traditions, bananas are believed to have protective qualities, and their presence in rituals ensures good fortune and well-being. From a nutritional perspective, bananas are rich in potassium, vitamin B6, and fiber, making them an essential fruit for maintaining energy levels, digestive health, and overall vitality.



The Date: A Fruit of Divine Sustenance

Dates hold great importance in Islamic tradition. The Prophet Muhammad is believed to have broken his fast with dates, and they are commonly consumed during Ramadan. In Christian tradition, dates are associated with Palm Sunday, when Jesus was welcomed into Jerusalem with palm fronds. In ancient Mesopotamian cultures, dates were considered a gift from the gods, often used in religious feasts and temple offerings. The date palm is often called the 'Tree of Life' due to its ability to thrive in harsh desert climates and provide nourishment to travelers and inhabitants. The longevity of date palms and their ability to regenerate make them symbols of endurance, renewal, and divine providence.



The Apple: A Symbol of Temptation and Knowledge

In Christian mythology, the apple is often linked to the story of Adam and Eve and the concept of original sin. However, in Norse mythology, apples were considered a source of eternal youth. In Chinese culture, apples symbolize peace and harmony. The Greek myth of the golden apple further highlights its importance as a fruit linked to power, desire, and divine intervention. Apples are also associated with love, wisdom, and transformation in various traditions. The idea that an apple a day keeps illness away stems from its long-standing reputation as a fruit of health and vitality.



The Mango: A Divine Fruit in Hinduism

The mango is regarded as a sacred fruit in Hinduism, often associated with Lord Ganesha. It symbolizes love and spiritual attainment. Mango leaves are used in religious ceremonies and are hung at the entrances of homes to bring good fortune. The fruit itself is often included in offerings during important festivals and pujas, reinforcing its sacred status in Indian traditions. Mangoes are also revered in Buddhist traditions, as it is believed that Buddha meditated under a mango tree. The rich, golden color of mangoes represents prosperity and divine blessings, making it a favored fruit for religious and celebratory occasions.



Conclusion

Throughout history, fruits have carried deep spiritual and symbolic meanings in various cultures and religions. Whether as offerings, symbols of divine favor, or representations of life and purity, sacred fruits continue to bridge the material and the spiritual worlds, enriching religious traditions and cultural heritage.

From the fig tree of enlightenment to the pomegranate of fertility and the coconut of devotion, the sacred fruits of the world remind us of the profound connections between nature and faith. They nourish not only the body but also the soul, reinforcing the timeless bond between humanity and the divine. Their presence in religious texts, rituals, and myths underscores their universal significance, making them timeless symbols of faith, abundance, and spiritual fulfillment.

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Cucurbits Plants: A Key Emphasis to its Medicinal Properties

Article ID: 72316

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Introduction

Consumption of some fruits is strongly associated with several health benefits due to their high nutritional value and properties in risks reduction of certain illness such as cancers, cardiovascular diseases and cataracts fully justified and attributed to the presence of bioactive compounds (BCs) in the plant matrices (Shofian *et al.*, 2011). Due to their centuries-old medicinal properties, vegetables are utilized as medicine in many nations; their use has grown to be a significant component of daily diets throughout individuals. Any vegetable's ability to heal depends entirely on its phytochemicals and various chemical components. The term "pytochemical" refers to substances that are not recognized as food nutrients but that have therapeutic properties for a variety of human ailments. Various vegetable parts, including flowers, fruits, leaves, stems, petioles, and roots, are employed as medicines in traditional medical systems. Cucurbitaceae (Cucurbit) is an important family comprising one of the most genetically diverse groups of food plants. Most of the plants belonging to this family are frost sensitive and drought-tolerant. Some important Cucurbit family members include gourd, melon, cucumber, squash and pumpkin. Muskmelon is considered to be native of Persia (Iran) and adjacent areas on the west and the east. Central Asia comprising southern Russia, Afghanistan, Pakistan and north-west India is regarded as its secondary centre. Muskmelon had been cultivated in Egypt since 2400 BC. Vegetable crops known as cucurbits are members of the family Cucurbitaceae, which includes 750 species and 90 genera that are used in a variety of ways for human consumption across the globe. Cucurbits are a diverse family that includes salad crops like cucumber and long melons, dessert fruits like water and musk melons, and culinary crops like bitter gourd, bottle gourd, and pumpkin. Nearly all of the nutrients needed for human health are found in cucurbits, including sugar, protein, carbohydrates, vitamins, minerals, and other nutrients (Vanam, 2007). The various species within this family are rich in phytochemicals that exhibit a broad spectrum of bioactivities. These plants were used in ancient civilizations for healing wounds, detoxifying the body, and treating conditions such as jaundice, kidney disorders, and respiratory diseases (Chen *et al.*, 2024). In regions like India, China, and Africa, cucurbit-based formulations have been included in traditional healing practices for generations, often in combination with other herbs to enhance their effectiveness.

Bitter Gourd

The fruit acts as an anthelmintic, stomachic, antibilious and laxative. In fact, it is a tonic fruit, used in rheumatism, gout and also for diabetes. The juice of fresh leaves is given to children as a mild purgative but is not un-attended with danger. In case of migraine, the juice of a leaf is prepared in which a little salt is mixed, and then a drop is put into nostril, the same side as the migraine just once. In case of burning soles, the juice of tender leaves is just applied at bed time for seven days⁷. The root of bitter gourd has an abortifacient effect. A decoction of the root extract is helpful in abortion, hemorrhoids and also in biliaesness.

Cucumber

The excessive internal heat is supposed to be detrimental to body system. If the body keeps burning continuously more than necessary, the effect on the person is in extreme exhaustion. Cucumber juice is highly recommended. For quick symptomatic cooling of the head, hand and feet, cucumber paste when applied on the body part is very effective in bringing a refrigerator effect. It should be noted that cucumber juice is frequently used to treat gum and tooth disorders. Its juice continues to be beneficial for rheumatism and healthful hair growth. The seed possesses diuretic and tonic qualities that make it useful in medicine.

Ridge Gourd

In case of jaundice, the juice is prepared from the leaves and every morning 2-3 drops are put into nose for four days. Anus tag: A paste of root is prepared with a little water. Then it is applied at the anus for ten nights. In local treatment, leaves are used as poultice in haemorrhoids, leprosy and splenitis; juice in conjunctivitis; decoction for uraemia and amenorrhoea. Ripe seeds are emetic and purgative.

Sponge Gourd

The plants contain a compound called luffein. Juice from the leaves are use to cure conjunctivitis of the eye. The leaves and fruits are good remedies for Jaundice. Roots have laxative effects and the oil from the seeds is used for cutaneous complains.

Snake Gourd

While the fruits are served as an appetizer, the leaves and stems are utilized to heal skin conditions. The seeds have the ability to deworm.

Sweet Gourd

While seeds are used to cure chest issues and encourage urine production, fruits are used to treat ulcers, piles, sores, and obstruction of the liver and spleen. Pile removal, migraines, excessive perspiration, coughing, and stones can all be effectively treated with roots.

Pointed Gourd

Commonly used for digestive issues, the leaves and stems include hypocholesterolemic, hypoglyceridimic, hypoglycemic, and hypophospholipemic properties. Fruits are excellent mouth fresheners and can be used to cure blisters, wounds, and fever. The roots are an effective treatment for ascites and a diuretic. *Trichosanthes dioica* herbage is widely used to cure a variety of human ailments.

Bottle Gourd

The leaves are used to control skin disease. Roots are used against osteoarthritis. The fruits are widely used as antidiabetic, antianaphylactic and antihistaminic. Fruits are also used for the treatment of leprosy, fever, asthma, bronchitis and jaundice.

Ash Gourd

Ash gourd has strong therapeutic and restorative qualities and is nutritious and healthful. People with diabetes and obesity can benefit from it because the fruit has a low calorie content. The fruit has cooling, diuretic, styptic, purgative, and tonic properties. As a blood coagulant, the fruit juice helps treat respiratory issues, peptic ulcers, hemoptysis, and other internal hemorrhage discharges from the kidneys, lungs, and stomach. Regular use reduces inflammation in the digestive system, diabetes, and piles dyspepsia. It also relieves in periodic attacks of hysteria, convulsion and other nervous diseases. The fruit increase the secretion and discharge of urine, washing out toxins from body system. In case of general debility, a delicacy from fruit pulp by boiling its pieces in water and water and adding sugar to it is used as a domestic recipe to increase weight, in T.B., heart weakness, heart in the body, thinness of semen and anaemia.

Pumpkin

While fresh pulps can be used as a poultice for boils, burns, and inflammations, seeds have diuretic and tonic properties. Young branches and leaves have a slight laxative effect. To alleviate night blindness, the year-old pumpkin is simply cooked with water and taken on a regular basis for approximately a week.

Watermelon

Due to its 90% water content, which acts as a natural diuretic to cleanse the kidneys and bladder, it is consumed all over the world. Especially advised for pregnant and menstruating women who retain fluids. Malnutrition, typhoid fever, tiredness, and scanty urination are all treated with the plants.

Muskmelon

The plants are used against scanty urination, anaemic scanty urination, loss of appetite, vomiting, problems in prostate gland and wound in urinary tract.

Conclusion

India has a climate that is ideal for growing a variety of cucurbitaceous crops. There is a wide variety of cucurbits in the farmhouse gardens of many states and communities. Crop species and cultivars vary in a variety of morphological characteristics. This varied biodiversity has several ethymetic qualities that could help the most underprivileged members of society with their basic medical requirements. A rich source of bioactive substances with enormous therapeutic potential are cucurbits. They are an essential component of both conventional and contemporary medicine because to their anti-inflammatory, anti-cancer, antibacterial, antioxidant and cardioprotective qualities. Nevertheless, despite their many health advantages, cucurbits also carry a toxicity risk since they contain cucurbitacins, which can upset the stomach and, in extreme situations, harm organs. Cucurbit-based goods, particularly those in pharmaceutical form, should be consumed with caution by people who already have health issues.

3G Cuttings: Simple Tool for Higher Yield in Cucurbits

Article ID: 72317

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Introduction

3G cutting is a simple cultural practice for achieving ultimate goal of higher yields for farmers. It is being popular in Vegetable crops like- Tomato, Brinjal and other solanaceous vegetables but found highly successful and practically useful in Cucurbits like- Cucumber, Bottle Gourd, Ridge Gourd and Pumpkin etc. In simple terms, 3G stands for third generation in all crops. By trimming or pinching the first (primary) and second (secondary) branches off the plant, 3G cutting may be used to encourage the growth of 3rd generation (tertiary) branches. Following seed germination, only one main branch known as the first or fifth generation branch continues to grow. Second generation branches are those are produced by the main branch. Third generation branches are those that arise from any one of the initial second-generation branches. In all the cucurbits 1st and 2nd generation branches produced male and female flowers in ratio of 14:1 which gives impression of high flowering in plant but fruit setting remains low due to less female flowers. 3G cuttings promotes female flower initiation in plant as in 3 generation branches male and female ratio is reported 2:1, which further leads to better fruit setting and higher yield in cucurbits.

Importance and Practice

The development of fruits primarily depends on the female flowers, as they play a crucial role in fruit production. However, male flowers are also essential for pollination. Therefore, increasing the number of female flowers on a plant can lead to a higher yield of fruits. This is where the technique of 3G cutting comes into play, as it helps boost the number of pistillate (female) flowers on a plant. In many crops, the natural ratio of male to female flowers is imbalanced, with male flowers typically being more abundant. Observations have shown that after 3G cutting, the number of female flowers increases, sometimes equalling or surpassing the number of male flowers, which can significantly enhance crop production. For instance, in crops from the Cucurbitaceae family, the ratio of male to female flowers before 3G cutting is around 14:1, while after 3G cutting, the ratio shifts to 1:2, favouring higher fruit production.

The 3G cutting technique is practiced to increase the production of cucurbitaceous crops like gourds, cucumbers, pumpkins, and even other crops such as tomatoes, brinjal (eggplant) and okra. In India, agricultural universities and research institutes have been promoting 3G cutting, especially in states like Uttar Pradesh and Punjab, where farmers cultivate cucurbits extensively. In Nepal farmers has also adopted this method in its efforts to boost small scale farming, given the country's reliance on cucurbit crops for both domestic consumption and local markets.

Objective of 3G Cutting

Main objective of 3G cutting is to make balance between male and female flowers in cucurbits. It makes balance the ratio between male and female flower ratio in cucurbits. Higher number of female flowers is essential for higher fruit set. However male flower is also important in relation to yield. One male (Staminate) flower can fertilize many female flowers (Pistillate) but it is female flower which is necessity for fruit set. Farmers use chemicals in abundance for higher yield which can be reduced with this basic interculture operation. With use of 3G cutting in cucurbits adds benefits to the yield with simple interculture operation, which requires little precision.

Procedure of 3G Cutting

3G cutting in cucurbits is a simple interculture operation requires basic steps with a bit technical precision:

1. Allow main (Primary) branch to grow uninterrupted with proper care and maintenance till it attain a height of 6-7 feet.

2. When main branch attains height of 7 to 8 feet, apical portion of the plant about 4-5 inch should be removed.
3. Removal of apical portion promotes initiation of secondary branch formation in the plant due to translocation of food reserve to the secondary branch.
4. Same as the previous one, tip portion (4-5 inch) of the secondary branch should be removed after it grows 3 to 4 feet. This action promotes the initiation of the tertiary branch or 3rd generation branch.
5. This 3rd generation (3G) branch is heavy bearer and allowed to be grow for the high production as it blossoms with high female flower.

Advantages

The 3G cutting technique is a newly developed method in agriculture, and researchers have observed remarkable results from its application. This technique can significantly enhance crop production, especially in organic farming systems, making it a valuable tool for farmers. By increasing the number of female flowers per plant, the likelihood of fruit set also rises, leading to improved yields. Additionally, the quality and size of the fruits are superior, which is beneficial for farmers with small land holdings, as it helps them generate more income from limited space. Moreover, the overall increase in production directly translates into higher net profits, contributing to the better livelihoods of rural farmers. One of the key advantages of 3G cutting is that it boosts yield without requiring significant additional investment, aside from the need for skilled labor on larger farms. Furthermore, this technique aids in the proper training of gourd, melon, pumpkin, and cucumber plants, ensuring that each vine receives adequate sunlight for photosynthesis, thus promoting optimal growth and development. Challenges in 3G cutting. Despite its broad benefits 3G cuttings have its own challenges that should have to be in mind while planning this practice to perform:

1. It requires more labours with technical knowledge
2. It needs regular attention and inspection which is tedious work
3. Cutting leads to disease and infection if no proper cure given at right time
4. Production time slight delay.

Conclusion

3G cutting is benefiting cultural practice and can be a great asset in higher production of certain crops. It applicable in various crops like- Tomato, Brinjal, Chilli and Okra etc. but it has more significant and positive response in Cucurbitaceous crops. Apart from its few challenges it is simple and highly useful technique in increasing yield of crop.

Choanephora Blight – An Emerging Threat to Chilli Production

Article ID: 72318

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Summary

Choanephora blight, caused predominantly by *Choanephora cucurbitarum* and *C. infundibulifera*, has become a formidable disease constraint in chilli (*Capsicum annuum* L.) cultivation across tropical and subtropical regions. The pathogen attacks both vegetative and reproductive organs, leading to rapid necrosis and severe yield losses under warm and humid conditions. Once confined to cucurbits and legumes, *Choanephora* species have now expanded their host range to include solanaceous crops, particularly chilli. The disease thrives during the flowering and fruiting stages, making it a recurrent challenge for farmers, especially during the monsoon season. This article comprehensively examines the pathogen biology, epidemiology, symptomatology, host-pathogen interactions, diagnosis, and integrated management approaches of Choanephora blight, with special emphasis on its rising prevalence in India and Southeast Asia. It also highlights the latest advancements in biocontrol technologies, resistance breeding, and integrated disease management (IDM) strategies aimed at sustainable control.

Introduction

Chilli (*Capsicum annuum* L.) holds immense global importance as a spice and vegetable crop, valued for its pungency, color, and high nutritional content, particularly vitamins A and C. India stands as the largest producer, consumer, and exporter of chilli worldwide. However, production is increasingly hampered by various fungal diseases, among which Choanephora blight has gained significance in recent years. Historically reported in cucurbits, the pathogen has adapted to infect solanaceous crops, including chilli and brinjal, reflecting its evolving pathogenic potential. Favorable environmental conditions—namely high humidity and temperatures ranging between 25–35°C—contribute to disease proliferation. These conditions are common in major chilli-producing regions, particularly during the kharif season, leading to substantial yield and quality losses.



Pathogen Biology

The causative agents, *Choanephora cucurbitarum* (Berk. & Ravenel) Thaxt. and *C. infundibulifera* (Curr.) Sacc., belong to the order Mucorales under the class Zygomycetes. They are opportunistic necrotrophic fungi that typically survive as saprophytes on decomposing organic matter but switch to parasitic modes under favorable climatic conditions.

Morphological characteristics:

- The fungi produce erect, unbranched, hyaline sporangiophores bearing terminal sporangia.
- Sporangia are globose to ellipsoidal and contain numerous smooth-walled spores.
- Infected tissues often exhibit a distinctive silvery, hair-like appearance due to the reflective sporangiophores, imparting a wet, cottony texture.

Reproductive biology:

- a. Asexual reproduction dominates under field conditions.
- b. Sporangiospores are disseminated primarily by wind, rain splash, insects, and contaminated farm tools (Chandrakala & Vidyasagar, 2018).

Symptoms of Choanephora Blight in Chilli

Symptoms manifest on flowers, fruits, and occasionally on stems and leaves:

- 1. Flowers:** The disease initiates as water-soaked necrotic lesions on petals, leading to flower collapse within 24–48 hours.
- 2. Fruits:** Young fruits develop soft, darkened lesions, followed by rapid shrivelling and a characteristic silvery fungal coating.
- 3. Pedicels and Stems:** Infected pedicels turn brown, collapse, and cause premature fruit drop.
- 4. Leaves (rare cases):** Water-soaked spots may appear on lower leaves, progressing to necrosis under severe infection.

The disease progresses rapidly, often rendering the fruits unmarketable within a few days (Sinha, 1962).

Disease Cycle and Epidemiology

Choanephora spp. persist in soil and crop debris as saprophytic mycelia and spores. They act as both soil-borne and air-borne inocula, enabling widespread dissemination.

Favourable conditions:

- a. Relative humidity above 90%
- b. Temperature range between 25–35°C
- c. Prolonged leaf wetness due to rainfall, dew, or overhead irrigation

Epidemiological features:

- a. Primary inoculum arises from infected residues or alternate hosts.
- b. High inoculum density, combined with humid conditions, accelerates disease development.
- c. Insect-mediated wounding, particularly by thrips and beetles, enhances pathogen entry.

Outbreaks are most severe during the flowering and fruiting stages of the crop, especially in the kharif season (Roberts *et. al.*, 2003).

Host Range and Economic Impact

Originally described in cucurbits, *C. cucurbitarum* now infects a wide array of crops including:

- a. Leguminous crops:** Cowpea, French bean
- b. Solanaceous crops:** Chilli, brinjal
- c. Others:** Okra, marigold

Economic implications in chilli:

- a. Yield reductions ranging from 40–70% in severe outbreaks
- b. Deterioration in fruit quality due to soft rot and shrivelling
- c. Increased production costs due to fungicide applications
- d. Reduced export potential owing to compromised fruit integrity.

Diagnosis and Detection

Field diagnosis:

- a. Presence of wet, cottony growth on infected floral parts and fruits
- b. Water-soaked lesions on pedicels
- c. Silvery sheen due to spore masses

Laboratory diagnosis:

- a. Isolation on Potato Dextrose Agar (PDA) for morphological identification
- b. Microscopic observation of sporangia and sporangiophores
- c. Molecular confirmation** through ITS region sequencing to differentiate *C. cucurbitarum* and *C. infundibulifera*

Management Strategies

Effective management of *Choanephora* blight requires an integrated approach combining cultural, biological, and chemical measures.

1. Cultural control:

- Adopt crop rotation with non-hosts such as cereals to minimize inoculum load.
- Maintain field sanitation by removing and destroying infected plant debris.
- Ensure adequate spacing and proper drainage to reduce humidity.
- Avoid overhead irrigation during reproductive stages.

2. Chemical control:

- Fungicides including Mancozeb, Carbendazim, Azoxystrobin, and Zineb have shown efficacy.
- Initiate fungicide sprays at the onset of flowering, repeating every 7–10 days as necessary (Yin *et. al.*, 2023).

3. Biological control:

- Application of *Trichoderma* spp. and *Pseudomonas fluorescens* as soil or foliar inoculants has effectively reduced disease incidence.
- Eco-friendly alternatives such as neem oil and chitosan formulations provide additional suppression.

4. Host resistance:

- Breeding for resistance is at a nascent stage.
- Certain wild accessions of *Capsicum chinense* have demonstrated partial tolerance, warranting further exploration for genetic improvement.

5. Integrated Disease Management (IDM):

- Employ a combination of resistant varieties, cultural hygiene, and biocontrol agents.
- Use weather-based forecasting systems to schedule fungicide applications.
- Promote farmer training and early surveillance for timely intervention.

Recent Research and Advancements

Recent research has focused on molecular characterization and genomics to elucidate pathogenic mechanisms in *Choanephora* spp. Whole-genome sequencing and transcriptomic studies are uncovering virulence-associated genes that may serve as potential targets for novel control measures. Furthermore, CRISPR/Cas9-based genome editing in chilli is being explored to develop resistant cultivars. Integration of molecular diagnostics with precision agriculture tools promises early detection and site-specific management in the future.

Conclusion

Choanephora blight has emerged as a major limiting factor in chilli cultivation across humid tropical regions. Its expanding host range, combined with favourable climatic conditions, underscores the need for comprehensive and sustainable management approaches. Reliance solely on fungicides is neither economical nor environmentally viable. Therefore, integrating resistant cultivars, cultural sanitation, biological control, and predictive disease modelling is essential. Strengthened research collaborations among pathologists, breeders, and extension specialists will play a pivotal role in mitigating the disease's impact and ensuring sustainable chilli production.

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Integrating Light Spectrum Modification and Nano-Coating Strategies for Enhanced Postharvest Preservation of Fruits – A Short Review

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Summary

Postharvest losses of fruits are a major global problem driven by physiological senescence, water loss, and microbial decay. Two promising, relatively low-residue strategies for extending shelf life are manipulation of light spectra (LEDs, UV-A/B/C, pulsed light) to slow senescence, induce defense responses and enhance antioxidants, and nano-enabled edible or packaging coatings (nanoparticles, nanocomposites, nanoemulsions) that reduce gas/water exchange, provide antimicrobial activity, and enable controlled release of bioactives. This review synthesizes mechanisms, crop-specific findings, formulation/practical considerations, synergies between light treatments and nano-coatings, safety/regulatory issues, knowledge gaps and future directions. Key recent reviews and experimental studies are cited throughout.

Introduction

Reducing postharvest losses while maintaining nutritional and sensory quality is essential for food security and value chain efficiency. Traditional fungicides and cold storage remain important, but consumer and regulatory pressure favors residue-free, sustainable approaches. Targeted light treatments and nano-coatings have emerged as two complementary approaches: spectral treatments can directly reduce pathogen development and modulate fruit physiology, while nano-coatings create barrier and antimicrobial functionalities (Obajuluwa *et. al.*, 2025).

Types of Light Treatments Used Postharvest

1. LED spectral treatments (narrow bands of red, blue, far-red, green, white) delivered continuously or in pulses.

2. Ultraviolet treatments (UV-C: 100–280 nm; UV-B: 280–315 nm; UV-A: 315–400 nm), mostly applied as short, hormetic doses.

3. Pulsed light and broad-spectrum visible light (intense, short bursts).

LED systems are attractive due to low heat emission, wavelength control and energy efficiency; UV-C is widely used because of its strong antimicrobial effect (Obajuluwa *et. al.*, 2025).

Biological Mechanisms — Host and Pathogen Effects

Direct antimicrobial action: UV-C (especially ~254 nm) damages microbial DNA and cell structures, reducing surface inoculum. LED photons (particularly blue) can generate ROS at microbial surfaces, inhibiting sporulation (Algarni *et. al.*, 2022).

Host defense induction (elicitation): Sub-lethal light doses elicit plant innate defenses — upregulation of phenylpropanoid pathway enzymes (e.g., PAL), accumulation of phenolics, activation of pathogenesis-related proteins and antioxidant enzymes — improving resistance to fungal invasion. Blue and red LED treatments are repeatedly reported to increase phenolics and antioxidant capacity in many fruits (Pinheiro *et. al.*, 2015).

Physiological modulation: Light spectra alter hormone balances (ethylene, ABA, salicylic acid), membrane stability, respiration and pigment synthesis, thereby modulating ripening and visual quality. Far-red may accelerate senescence in some cases; red and blue often slow or tune ripening depending on crop and timing (Obajuluwa *et. al.*, 2025).

Practical Parameters That Matter

Wavelength (nm), intensity (fluence rate), dose (total energy/time), timing (immediately after harvest vs intermittent), temperature during treatment, and commodity physiology (climacteric vs non-climacteric) all determine outcomes. Optimized, crop-specific protocols are required.

Nano-Coatings and Nanocomposites — Principles and Categories

1. Definitions and aims: Nano-coatings represent a sophisticated advancement in postharvest technology, defined as ultra-thin layers that incorporate nanoscale components such as nanoparticles, nanofibres, nanoemulsions, or nanocomposites (Mani *et. al.*, 2018). These materials can be applied directly onto the produce as edible films or used to functionalize packaging surfaces. The primary aims of these nano-engineered coatings are multifaceted: they serve as a selective barrier to significantly reduce water loss and slow down the exchange of oxygen and carbon dioxide, thereby directly delaying ripening and senescence. Beyond this passive role, they are designed to provide active functions, including inherent antimicrobial activity and, most importantly, acting as intelligent carriers for the controlled release of bioactive agents such as antimicrobials, antioxidants, or ethylene scavengers, which proactively maintain quality and extend shelf life (Algarni *et. al.*, 2022).

2. Common materials and their roles: The efficacy of nano-coatings is derived from a diverse portfolio of materials, each selected for a specific functional role. Chitosan and its nanocomposites are widely used due to their biodegradability, excellent film-forming properties, and inherent polycationic antimicrobial nature; when engineered into nanoparticles, as demonstrated by Algarni *et al.* (2022) on apricots, they offer superior surface adherence and controlled release of active compounds, effectively reducing decay and preserving vital nutrients like ascorbic acid (Obajuluwa *et. al.*, 2025). For potent pathogen control, metal and metal-oxide nanoparticles such as silver (Ag), zinc oxide (ZnO), and titanium dioxide (TiO₂) are embedded into biopolymer matrices, where their strong antimicrobial activity is harnessed while the matrix helps mitigate potential migration concerns. Simultaneously, nanoemulsions and lipid nanoparticles are employed to enhance the barrier against moisture vapor and to effectively encapsulate and provide sustained release of lipophilic compounds like essential oils, all while maintaining better transparency and sensory acceptance than their macro-scale counterparts. To reinforce the physical integrity of the coating, non-toxic nanofillers like nanoclay and cellulose nanofibres are incorporated to significantly improve mechanical strength and modulate gas permeability (Mani *et. al.*, 2018).

3. Functional mechanisms: The performance of nano-coatings is governed by several synergistic mechanisms that operate at the interface between the fruit and its environment. The primary mechanism is the establishment of a superior physical barrier that directly reduces transpiration and moderates the exchange of oxygen and carbon dioxide, creating a modified atmosphere that slows down respiratory activity and ripening. Concurrently, an antimicrobial mechanism is activated, which can function through direct contact-mediated killing of microbes on the surface or via the sustained release of antimicrobial ions or compounds from nanocarriers like chitosan or silver nanoparticles. A key advanced functionality is the principle of controlled release, where the nano-coatings act as an active packaging system, enabling the time-regulated delivery of natural preservatives such as essential oils or organic acids, ensuring prolonged protection. Collectively, these mechanisms allow the edible coating to function as a sophisticated microenvironment manager, creating a stable, immediate micro-atmosphere around the fruit that mitigates the detrimental effects of ethylene and respiration more effectively than conventional methods (Pinheiro *et. al.*, 2015).

4. Evidence of efficacy: The practical value of nano-coatings is substantiated by a growing body of evidence from both laboratory and pilot-scale studies across a wide range of fruit commodities. Research has consistently demonstrated that various nano-coating formulations, including chitosan nanoparticles, silver-chitosan composites, and lipid-based nanoemulsions, can significantly extend the postharvest shelf life of fruits such as strawberries, grapes, mangoes, and papayas. The measurable benefits documented in these studies include a marked reduction in microbial decay and physiological weight loss, coupled with the better retention of critical quality attributes like firmness, titratable acidity, and antioxidant compounds including phenolics and carotenoids. The work of Algarni *et al.* (2022) on apricots serves as a representative and robust experimental demonstration, showcasing how a chitosan nanoparticle coating

effectively preserved fruit quality and storability, thereby providing a compelling case for the commercial potential of this technology.

Table 1. Summary of light and nano-coating treatments for shelf-life extension in fruits:

Treatment Type	Crop Example	Observed Effect	Reference
UV-C light (254 nm)	Tomato	Reduced microbial load, maintained firmness, delayed senescence	(Pinheiro <i>et. al.</i> , 2015)
Blue/Red LED light	Citrus, Strawberry	Enhanced phenolic content and antioxidant activity	(Obajuluwa <i>et. al.</i> , 2025)
Chitosan nanoparticles	Apricot	Reduced decay, weight loss, and retained vitamin C	(Mani <i>et. al.</i> , 2018)

Formulation, Application and Scaling Considerations

1. Coating formulation & application: The transition from a laboratory-proven coating to a commercially viable one hinges on meticulous optimization of its formulation and application methodology. Critical parameters such as nanoparticle concentration and size distribution must be precisely controlled, as they directly influence key characteristics including the solution's viscosity, the film's transparency and integrity, and its ultimate functional efficacy; for instance, chitosan nanoparticles (CHNP) typically function within a 10–200 nm range, with specific studies demonstrating highly effective coatings based on particles as small as ~16 nm. The choice of application method whether dipping, spraying, or brushing presents a trade-off between uniformity and scalability, where dipping ensures excellent coverage but is less suited for high-speed packing lines, while spraying is more mechanization-friendly but requires careful optimization of drying conditions and adhesion, particularly on naturally waxy fruit surfaces. Furthermore, any successful coating must demonstrate full compatibility with existing industrial infrastructure, meaning it must not cause fruits to stick together or to their packaging, must not clog application equipment, and must retain its functional properties—such as flexibility and barrier function—throughout the rigors of the cold chain without cracking or degrading (Mani *et. al.*, 2018).

2. Light systems and integration: The practical integration of light-based treatments, such as UV-C and LED, into commercial packing operations requires specialized engineering to ensure both efficacy and efficiency. This involves designing treatment chambers—from UV-C tunnels for surface sanitation to custom LED arrays for metabolic modulation—that can be seamlessly incorporated into conveyor systems, with a paramount focus on achieving uniform irradiation dosages across all produce items and ingeniously designing the system to minimize shadowing effects that create untreated spots (Algarni *et. al.*, 2022). While the energy efficiency of LEDs presents a significant advantage over traditional broad-spectrum lamps, the commercial viability of any light treatment is ultimately a function of energy consumption, which is dictated by exposure duration and daily throughput; therefore, a thorough cost-benefit analysis comparing the operational expenses of the treatment against the financial gains from reduced postharvest losses is an indispensable step for justifying commercial adoption.

3. Quality trade-offs & sensory impacts: A paramount consideration often determines consumer acceptance: even the most technically effective treatment is a commercial failure if it adversely affects the product's sensory qualities. Specific light doses can potentially induce off-flavors or cause superficial discoloration, while certain nanoparticle formulations can create coatings that are opaque, sticky, or impart an undesirable mouthfeel, rendering them utterly unacceptable for fresh-eating fruits where visual appeal and texture are primary purchase drivers. Consequently, comprehensive sensory evaluation—encompassing visual appearance, aroma, texture, and taste—must be an integral, non-negotiable component of the product development cycle from its earliest stages, ensuring that the pursuit of extended shelf-life does not come at the cost of the very qualities that make the fruit desirable to consumers in the first place (Algarni *et. al.*, 2022).

Safety, Toxicology and Regulatory Landscape

Navigating the safety, toxicology, and regulatory landscape is a critical pillar for the successful commercialization of novel postharvest technologies, with a primary concern being the migration and residual profiles of the materials used, where traditional metal nanoparticles like silver, zinc oxide, and titanium dioxide face intense regulatory scrutiny due to potential leaching into edible tissues and uncertainties regarding long-term dietary exposure, thereby making biopolymers such as chitosan which are often classified as Generally Recognized As Safe (GRAS) for their bulk forms a more prudent starting point, though their novel nanoparticulate versions still necessitate a thorough and case-by-case safety assessment to confirm their benign nature. Concurrently, the operational deployment of physical treatments like UV-C light demands stringent worker safety protocols, including fully shielded applications, robust safety interlocks, and comprehensive standard operating procedures to prevent harmful exposure to radiation, ensuring a secure industrial environment (Obajuluwa *et. al.*, 2025). From a regulatory standpoint, edible coatings are typically evaluated under food additive or processing aid frameworks, but the introduction of nano-enabled materials often triggers a more rigorous approval pathway in many jurisdictions, mandating the submission of extensive toxicological dossiers that must encompass detailed nanoparticle characterization, thorough risk assessments of chronic dietary exposure, and a comprehensive evaluation of the ecotoxicological fate of these materials throughout their lifecycle.

Future Recommendations

For researchers and industry professionals aiming to translate postharvest biotechnology into practical applications, a strategic and methodical implementation plan is paramount, beginning with the adoption of a hormetic approach where initial protocols must prioritize low-dose, short-duration exposures to novel treatments like UV-C or specific LED spectra to meticulously map the narrow benefit window that induces beneficial stress responses—such as enhanced phytochemical production or pathogen resistance—without crossing the threshold into cellular or tissue damage. When progressing to pilot-scale operations, a pragmatic first step involves leveraging biopolymer-based nanocarriers, such as chitosan or cellulose nanofibres, which not only offer proven efficacy but also significantly reduce the regulatory burden and mitigate potential consumer apprehension compared to synthetic alternatives, thanks to their generally recognized as safe status, biocompatibility, and biodegradability. Furthermore, while combination treatments often hold the greatest promise for synergistic effects, they must be deployed sparingly and with rational design—for instance, sequencing a brief UV-C sanitation step to reduce microbial load, followed by a chitosan-nanoparticle coating to form a protective barrier, and complemented by intermittent LED exposure during storage to modulate metabolism—with the critical caveat that these multi-hurdle technologies require early and rigorous assessment of sensory attributes and migration studies of any active compounds to ensure no detrimental impacts on quality or safety (Obajuluwa *et. al.*, 2025). Finally, fostering a culture of transparency by systematically documenting and publishing negative or null results is an essential practice that serves the broader community by preventing redundant research efforts and building a more realistic evidence base for the practical potential and limitations of these interventions across diverse crop commodities.

Conclusion

Light spectrum manipulation (LEDs and UV-C) and nano-coatings are scientifically validated, complementary strategies to extend the postharvest life of fruits. LEDs (particularly blue and red bands) can elicit host defenses and improve functional quality, while UV-C is a robust surface sanitizer when applied correctly. Nano-coatings—especially chitosan nanoparticles and well-designed nanoemulsions—improve barrier properties and add antimicrobial function. Combined strategies appear promising, but scaling, safety, regulatory acceptance and comprehensive cost-benefit analyses remain critical next steps before widespread commercial adoption. Continued interdisciplinary work (plant physiology, materials science, toxicology, supply-chain engineering) is needed to translate laboratory successes into safe, effective commercial solutions.

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Towards Climate-Resilient Agriculture: Integrating Solar Farming and Crop Rotations for Sustainable Productivity – A Short Review

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Summary

In the face of escalating global climate change, the agricultural sector is under immense pressure to undergo a transformative evolution. Climate-responsive cropping systems have emerged as a pivotal and forward-thinking approach, designed not merely to cope with but to proactively adapt to the new realities of a volatile climate, all while significantly mitigating the environmental footprint of farming practices. Two synergistic strategies have recently surged to the forefront of sustainable agriculture: (1) solar farming, scientifically termed agrivoltaics—an innovative paradigm that facilitates the simultaneous use of land for both photovoltaic energy generation and agricultural crop cultivation, and (2) the practice of sustainable crop rotations, a time-honored technique revitalized to diversify cropping sequences, thereby enhancing soil health, natural pest suppression, and overall farm resilience. The strategic integration of these two approaches presents a profoundly synergistic pathway, offering a multi-faceted solution that optimizes land use efficiency to an unprecedented degree, actively contributes to the reduction of greenhouse gas emissions, and provides a crucial buffer to stabilize agricultural yields under increasingly variable and extreme climatic conditions. This comprehensive review meticulously examines the multifaceted dimensions—encompassing agronomic, ecological, physiological, and socio-economic aspects—of merging agrivoltaic systems with sophisticated crop rotation practices. It delves into the critical design principles that govern their success, synthesizes recent research advances, elaborates on the extensive benefits and practical limitations, and outlines pivotal future research directions. The ultimate aim is to provide a robust framework to guide the effective implementation of these integrated systems, steering the global agricultural community toward a future of sustainable and climate-resilient agri-energy systems.

Introduction

The pervasive impacts of climate change have dramatically intensified the challenges confronting global agricultural productivity. Rising average temperatures, increasingly erratic and unpredictable precipitation patterns, and a higher frequency of extreme weather events, such as droughts and floods, are destabilizing food production systems worldwide. To safeguard global food security for a growing population, it is imperative to transition toward climate-responsive cropping systems—dynamic and intelligent systems capable of adapting to environmental variability in real-time while simultaneously minimizing their carbon footprints. Among the plethora of adaptive strategies being explored, agrivoltaics and sustainable crop rotations stand out as particularly powerful and inherently complementary solutions. Agrivoltaics represents a technological synergy, integrating solar panels directly with agricultural crop production to create a dual-purpose land-use system that generates renewable energy and food on the same parcel of land. Sustainable crop rotations, conversely, leverage ecological principles, using planned sequences of diverse crops to enhance soil fertility, promote biodiversity, and build systemic resilience against climatic stresses. The convergence of these two paradigms—one rooted in renewable energy technology and the other in ecological farming—signifies a promising and holistic pathway toward a more sustainable and resilient agricultural future.

Agrivoltaics: Concept and Functional Principles

Agrivoltaics, at its core, is defined by the co-location of agricultural activities beneath elevated solar panel arrays, which are strategically designed to optimize the capture of solar energy for electricity generation while allowing sufficient photosynthetically active radiation (PAR) to reach the plants below. This

configuration induces significant microclimatic modifications beneath the solar array. The partial shading provided by the panels leads to reduced soil surface temperatures, moderates the heat stress on plant canopies, and substantially lowers rates of evapotranspiration. This created microclimate enables crops to thrive under conditions of reduced heat and water stress, which is particularly advantageous in arid and semi-arid regions. Technological advancements, such as the development of semi-transparent PV panels and dynamically adjustable tilt systems, allow for precise management of light penetration, thereby enhancing compatibility with a wider variety of agricultural crops.

The agrivoltaic approach has demonstrated notable success with shade-tolerant and high-value crops, including leafy greens like lettuce and spinach, as well as certain medicinal herbs. In contrast, light-demanding crops, such as maize and sunflowers, require more careful system design, including wider spacing between panels and higher mounting structures, to prevent significant yield penalties. Consequently, the engineering of the microclimate within an agrivoltaic system, through thoughtful panel configuration and crop selection, plays a decisive role in determining its agricultural and energetic success.

Sustainable Crop Rotations: Mechanisms and Climate Benefits

Crop rotation, the planned temporal sequence of different crops on the same area of land, has long been a cornerstone of sustainable agriculture. Modern, climate-responsive rotations have evolved this practice to emphasize strategic legume integration, the use of cover crops, and complex multi-species sequences specifically designed to enhance overall ecosystem functioning. The multifaceted benefits of such diversified rotations are extensive:

- 1. Soil Structure Improvement:** The alternation between deep-rooted and shallow-rooted crops naturally breaks up soil compaction, improves soil porosity, and enhances water infiltration and retention capacity.
- 2. Nutrient Cycling Enhancement:** The inclusion of leguminous crops, which form symbiotic relationships with nitrogen-fixing bacteria, reduces dependency on synthetic nitrogen fertilizers by adding this essential nutrient directly to the soil.
- 3. Pest and Disease Suppression:** By regularly changing the host crop species, rotation effectively interrupts the life cycles of soil-borne pathogens and specialist insect pests, reducing their populations and the need for chemical pesticides.
- 4. Carbon Sequestration Acceleration:** Diversified rotations typically produce greater and more varied biomass inputs through root exudates and crop residues, which in turn enhance soil organic carbon content, drawing down atmospheric CO₂.

Empirical evidence from agricultural systems across Europe, Asia, and North America consistently shows that diversified crop rotations lead to greater yield stability and significantly reduce vulnerability to climatic stresses like drought and heat, thereby substantially improving a farm's overall climate resilience.

Integration of Agrivoltaics with Sustainable Crop Rotations

The integration of solar farming with sustainable crop rotations represents a powerful synergy, merging energy resilience with deep ecological sustainability. This requires strategic, context-sensitive planning to ensure that the shading patterns cast by PV panels complement, rather than conflict with, the chosen crop rotation sequences.

1. Design Principles for Integration:

- a. Strategic Crop Compatibility:** Careful selection of crops based on their light requirements is essential. Shade-tolerant species (e.g., leafy vegetables, legumes, tubers) are ideally suited for areas with denser PV arrangements, while sun-loving crops can be cultivated in rows with wider panel spacing.
- b. Intelligent Panel Configuration:** Panels should be elevated to a significant height (typically ≥ 3 meters) to accommodate farm machinery and allow for adequate air circulation. The use of adjustable tilt mechanisms or semi-transparent modules can dynamically manage light distribution.

c. Holistic Soil Health Integration: The spaces between panel rows can be effectively utilized for cover crops, which protect the soil from erosion, suppress weeds, and contribute organic matter, thereby maintaining and enhancing soil fertility within the system.

d. Temporal Rotation Alignment: Crop sequences can be intelligently scheduled so that shade-sensitive crops are grown during cooler seasons or under panels with adjusted transparency, while shade-tolerant crops occupy the space during the hotter months to benefit from the moderated microclimate.

e. Synergistic Water Optimization: The reduced evapotranspiration rates under the panels naturally conserve soil moisture. This benefit can be further amplified by coupling the system with highly efficient drip irrigation or rainwater harvesting techniques, maximizing overall water-use efficiency.

2. Case Examples of Integrated Systems: Mediterranean Systems: Research in Mediterranean climates has shown that crops like lettuce, spinach, and alfalfa cultivated under semi-transparent PV arrays achieved water savings of up to 60% while experiencing only minimal yield losses, demonstrating efficient resource use.

Indian Context: Pilot agrivoltaic projects in states like Gujarat and Maharashtra have successfully cultivated high-value crops such as turmeric, various legumes, and okra under elevated PV arrays, effectively combining continuous energy production with stable and profitable crop yields.

Mechanistic Interactions in Integrated Systems

1. Light Modulation and Photosynthetic Efficiency: While agrivoltaic systems reduce the total intensity of direct solar radiation, they often increase the proportion of diffuse light. This diffuse light can penetrate deeper into the plant canopy, potentially enhancing photosynthesis in crops with high leaf-area indices. Furthermore, advanced semi-transparent panels can be spectrally optimized to allow the red and blue light wavelengths, which are most critical for photosynthesis, to pass through, while harvesting other parts of the spectrum, such as near-infrared light, for energy generation.

2. Soil Temperature and Water Relations: The shading from PV panels acts as a buffer, significantly reducing diurnal fluctuations in soil temperature. This creates a more stable and favorable root-zone environment and directly leads to decreased evaporation, conserving valuable soil moisture. This water-conserving effect synergizes powerfully with crop rotations that include deep-rooted species, which can draw up water from deeper soil layers, and legumes, which improve soil structure for better water retention.

3. Soil Carbon and Microbial Dynamics: The integration of diversified rotations within an agrivoltaic framework promotes a virtuous cycle for soil health. The continuous input of diverse organic residues from rotational crops serves as a rich substrate for soil microorganisms. This, combined with the stable, moderated microclimates beneath the PV structures, fosters greater microbial diversity and activity, which in turn accelerates nutrient mineralization and enhances long-term carbon sequestration in the soil.

Socio-Economic and Policy Dimensions

1. Economic Viability: A primary economic advantage of agrivoltaics is the creation of dual revenue streams from both food production and electricity generation. Studies from countries like Japan and Germany have indicated that the combined land-use profitability from these integrated systems can exceed that of conventional monocrop agriculture by up to 30% or more. However, the substantial initial capital investment required for the PV infrastructure remains a significant barrier, particularly for smallholder farmers, underscoring the critical need for public-private partnerships and targeted subsidy mechanisms.

2. Policy and Governance: Effective policy frameworks are essential to catalyze the adoption of these integrated systems. Governments can encourage dual-use land practices through mechanisms such as feed-in tariffs for renewable energy, tax incentives for agrivoltaic infrastructure, and revised land-use zoning regulations. The integration of agrivoltaics into national agricultural and energy policies, as exemplified by India's PM-KUSUM scheme, demonstrates the potential for linking renewable energy goals directly with rural economic development and income diversification.

3. Social Acceptance and Knowledge Gaps: Farmer perception, technical literacy, and the compatibility of these systems with existing mechanization practices are critical determinants of widespread adoption. Conducting participatory field trials and fostering close collaboration between farmers, scientists, and engineers are vital for bridging knowledge gaps, addressing practical concerns, and refining context-specific models for rotation-solar integration.

Environmental Trade-Offs and Limitations

Despite the considerable benefits, integrated AV-rotation systems are not without their challenges and limitations:

1. Shading Mismatch: An poorly designed PV layout can create excessive shading that hinders the growth of sun-loving crops and may impede the use of standard agricultural machinery.

2. Water Redistribution Issues: The physical structure of the panels can intercept rainfall and create uneven patterns of soil moisture beneath the array, leading to heterogeneity that must be managed.

3. Material Lifecycle Concerns: The manufacturing and eventual disposal of solar panels introduce embodied carbon emissions and electronic waste challenges. Therefore, a comprehensive life-cycle analysis is crucial to accurately assess the net environmental sustainability of any agrivoltaic project.

Future Research Directions

To fully harness the potential of climate-responsive cropping systems integrating agrivoltaics (AV) and sustainable crop rotations, comprehensive and long-term research is essential. Future studies should focus on conducting multi-season, location-specific experiments across diverse agro-climatic zones to assess yield dynamics, microclimatic interactions, and overall system resilience. Advancements in spectral optimization are also needed to design next-generation semi-transparent photovoltaic (PV) materials that cater to the specific photobiological requirements of different crops, enhancing light-use efficiency and productivity. Additionally, the development of sophisticated economic models integrating renewable energy outputs, carbon credit revenues, and yield stability parameters can provide a clearer understanding of system profitability and sustainability. Equally important are detailed biodiversity assessments to evaluate the impacts of these integrated systems on pollinators, beneficial insects, and other ecosystem service providers, ensuring that technological innovations align with ecological integrity and long-term sustainability goals.

Conclusion

The integration of solar farming and sustainable crop rotations stands as an innovative, holistic, and pragmatic strategy for advancing climate-responsive agriculture. Agrivoltaics provides a foundational layer of energy resilience and beneficial microclimate regulation, while diversified crop rotations enhance the underlying soil fertility, biodiversity, and adaptive capacity of the farming system. When designed with careful consideration of local ecological and socio-economic contexts, the powerful synergy between these systems can make a significant contribution to achieving global sustainability goals, simultaneously advancing the interconnected imperatives of food security, energy security, and climate change mitigation.

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Seaweed: A Super Food for Plants

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Introduction

A marine plant known as Seaweed which has substantial nutritional benefits and has paved a pathway from agriculture in to sustainable agriculture. It is bestowed with bioactive compounds, natural growth hormones and essential minerals. Seaweed has provided similar health benefits provides a full range of nutrition for plants, increase plant immunity to increase soil health to crop production. The earliest farmers to cultivate seaweed for food, traditional medicine, and soil amendments were coastal villages in China, Korea, and Japan. Farmers eventually realized that adding seaweed to the field might improve soil fertility, boost crop yield, and shield host plants from pests and disease impacts. In agriculture, seaweed has long been used. As modern farming methods have evolved, seaweed has also been used to support environmentally friendly, sustainable farming methods, where it holds promise as a natural substitute.

Seaweeds and its Classification

The multicellular, microscopic algae known as seaweeds are found in marine environments (Singh *et al.*, 2025). Although there are more than 9 thousand macroalgae species in the waters, they can be generically categorized into three classes (Khan *et al.*, 2009):

SN	Classification	Examples	Images
1.	Rhodophyta (Red algae)	<i>Acrosorium venulosum</i> <i>Callophyllis laciniata</i> <i>Chondria capillaris</i>	
2.	Chlorophyta (Green algae)	<i>Chlorella</i> <i>Chlamydomonas</i> <i>Spirogyra</i> <i>Ulva</i>	
3.	Phaeophyta (Brown algae)	<i>Cystoseira baccata</i> <i>Pylaiella littoralis</i> <i>Litosiphon pusillus</i>	

Source: <https://www.seaweed.ie/algae/chlorophyta.html>;

<https://www.seaweed.ie/algae/phaeophyta.html>; <https://www.seaweed.ie/algae/rhodophyta>

Seaweed as a Superfood for Plants: Applications of Seaweed in Agriculture

Seaweeds can be used as follows for plant nutrition;

- a. Liquid seaweed extracts for foliar applications.
- b. Dried and powdered seaweed for incorporation into soil.
- c. Compost activators to improve soil microbes.

In addition to providing some of the essential nutrients, like potassium, calcium, magnesium, and trace minerals, seaweeds are also a good source of natural plant hormones, like auxins, gibberellins, and cytokinins. When added to soil or crops, these substances can help with nutrient uptake, promote growth, and ultimately increase crop survival rates under environmental or climatic stress. A brief note on applications of seaweed in agriculture is given below;

1. Seaweed extracts are known to regulate plant development through the production of growth hormones. Seaweed concentrations may contain chemicals that regulate plant development, according to positive results seen in a variety of plant growth bioassays (Singh *et al.*, 2025).
2. Betaines present in various seaweeds can reduce osmotic stress of plants brought by salinity and drought stress (Blunden *et al.*, 1997).
3. Seaweeds act as bio-regulators due to its peculiar phytochemicals are reported by many authors.
4. It is well known that by employing seaweed biomass as adsorbents, heavy metal ions like cadmium and lead are effectively removed (Vinoj and Kaladharan, 2006).
5. The use of seaweed and seaweed extracts promotes the growth of beneficial soil microbes and the release of chemicals that condition the soil (Singh *et al.*, 2025).
6. Many scientists noted that seaweeds are good soil conditioners and which in turn will help to maintain soil quality.
7. Promoting the growth of roots. Because seaweed promotes root growth, plants are better able to absorb nutrients and water.
8. Increasing a plant's resilience to pests, illnesses, and harsh environmental conditions. Seaweed's natural components help plants become more resilient to a range of environmental and genetic stressors, including plant diseases, insect pests (herbivory), and stress from extreme weather fluctuations.
9. Better quality and yields. Cropland improvements, including increased production, improved fruit size, improved flavor, and longer shelf life, are regularly reported by farmers.
10. A better state of the soil, i. e., healthy soil. Additionally, seaweeds improve soil structure, nourish soil bacteria, and enrich soil.
11. Sustainable and beneficial to the environment. Seaweed decreases the demand for chemical fertilizers and is biodegradable and renewable.

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Food Waste on Farms: Causes and Smart Solutions

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Abstract

Food waste on farms represents a significant global issue, driven by a complex interplay of environmental, economic, and logistical factors. Key causes include market-driven cosmetic standards that reject perfectly edible produce, overproduction to mitigate risks like weather and disease, and unreliable market demand due to cancelled or altered orders. Further contributing to this waste are technological and infrastructural shortcomings, such as a lack of proper on-farm storage, inadequate transportation, and inefficient harvesting techniques.

Introduction

Food waste on farms, also known as on-farm food loss. The causes are varied and can result in large quantities of edible food being left to rot in the fields or discarded after harvest. Addressing this issue is critical for improving farmers' incomes, enhancing food security, and reducing the significant environmental impact of the food system. A proportion of waste food will end up in a landfill site, where it rots and releases methane, a powerful greenhouse gas. If we stopped throwing this good food away it would save the equivalent of at least 36 million tonnes of greenhouse gas emissions. Food waste on farms stems from cosmetic standards, weather damage, pests, poor infrastructure, and inefficient handling. Small-scale solutions include optimizing crop nutrition, implementing better harvesting and handling techniques, adopting better storage, redistributing surplus produce to local food banks, and engaging in composting of inedible plant materials (Minaei, 2022).

Causes of Food Waste on Farms

1. Environmental Factors:

Adverse Weather Conditions: Extreme weather, such as droughts, floods, or unseasonal frosts, can damage or destroy crops, leading to significant losses on the farm.

Pests and Diseases: Infestations of pests or outbreaks of plant diseases can render crops unfit for consumption or sale, causing them to be discarded.

Soil and Water Quality: Poor soil conditions and water scarcity or contamination can negatively impact crop health and yield, contributing to food loss.

Climate Change: Broader shifts in climate patterns can exacerbate existing environmental challenges, creating more unpredictable conditions for agricultural production and increasing the risk of crop failures and food waste.

2. Cosmetic Standards:

Rejection by Buyers: Supermarkets and other buyers often have strict aesthetic standards that reject produce with blemishes, inconsistent shapes, or wrong sizes, even when the food is still edible and safe.

Unmarketable Produce: This results in a large portion of harvested produce being deemed unmarketable by the market, despite its nutritional and safety quality.

Overproduction: To ensure enough product meets strict specifications, farmers may overproduce, further increasing the volume of non-conforming, but edible, crops.

Unsold Food: When produce doesn't meet these cosmetic grades, farmers may struggle to find alternative markets, leading to the food being discarded or left in the fields to rot.

3. Inefficient Practices:

Poor Harvesting and Handling: Ineffective or improper harvesting and post-harvest handling techniques can damage crops, leading to spoilage and waste even before they leave the farm.

Lack of Cold Chain/Storage: Insufficient cold storage and transportation infrastructure at the farm level means perishable goods spoil quickly, often forcing farmers to sell at low prices or discard them entirely.

Overproduction: Farmers may produce more than they can sell due to uncertain market demand, leading to unsold crops being wasted.

Strict Cosmetic Standards: Retailers often reject perfectly edible produce for minor imperfections in size, shape, or colour, which leads farmers to discard these "imperfect" but still nutritious and safe foods (Beausang et al, 2017).

Solution Of Farm Food Waste

1. Improving Farming Practices

Balanced Nutrient Application: Correct fertilizer application prevents over or under-nutrition, which can shorten shelf life or lead to crop failure and discard.

Pest and Disease Management: Integrated pest management (IPM) helps minimize spoilage from pests and diseases.

Post-Harvest Techniques: Implementing proper storage and harvesting methods reduces post-harvest losses and prolongs shelf life.

2. Utilizing Surplus and Imperfect Food:

Food Donation: Partner with food banks and charities to redirect wholesome, surplus food to those in need.

Whole Crop Contracts: Retailers can offer contracts that guarantee the purchase of all produce, including cosmetically imperfect items, reducing farm-level waste.

Value-Added Processing: Transform surplus or imperfect produce into jams, dried ingredients, or other products that can be stored and sold.

3. Leveraging Technology and Innovation:

On-Farm Storage & Processing: Invest in solutions like solar-powered dryers or cold storage units to preserve crops and extend their shelf life.

Innovative Packaging: Advanced and smart packaging can help monitor and extend the freshness of produce.

Online Platforms: Utilize e-commerce platforms that connect farmers with consumers, helping to sell surplus and imperfect products (Fan et al, 2025).

Conclusion

Food waste on farms is a complex issue driven by a combination of market pressures, inefficient infrastructure, and climatic factors. However, small-scale, actionable solutions can make a significant impact. By prioritizing improved on-farm storage, embracing creative markets for imperfect produce, and establishing strong connections with local food recovery programs, individual farmers can take control of their surplus. These small, decentralized actions, when adopted widely, can contribute to a more resilient and sustainable food system that reduces resource loss and improves financial stability for producers.

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Beyond the Farm: Women's Role in the Agricultural Value Chain

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Abstract

This paper examines the multifaceted roles of women in the agricultural value chain, focusing on the systemic challenges that limit their productivity and inhibit their economic empowerment. Women are heavily involved in labour-intensive agricultural tasks, livestock management and post-harvest activities, yet they are often confined to less profitable segments of the value chain. They face disproportionate barriers, including limited access to productive resources, education, financing, and decision-making power, all underpinned by restrictive gender norms. This analysis reveals that while targeted interventions can improve women's economic outcomes and translate into broader empowerment. Achieving holistic empowerment requires a comprehensive strategy that addresses gender inequalities.

Introduction

Women's role in agriculture is fundamental to food production and rural economies worldwide, particularly in low- and middle-income countries. They work as cultivators, labourers, entrepreneurs, and managers across all stages of the agrifood system. In many developing regions, women's agricultural labour accounts for the majority of household food production and a significant portion of the total agricultural workforce. The agricultural value chain is a complex system involving a wide array of activities, from crop production to processing, marketing, and distribution. Across the globe, women are crucial participants at every stage of this chain, especially in developing countries where they constitute a significant portion of the agricultural labour force. Despite their indispensable contributions, their work is often undervalued, unrecognized, and hampered by persistent socio-economic and cultural barriers. Empowering women within this value chain is not only a matter of gender equity but is also critical for achieving sustainable development and enhancing food security.

Women's Participation Across the Value Chain

Women are active in every phase of the agricultural value chain, but their involvement is highly segmented and often concentrated in low-profit activities:

- 1. Production:** Women are heavily involved in primary production tasks such as land preparation, weeding, planting, and harvesting.
- 2. Processing and Value Addition:** Women frequently dominate small-scale, manual processing activities, which add value to raw agricultural goods. However, they often use outdated technology, which limits their productivity and income.
- 3. Marketing and Distribution:** Women tend to be dominant in informal and local markets, selling smaller volumes of produce. Men, by contrast, typically control larger, more lucrative transport and wholesale operations. This limited market access is often compounded by cultural restrictions on women's mobility and networks.

Challenges and Barriers

Several interconnected challenges restrict women's full participation and limit the benefits they receive:

- 1. Unequal access to resources:** Women face significant barriers in accessing critical productive assets like land, credit, and modern technologies. In many patriarchal societies, legal and customary norms

prevent women from owning or inheriting land, which in turn limits their access to bank loans that require collateral.

2. Limited decision-making power: Women are often excluded from key decisions, both within the household and in producer organizations and cooperatives. This lack of agency can prevent them from accessing profitable market opportunities and controlling the income they earn.

3. Gendered division of labor: Women, often referring them to less prestigious and lower-paid tasks. As value chains become more commercialized and profitable, men frequently take over more lucrative activities than women out of those opportunities.

4. Increased workload and "time poverty": Women bear the "triple burden" of productive farm work, domestic chores, and community responsibilities. This overwork limits their time for training, market engagement, and leisure, reinforcing their subordinate position within the value chain.

5. Discrimination and exploitation: Gender biases can lead to lower wages for women performing the same work as men. In formal businesses, women are often concentrated in lower-skilled, casual jobs with poor working conditions.

A more holistic approach is needed to address the root causes of inequality by challenging gender norms and power dynamics. This involves engaging both men and women in the process, though there is a risk of criticism and conflict.

Conclusion

Women are fundamental to the agricultural value chain, yet their contributions are consistently undermined by structural and socio-cultural barriers that restrict their access to resources, power, and opportunities. While interventions focused on economic aspects can improve women's income and productivity, true empowerment encompassing greater control over assets, and decision-making. To elucidate women's full potential in agriculture and achieve sustainable development and food security, a multi-pronged and gender-sensitive approach is required which may include strengthening women's rights to land ownership and inheritance, providing equitable access to credit, technology, and gender-responsive extension services, offering training in technical skills, financial management, and leadership, promoting gender-transformative approaches that challenge restrictive norms and address imbalances in domestic labour and decision-making. By investing in women activities at all levels of the agricultural value chain, and addressing the underlying dynamics of gender inequality, it is possible to build more equitable, productive, and resilient systems that benefit entire communities.

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CRISPR-Cas9 and Beyond: Precision Genome Editing in Vegetable Crops – A Short Review

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Summary

The escalating global demand for nutritious, climate-resilient, and high-yielding vegetable crops has catalysed a paradigm shift in agricultural biotechnology, moving from traditional breeding to precise genome-editing technologies. CRISPR-Cas9 stands at the forefront of this revolution. Vegetables, which are indispensable sources of vitamins, minerals, fibre, and health-promoting phytochemicals, require continuous genetic enhancement to combat evolving biotic (pathogens, pests) and abiotic (drought, salinity, heat) stresses, all while maintaining superior yield, quality, and postharvest characteristics. The CRISPR-Cas9 system and its advanced derivatives—such as base editing, prime editing, and CRISPR-Cas12a—have fundamentally transformed plant biotechnology by facilitating targeted genomic modifications with unparalleled accuracy, efficiency, and flexibility. This review delves into the mechanistic underpinnings of CRISPR-Cas9, its extensive and successful applications in key vegetable crops like tomato, potato, eggplant, cucumber, and lettuce, and explores the next wave of innovations that extend beyond the foundational Cas9 system. A detailed, species-by-species summary of edited genes, resulting phenotypic outcomes, and their direct implications for modern breeding programs is provided. Furthermore, the review addresses persistent technical challenges, the evolving global regulatory landscape, and future trajectories for precision genome editing in securing a sustainable and nutritious food supply.

Introduction

Vegetable crops are cornerstones of global food security, human nutrition, and agricultural economic systems. They provide essential micronutrients often lacking in staple cereal diets. However, the productivity, quality, and geographic stability of these crops are perpetually jeopardized by a multitude of stressors. Biotic threats, including fungal, bacterial, and viral pathogens, as well as insect pests, can cause devastating yield losses. Simultaneously, abiotic pressures such as drought, soil salinity, and extreme temperatures, exacerbated by climate change, pose significant challenges to conventional cultivation. Traditional breeding methods, while responsible for many of the varieties grown today, are inherently slow, labour-intensive, and hampered by genetic linkage drag—where undesirable genes are co-inherited with beneficial ones—and are limited by sexual compatibility.

The advent of sequence-specific nuclease technologies, particularly the Clustered Regularly Interspaced Short Palindromic Repeats (CRISPR) and CRISPR-associated protein 9 (Cas9) system, has ushered in a new epoch of precision crop improvement. CRISPR-Cas9 functions as a programmable "molecular scissor," enabling researchers to make precise cuts in the DNA of living organisms. This technology induces targeted double-strand breaks (DSBs) at predetermined genomic loci, which the cell's innate repair machinery then fixes through either error-prone non-homologous end joining (NHEJ), leading to gene knockouts, or high-fidelity homology-directed repair (HDR), allowing for precise gene insertions or corrections. Compared to its predecessors—zinc-finger nucleases (ZFNs) and transcription activator-like effector nucleases (TALENs)—CRISPR-Cas9 offers a superior combination of simplicity, design flexibility, cost-effectiveness, and multiplexing capability, making it accessible to laboratories worldwide. In vegetable crops, it has rapidly transitioned from a basic research tool for functional genomics to a powerful engine for developing elite cultivars with enhanced agronomic performance.

Mechanism of CRISPR-Cas9 in Plants

The core CRISPR-Cas9 system, adapted from the immune system of the bacterium *Streptococcus pyogenes*, comprises two key components: the Cas9 endonuclease enzyme and a single-guide RNA (sgRNA). The sgRNA is a synthetic fusion of two natural RNAs, which serves as a homing device. It is engineered to

contain a ~20 nucleotide sequence that is complementary to the specific DNA target site within the plant's genome. For Cas9 to bind and cleave, the target sequence must be immediately adjacent to a short DNA motif known as a Protospacer Adjacent Motif (PAM), which, for the standard Cas9, is "NGG" (where 'N' is any nucleotide).

The mechanism unfolds in a series of steps: First, the sgRNA-Cas9 complex scans the genome. Upon locating a sequence that matches the sgRNA and is flanked by a PAM, the complex binds tightly. Cas9 then unzips the DNA double helix and introduces a precise DSB. The plant cell perceives this break as damage and activates its repair pathways. The predominant and more efficient pathway in plants, NHEJ, ligates the broken ends back together but is prone to introducing small insertions or deletions (indels). If these indels occur within the coding region of a gene, they can disrupt the reading frame, leading to a non-functional, "knocked-out" gene. The less frequent HDR pathway can be co-opted by providing a donor DNA template alongside the CRISPR machinery, enabling the incorporation of specific nucleotide changes or new gene sequences.

Delivery of the CRISPR-Cas9 components into plant cells is typically achieved through *Agrobacterium*-mediated transformation (the most common method), direct delivery into protoplasts (plant cells without cell walls), or biolistics (gene gun). The edited cells are then regenerated into whole plants through tissue culture. A critical innovation for both practical application and regulatory approval is the development of DNA-free editing. This involves delivering pre-assembled Cas9 protein and sgRNA complexes, known as Ribonucleoproteins (RNPs), directly into plant cells. This method transiently edits the genome without integrating foreign DNA, often resulting in non-genetically modified organism (non-GMO) classified plants.

Applications in Vegetable Crops

The implementation of CRISPR-Cas9 has yielded remarkable successes across a wide spectrum of vegetable species, targeting traits of paramount agricultural importance.

1. Tomato (*Solanum lycopersicum*): As a model system for fleshy-fruited vegetables, tomato has been at the forefront of CRISPR applications. Beyond the examples mentioned, editing has been used to enhance fruit quality profoundly. For instance, knocking out genes involved in the production of anti-nutritional compounds like steroidal glycoalkaloids (e.g., GAME genes) can improve fruit safety and taste. Furthermore, targeting transcription factors like SIJAZ2 can modulate the plant's sensitivity to the plant hormone jasmonate, leading to enhanced resistance to herbivorous insects. The ability to fine-tune ripening by editing genes such as SIRIN not only extends shelf life but also allows for fruit to be harvested at a more mature stage for better flavor, which can then be held until transport and sale without over-ripening.

2. Potato (*Solanum tuberosum*): The tetraploid nature of potato makes it a challenging but highly rewarding target for CRISPR. The success in knocking out all four alleles of the GBSSI gene to produce waxy, amylose-free potato starch is a landmark achievement, demonstrating the power of multiplexing. Beyond starch, CRISPR has been deployed to reduce the accumulation of acrylamide—a potential carcinogen that forms in fried and baked potato products. This is achieved by knocking out the *Asparagine synthetase-1 (StAS1)* gene, which lowers the levels of the acrylamide precursor, asparagine. This direct application addresses a major food safety concern.

3. Eggplant (*Solanum melongena*): The editing of the SmPPO gene to reduce enzymatic browning is a prime example of improving postharvest quality, a critical economic trait. Browning leads to unappealing discoloration and nutrient loss. CRISPR has also been instrumental in manipulating the biosynthesis of bioactive compounds. For example, increasing the levels of anthocyanins, powerful antioxidants responsible for the vibrant purple color in some varieties, can enhance the nutritional profile and market value. Efforts are also underway to introduce natural resistance to the devastating Fusarium wilt by targeting susceptibility genes, akin to the SIMlo1 strategy in tomato.

4. Cucumber (*Cucumis sativus*): The knockout of the eukaryotic translation initiation factor eIF4E in cucumber is a textbook case of engineering pathogen resistance by disrupting a host factor essential for the virus's life cycle. This approach provides durable, broad-spectrum resistance to multiple potyviruses. Another significant application in cucumber involves manipulating its sex expression. Cucumber is a monoecious plant with separate male and female flowers. Editing genes like CsWIP1 or CsACS2 can

promote female flower development, which is highly valuable for streamlining hybrid seed production, a cornerstone of the modern vegetable seed industry.

5. Lettuce (*Lactuca sativa*): Lettuce's compact genome and rapid life cycle make it an excellent model for testing new genome-editing tools. Beyond altering leaf morphology and color via genes like *LsTTG1* and *LsKIX8*, CRISPR is being used to tackle nutritional deficiencies. A key target is reducing nitrate accumulation in leaves, as high nitrate levels can be a health concern. Editing genes involved in nitrate transport and assimilation can lead to safer, "low-nitrate" lettuce varieties. Furthermore, enhancing the content of vitamins like folate (Vitamin B9) through metabolic pathway engineering is an active area of research.

Table 1. Species-Specific CRISPR-Cas9 Applications in Major Vegetable Crops:

Crop	Gene Target(s)	Function/Goal	Experimental Outcome	Phenotypic Effect	Reference
Tomato (<i>S. lycopersicum</i>)	<i>SlMlo1</i>	Powdery mildew susceptibility gene	Knockout lines showed enhanced resistance to <i>Oidium neolycopersici</i>	Complete resistance without growth penalty	Pan et al. (2016)
	<i>SLAGL6</i> , <i>SLAGL11</i>	Ovule development and fruit formation	Gene knockout induced seedless (parthenocarpic) fruit	Parthenocarp and increased fruit set	Zsögön et al. (2018)
	<i>SIRIN</i> , <i>SINOR</i>	Fruit ripening regulators	Mutation delayed ripening and extended shelf life	Prolonged firmness and improved storability	Zsögön et al. (2018)
Potato (<i>S. tuberosum</i>)	<i>GBSSI</i>	Starch biosynthesis enzyme	Loss of <i>GBSSI</i> activity reduced amylose content	Amylopectin-rich starch beneficial for industry	Andersson et al. (2017)
	<i>StDMR6-1</i>	Disease susceptibility gene	Knockout conferred resistance to late blight (<i>Phytophthora infestans</i>)	Improved disease resistance	Andersson et al. (2017)
Eggplant (<i>S. melongena</i>)	<i>SmPPO</i>	Polyphenol oxidase enzyme	Reduced enzymatic browning in edited lines	Improved postharvest appearance	Maioli et al. (2020)
Cucumber (<i>C. sativus</i>)	<i>eIF4E</i>	Virus susceptibility factor	Knockout plants resistant to CVYV and ZYMV	Broad-spectrum viral resistance	Chandrasekaran et al. (2016)
Lettuce (<i>L. sativa</i>)	<i>LsTTG1</i> , <i>LsKIX8</i>	Leaf morphology and pigment regulation	Altered leaf structure and anthocyanin levels	Modified leaf shape and color	Maioli et al. (2020)

Advances Beyond CRISPR-Cas9

The rapid evolution of genome-editing technology has produced a sophisticated toolkit that addresses limitations of the standard CRISPR-Cas9 system.

1. CRISPR-Cas12a (Cpf1): This alternative nuclease recognizes a T-rich PAM (e.g., "TTTV"), vastly expanding the repertoire of targetable sites in AT-rich genomic regions. Unlike Cas9, which produces blunt ends, Cas12a creates staggered cuts, which can be more efficient for certain types of gene insertions.

2. Base Editing: This revolutionary technology moves beyond cutting DNA. It uses a catalytically "dead" Cas (dCas9) or a Cas9 nickase fused to a deaminase enzyme. This complex can directly convert one base pair to another at the target site without creating a DSB. Cytidine base editors (CBEs) change C•G to T•A, while adenine base editors (ABEs) change A•T to G•C. This allows for precise single-nucleotide changes to correct point mutations or create new alleles, all while minimizing unintended indels.

3. Prime Editing: Representing the pinnacle of precision, prime editing is a "search-and-replace" system. It uses a Cas9 nickase fused to a reverse transcriptase and a specialized prime editing guide RNA (pegRNA). The pegRNA not only directs the nCas9 to the target site but also contains the template for the new genetic information. This system can mediate all 12 possible base-to-base conversions, as well as small insertions and deletions, without requiring DSBs or donor DNA templates, offering unparalleled versatility and reducing off-target effects.

4. Multiplexing and Gene Stacking: Advanced systems allow for the simultaneous editing of multiple genes by incorporating several sgRNAs into a single construct. This is crucial for polygenic traits, such as complex disease resistance or the orchestration of entire metabolic pathways to enhance nutritional content.

Challenges and Regulatory Perspectives

The path from laboratory breakthrough to commercially viable, widely adopted genome-edited vegetable varieties is not without hurdles.

1. Technical Hurdles: While improved bioinformatics tools have minimized the risk, off-target effects remain a consideration, especially when using promoters that drive high, continuous expression of Cas9. The delivery of editing components remains inefficient in many recalcitrant vegetable species, and the regeneration of whole plants from edited cells (like protoplasts) is a major bottleneck. In polyploid crops, achieving homozygous mutations in all gene copies requires highly efficient editing systems.

2. Regulatory and Public Acceptance: The global regulatory landscape for genome-edited crops is complex and fragmented. A key differentiator is whether a product contains foreign DNA (transgene). Many countries, including the United States, Japan, and Australia, have exempted certain types of genome-edited products that are indistinguishable from naturally occurring mutations or those developed through conventional breeding. India's regulatory framework is also evolving in this direction, with recent guidelines proposing a tiered approach that facilitates the development and release of transgene-free genome-edited plants. However, the European Union's strict GMO regulations still apply to most genome-edited organisms, creating uncertainty for developers and breeders. Public perception and clear science communication will be vital for the successful deployment of these technologies.

Future Prospects

The future of genome editing in vegetables is intrinsically linked to convergence with other disruptive technologies. The integration of multi-omics data—genomics, transcriptomics, proteomics, and metabolomics—will enable the systems-level identification of key genetic nodes for editing to design ideal crop "ideotypes." Machine learning and artificial intelligence are being harnessed to predict the most effective and specific sgRNA designs, the outcomes of edits, and the complex interplay between genes and the environment. Furthermore, emerging frontiers like CRISPR-mediated epigenetic editing—which can reversibly turn genes on or off without changing the underlying DNA sequence—and the editing of organellar genomes (chloroplasts and mitochondria) promise to unlock a new layer of regulatory control and trait enhancement.

Conclusion

CRISPR-Cas9 and its advanced derivatives have irrevocably transformed the landscape of vegetable crop improvement. They provide a precise, powerful, and relatively accessible means to accelerate breeding, address urgent agricultural challenges, and enhance the nutritional value of our food. The documented successes in improving disease resistance, shelf life, nutritional content, and yield components across major vegetable crops are a testament to this potential. As the technology continues to mature, overcoming delivery and regulatory hurdles, its integration with data-driven biology will be the cornerstone of

developing a new generation of sustainable, climate-resilient, and nutritionally optimized vegetable varieties to feed a growing global population.

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A Success Story: Performance Of Mid Altitude Variety of Rice (SR-4) at High Altitude Area of Budgam District: A Benefit of Climate Change

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Abstract

Jammu & Kashmir is an Agri-horticulture state where a large population is economically dependent on agriculture and horticulture, directly or indirectly, for livelihood security. Rice production and food security is greatly affected with climate change like high temperature, uncertain rainfall and extreme weather events leading to water stress, reduced yields, increased pests, and soil degradation. Low-lying rice production regions could be the most susceptible to changing environmental conditions, while mid and high-altitude areas in Kashmir valley could see improvements in rice-growing conditions. Future climate change could reduce the suitable low altitude area for rice production by 60%, (Castro-Llanos, 2019). For the dissemination of various technologies KVKs are conducting frontline demonstrations (FLDs) to demonstrate the production potential of newly released varieties on the farmer's fields at different locations in a given farming system. In the similar way KVK Budgam also conducted the FLD Programme on rice (SR-4) at higher altitude areas of Khag block of Budgam Dist. (Hamchipora and Lobrin) during the successive years of 2021-2022, 2022-2023, 2023-24 and 2024-25 for the performance/evaluation of SR-4. During the FLD programme the average seed yield of SR-4 during the four years was 86.48 q/ha in demonstrated fields as compared to average seed yield of 57.38 q/ha from the local check. The average technology gap over the four years was found to be 3.5 q/ha and extension gap 29.10 q/ha. The average technology index was 3.91 per cent. Higher gross returns (Rs 172967.5 ha⁻¹), net returns (Rs 120982.5 ha⁻¹) with a benefit-cost ratio of 2.32 were found in demonstrated fields as compared to 1.2 in case of local check.

Keywords: Climate change, Rice, SR-4, performance.

Introduction

Rice (*Oryza sativa*), the staple food of the majority population, is cultivated in diverse agro-ecological conditions from the subtropical area (1000 m amsl) of Jammu, through the temperate valley to cold high-altitude regions (1650-2400 m amsl) of Kashmir (Amjad and sofi, 2018). Shalimar Rice-4 (SR-4) is not specifically adapted to high altitudes but is a high-yielding, early-maturing variety that is highly adaptive to the plains and mid-altitude areas of the Kashmir Valley. It is the superior variety for low-temperature stress during the seedling stage, which is common in Kashmir's temperate climate, leading to its adoption over traditional varieties for its higher yield potential, good grain quality, and resistance to blast disease, which are desirable traits for farmers. Warming temperatures can extend the growing seasons and make previously unsuitable high-altitude regions viable for mid-altitude rice varieties particularly SR-4, a benefit of climate change. Regional and national studies in Asia suggest that rice production will suffer under climate change, researchers also conducted few studies for other parts of the world.

Observations

The study was carried out on farmer's field of block Khag, District Budgam under the supervision of KVK Budgam scientists during the successive years of Kharif seasons of 2021-2022, 2022-2023, 2023-24 and 2024-25. Most of the farmers of Khag belt cultivates the K-39 variety a high-yielding, cold-tolerant indica-type rice variety developed in Kashmir for cultivation in temperate and high-altitude areas. For the dissemination of HYV of paddy (SR-4) the selected farmers of the block Khag, District Budgam were supplied with the critical inputs like seed and organic fertilizers by the KVK while the other inputs like herbicides, irrigation and agro chemicals were managed by the farmers according to the SKUAST K

recommended package of practices. The Rice variety “SR-4” was transplanted manually during the first fortnight of June. The number of seedlings/hills used were 5-6 for the cultivation of SR-4. The size of the field under SR-4 cultivation was of variable size. Half dose of nitrogen (40 Kg/ha) along with full Dose of Phosphorus (60 Kg/ha) and Potassium (30 Kg/ha) was applied as basal dose. The remaining quantity of nitrogen in the form of urea was applied in two splits, first split (20 Kg/ha) at tillering stage (18-22 DAT) and second top dose of urea (20 Kg/ha) at panicle initiation stage (35-40 DAT). The FLD programme was conducted to study the performance of mid altitude variety of rice (SR-4) at high altitude area of Budgam district: a benefit of climate change on the yield, technology gap, extension gap and Technology index (%) The yield data was collected from both the demonstration and farmers practice by random crop cutting method and analysed by using simple statistical tools. Different parameters as suggested by Yadav *et al.*, (2004) were used for calculating gap analysis, costs and returns. The details of different parameters are as follows:

Technology gap=Potential Yield-Demonstration yield.

Extension gap=Demonstration Yield-Farmer's yield.

Technology index (%) = Technology gap/ Potential yield×100.

Table 1: Details of farmers of Budgam District under FLD Programme:

Year	Number of Demos.	No. of clusters	Location	Block
2021-22	30	1	Hamchipora	Khag
2022-23	40	1	Hamchipora	Khag
2023-24	40	1	Lobrin	Khag
2024-25	50	1	Lobrin	Khag
Average	40			

Observations

Yield: The result of 40 demonstrations (average) conducted during the *Kharif* seasons of 2021-22, 2022-23, 2023-24 and 2024-25 at farmers field in different villages of Budgam District are shown in Table 2. Farmers adopted the SKUAST K package of practices and supervised by the scientists of KVK Budgam. The data depicts the remarkable impact of FLD over the farming community. The average seed yield of SR-4 was 86.48 q/ha in demonstrated fields as compared to average seed yield obtained from farmers field (54.96 q/ha). The per cent increase in yield was ranging between 54.38 to 55.99 q/ha. On the basis of four years, demonstration plots resulted in 50.88 % higher seed yield over local check. Though this variety is suitable for mid-altitude areas but because of its ideotype character and climate change it thrives well at higher altitude and tribal areas of Khag block and resulted in higher yield. The average technology gap over the four years was 3.5 q/ha, this indicates the gap between technology evolved and technology adoption at farmer's field and also reflects the farmer's cooperation in carrying out such demonstrations with encouraging results in subsequent years. In order to reduce this gap, location specific recommendations for varieties and timely transplantation appear to be necessary. On an average extension gap of 29.10 q/ha was observed which emphasized the need to aware the farmers about the high yielding varieties, about the latest technologies and climate change through trainings and method demonstrations. On an average technology index of 26.71 percent was observed during the four years of FLD programmes, shows the efficacy of good performance of technical interventions. The lower the value of technology index the more is the feasibility of technology.

Economics: An interpretation on economics (Table 3) revealed that SR-4 under FLD programme recorded higher gross returns (Rs 172967.5 ha⁻¹), net returns (Rs 120982.5 ha⁻¹) with a benefit-cost ratio of 2.32 as compared to 1.2 in case of local check. The average sale rate of SR-4 seed was 2000/q. the higher benefit cost ratio in demonstrated plots is due to the higher yield obtained under improved technologies as compared to farmers practice during the demonstration years. Similar results were obtained by Mitra *et al.*, 2014 and it is concluded from the study that under FLD programme the high yielding variety of paddy along with improved technologies has remarkable impact on yield and economics of paddy in Budgam District.

Table 2: Yield, technology gap, extension gap and technology index of Paddy (SR-4) in Budgam District:

Year	Name of crop	No. of Demonstration	Yield (q/ha)						% Increase over check	Technology gap (q/ ha)	Extension gap (q/ha)	Technology index (%)
			Demonstration		Check							
			Max.	Min.	Av.	Max.	Min.	Av.				
2021-22	SR-4	30	87.00	83.54	85.27	56.7	51.23	58.01	46.99	4.73	27.3	5.26
2022-23		40	87.67	84.37	86.02	55.89	52.32	58.99	45.82	3.98	27.0	4.42
2023-24		40	88.50	85.23	86.86	57.2	55.33	54.38	59.73	3.14	32.5	3.49
2024-25		50	90.00	85.57	87.785	56.76	54.26	58.14	50.99	2.22	29.6	2.47
Average		40			86.48			57.38	50.88	3.5	29.10	3.91

Table 3: Gross cost, gross return, net return and B:C ratio of Paddy (SR-4):

Year	Demonstration Plots				Check Plots			
	Cost of Cultivation (Rs/ha)	Gross Returns (Rs/ha)	Net Returns (Rs/ha)	B:C ratio	Cost of Cultivation (Rs/ha)	Gross Returns (Rs/ha)	Net Returns (Rs/ha)	B:C ratio
2021-22	51240	170540	119300	2.33	51240	116020	64780	1.26
2022-23	51700	172040	120340	2.33	51700	117980	66280	1.28
2023-24	52500	173720	121220	2.31	52500	108760	56260	1.07
2024-25	52800	175570	123070	2.33	52800	116280	63480	1.20
Average		172967.5	120982.5	2.32				1.2

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