

A close-up photograph of a hand pouring a stream of golden-brown grains, likely wheat or corn, into a large, overflowing pile of the same grains. The background is a soft, out-of-focus blue sky. The text is overlaid on this image in white rounded rectangular boxes.

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Role of Biofilm-Forming Ability in Plant Pathogenic Bacteria: Mechanisms, Virulence, and Disease Management

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Abstract

Biofilm formation is a widespread survival and virulence strategy among plant pathogenic bacteria, allowing cells to attach to host surfaces, aggregate within a self-produced matrix of extracellular polymeric substances (EPS), and persist under adverse environmental conditions. This article reviews the process, regulation, and pathological significance of biofilm formation in phytopathogenic bacteria such as *Xylella fastidiosa*, *Ralstonia solanacearum*, *Pseudomonas syringae*, *Xanthomonas species*, and *Erwinia/Pectobacterium species*. The stages of biofilm development—initial attachment, microcolony formation, maturation, and dispersal—are discussed alongside the roles of quorum sensing, cyclic-di-GMP signaling, and EPS composition in coordinating these processes. Biofilms contribute directly to disease development by occluding vascular tissue, enhancing resistance to plant defence compounds, protecting bacteria from desiccation and UV radiation, and increasing tolerance to antimicrobial treatments by several-fold. Because biofilm-associated bacteria are inherently difficult to eradicate with conventional bactericides, understanding biofilm biology is essential for designing improved disease management strategies, including anti-biofilm compounds, quorum-quenching agents, and resistant crop varieties. The review concludes that biofilm-forming ability is not merely a colonisation trait but a central determinant of pathogenicity, persistence, and epidemiological success in many economically important plant diseases.

Introduction

Plant pathogenic bacteria cause substantial yield and economic losses across staple, horticultural, and plantation crops worldwide. More than two hundred bacterial species are recognised as causal agents of plant disease, producing symptoms ranging from leaf spots, blights, and cankers to vascular wilts and soft rots. A common feature shared by many of these pathogens is the ability to form biofilms—structured, surface-associated communities of bacterial cells encased within a self-produced matrix of extracellular polymeric substances (EPS) composed of polysaccharides, proteins, extracellular DNA, and lipids.

Biofilm formation confers a considerable adaptive advantage over the free-living (planktonic) state. Within a biofilm, bacterial cells are protected from desiccation, ultraviolet radiation, host defence compounds, and antimicrobial treatments, and they benefit from close cell-to-cell proximity that facilitates nutrient exchange, horizontal gene transfer, and coordinated gene expression through quorum sensing. For plant pathogens, biofilms are not simply a passive protective structure; they are an active component of the infection process, influencing attachment to host tissue, colonisation of intercellular spaces or vascular elements, and the ability to persist on plant surfaces, in soil, in irrigation water, and on agricultural equipment between cropping cycles.

This article reviews current understanding of biofilm formation in plant pathogenic bacteria, the molecular mechanisms that regulate this process, its contribution to virulence and disease development, and the implications of biofilm biology for the management of bacterial plant diseases.

Stages of Biofilm Formation

Biofilm development in plant pathogenic bacteria generally proceeds through four interconnected stages:

- 1. Initial Attachment:** Bacterial cells make reversible contact with a plant surface—such as the leaf cuticle, root epidermis, stomatal opening, wound site, or xylem vessel wall—mediated by flagella, pili, and surface adhesins. Motility and chemotaxis toward root or leaf exudates often precede this step, guiding cells toward favourable colonisation sites.
- 2. Microcolony Formation and Irreversible Attachment:** Once attached, cells begin to multiply and produce EPS, converting reversible attachment into a firmer, irreversible association with the surface. Cells aggregate into

microcolonies, and surface adhesins such as type IV pili and cell-surface proteins strengthen cell-to-cell and cell-to-surface bonds.

3. Maturation: The biofilm develops a complex three-dimensional architecture with channels that allow nutrient and gas exchange. EPS accumulates substantially at this stage, forming the structural matrix that shields embedded cells from external stresses, plant-derived antimicrobial compounds, and applied bactericides.

4. Dispersal: In response to nutrient depletion, quorum-sensing signals, or other environmental cues, cells detach from the mature biofilm, either individually or as aggregates, and disperse to colonise new sites or spread systemically within the host—for instance, moving to new xylem vessels or being acquired by insect vectors.

Regulatory Mechanisms

1. Quorum Sensing: Quorum sensing (QS) enables bacterial populations to coordinate gene expression in a cell-density-dependent manner through the production and detection of diffusible signal molecules. In many phytopathogens, QS systems regulate EPS production, motility, and the transition between biofilm formation and dispersal. In *Xylella fastidiosa*, for example, the diffusible signal factor (DSF) system regulates the balance between adhesive, biofilm-forming behaviour and motile, dispersive behaviour, directly influencing the bacterium's ability to colonise xylem vessels and to be acquired by insect vectors.

2. Cyclic-di-GMP Signalling: The second messenger cyclic-di-GMP (c-di-GMP) is a central regulator of the switch between motile and sessile (biofilm) lifestyles in bacteria. High intracellular c-di-GMP levels generally promote EPS synthesis and biofilm formation, while low levels favour flagellar motility and dispersal. This signalling network is modulated by environmental cues such as nutrient availability, surface contact, and host-derived signals.

3. Extracellular Polymeric Substances (EPS): EPS forms the structural scaffold of the biofilm matrix and is a key virulence determinant in several vascular pathogens. In *Xanthomonas* and *Xylella* species, EPS (such as xanthan gum analogues) contributes to vessel occlusion, water-stress symptoms, and protection from host defences. Mutants deficient in EPS production typically show reduced virulence and impaired biofilm formation, underscoring the importance of this polymer in pathogenesis.

Role of Biofilms in Pathogenicity and Disease Development

1. Vascular occlusion: In xylem-colonising pathogens such as *Xylella fastidiosa* and *Ralstonia solanacearum*, biofilm accumulation physically blocks water-conducting vessels, producing wilting, leaf scorch, and eventual plant death.

2. Protection from host defences: The EPS matrix shields bacterial cells from plant-derived antimicrobial compounds, reactive oxygen species, and components of the plant immune response.

3. Environmental resilience: Biofilms protect bacteria from desiccation, ultraviolet radiation, and nutrient limitation, allowing survival on leaf surfaces, in soil, and on contaminated equipment or seed between growing seasons.

4. Increased antimicrobial tolerance: Bacteria embedded in biofilms can show markedly greater tolerance to bactericides and antibiotics compared with planktonic cells, complicating chemical control efforts.

5. Vector transmission: In insect-transmitted pathogens such as *Xylella fastidiosa*, biofilm formation within the vector's foregut is required for efficient acquisition and transmission to new host plants.

6. Persistence and epidemiology: Biofilms on seeds, plant debris, irrigation systems, and farm equipment serve as reservoirs for disease re-emergence, contributing to the epidemiological spread of bacterial diseases.

Examples in Economically Important Pathogens

1. *Xylella fastidiosa*: Causal agent of Pierce's disease of grapevine, citrus variegated chlorosis, and olive quick decline syndrome. Biofilm formation within xylem vessels is central to vascular occlusion and to acquisition and transmission by xylem-feeding insect vectors such as sharpshooters.

2. *Ralstonia solanacearum*: Causal agent of bacterial wilt in solanaceous crops including tomato, potato, and tobacco. EPS-rich biofilms formed within xylem vessels contribute to vessel blockage and to the characteristic wilting symptom.

3. *Xanthomonas* species: *Xanthomonas campestris* and related species produce xanthan-based EPS that supports biofilm formation on leaf surfaces and within vascular tissue, contributing to leaf spot and blight diseases across a wide host range.

4. *Pseudomonas syringae*: A foliar pathogen capable of both epiphytic (surface) survival and biofilm formation on leaf surfaces, contributing to its persistence prior to infection through natural openings or wounds.

5. *Pectobacterium* and *Dickeya* species: These soft-rot pathogens rely on biofilm-associated attachment to plant tissue and coordinated, quorum-sensing-regulated secretion of plant cell-wall-degrading enzymes to establish infection.

Table: biofilm-forming phytopathogenic bacteria which have been reported since 2015, including the diseases and symptoms to which they are associated:

Species (Infectious Agent)	Host (Sensitive Plant)	Disease	Symptoms	References
<i>Pseudomonas syringae</i> pv. <i>syringae</i>	Wheat	Bacterial leaf blight	Water-soaked lesions that turn gray-green, leaf necrosis	[21]
<i>Pseudomonas syringae</i> pv. <i>syringae</i>	Tomato, cereals, citrus plants, kiwifruit	Spot, speck, and bacterial blight	Foliar and stem necrotic lesions; basal stem and root rot	[22]
<i>Pseudomonas syringae</i> pv. <i>atrofaciens</i>	Wheat	Basal glume rot	Dull brownish-blackish discoloration in the lower part of the glume	[21]
<i>Pseudomonas syringae</i> pv. <i>tomato</i>	Tomato	Bacterial speck	Chlorosis and necrotic lesions	[23]
<i>Pseudomonas syringae</i> pv. <i>actinidiae</i>	Kiwi	Bacterial bleeding canker	Brown leaf spots with chlorotic haloes, fruit specks and scabs, brown discoloration of buds, and cankers with exudates on trunks and twigs	[13]
<i>Pseudomonas syringae</i> pv. <i>phaseolicola</i>	Bean	Halo blight	Necrotic lesions on the leaf	[24]
<i>Pseudomonas savastanoi</i> pv. <i>glycinea</i>	Soybean	Bacterial leaf blight	Circular necrotic lesions on leaves surrounded by a chlorotic halo	[20,25]
<i>Xanthomonas citri</i> subsp. <i>citri</i>	Citrus plants	Citrus canker	Eruptive lesions on fruit, foliage, and young stems	[26]
<i>Xanthomonas axonopodis</i> pv. <i>phaseoli</i>	Bean	Common bacterial blight	Dark green water-soaked lesions, necrotic symptoms on the margins of leaves	[27,28]
<i>Xanthomonas oryzae</i> pv. <i>oryzae</i>	Rice	Bacterial leaf blight	Tannish gray-white lesions along the veins	[12,29]
<i>Xanthomonas campestris</i> pv. <i>campestris</i>	Cruciferous plants	Black rot	V-shaped necrotic lesions on the foliar margins and blackened veins	[30]
<i>Xanthomonas translucens</i> pv. <i>undulosa</i>	Wheat	Bacterial streak and black chaff disease	Water-soaked necrotic streaks which eventually change into translucent lesions	[21]
<i>Pantoea stewartii</i> subsp. <i>stewartii</i>	Corn	Stewart's wilt, severe seedling wilt	Water-soaked lesions, wilting in young seedlings	[31]
<i>Pectobacterium carotovorum</i> subsp. <i>carotovorum</i>	Potato	Soft rot	Severe bacterial tuber soft rot	[32]
<i>Pectobacterium carotovorum</i> subsp. <i>brasiliense</i>	Potato, tomato, cucumber, radish	Soft rot	Severe and typical bacterial soft rot, water-soaked and macerated tissues	[33,34]
<i>Agrobacterium tumefaciens</i>	Dicotyledonous plants	Crown gall	Tumors	[35]
<i>Rhizobium rhizogenes</i>	Tomato, cucumber, apple	Hairy root	Smaller root structures sprout at right angles from the main root. In the aerial form, tumors or knots (wooly-knots) appear in the limbs	[18,19]
<i>Clavibacter michiganensis</i>	Tomato	Bacterial canker, wilt disease	Deterioration of the internal vascular tissues, stem cankers, foliar chlorosis, unilateral wilt, marginal leaf necrosis, fruits with localized bird's-eye spots	[17,36]

<i>Xylella fastidiosa</i>	Citrus plants, grape, coffee, almond, olives, peach, blueberry, among others	Pierce's disease, leaf scorch, and citrus-variegated chlorosis	Leaf chlorosis, marginal scorching, and/or dwarfing, depending on the host	[11,37]
<i>Erwinia amylovora</i>	Apple, pear	Fire blight	"Shepherd's crook" of the twigs and a yellowish bacterial exudate on infected tissues. Infection of leaves at shoot tips, wilting of leaves, cankers	[38,39]
<i>Ralstonia solanacearum</i>	Tomato, brinjal, tobacco, potato, banana	Bacterial wilt	Rolling of leaves, chlorosis, and necrosis	[14]
<i>Dickeya dadantii</i>	Sweet potato	Bacterial stem and root rot	Maceration of plant tissues	[15]
<i>Acidovorax citrulli</i>	Melon, watermelon, pumpkin	Bacterial fruit blotch	Water-soaked seedlings and light brown-reddish lesions on the leaves, small water-soaked regions on the fruit surface	[16,40]

Implications for Disease Management

Because biofilm-embedded bacteria are substantially more tolerant of copper-based bactericides, antibiotics, and other conventional treatments than their planktonic counterparts, biofilm biology has direct implications for disease control strategies. Approaches under investigation or in use include:

1. Anti-biofilm and anti-adhesion compounds that interfere with EPS synthesis or surface attachment.
2. Quorum-quenching strategies that disrupt bacterial cell-to-cell signalling required for coordinated biofilm development.
3. Bacteriophage-based biocontrol targeting biofilm-associated cells.
4. Sanitation of seeds, propagation material, irrigation systems, and equipment to reduce biofilm reservoirs.
5. Breeding and selection of host genotypes with reduced susceptibility to bacterial attachment and vascular colonisation.
6. Integrated pest management combining vector control with biofilm-disruption strategies for insect-transmitted pathogens.

Conclusion

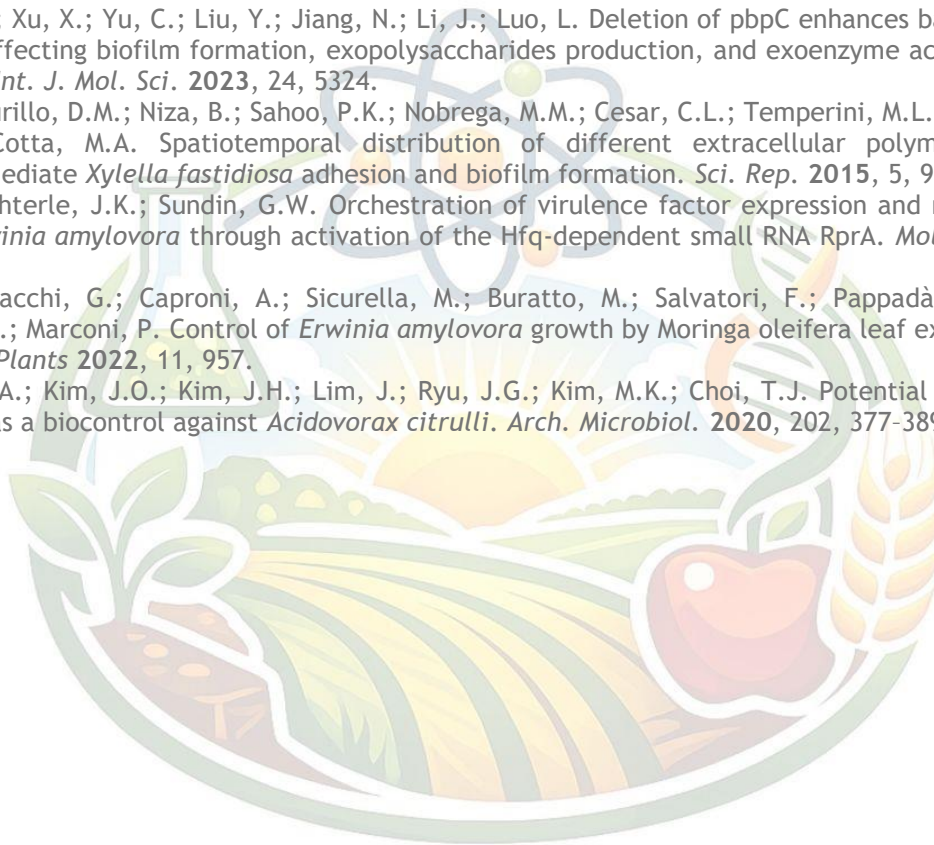
Biofilm-forming ability is a central, multifunctional trait in the biology of plant pathogenic bacteria, extending well beyond simple surface attachment. Through coordinated regulation by quorum sensing and c-di-GMP signalling, and through the physical and chemical protection afforded by the EPS matrix, biofilms enhance bacterial survival, host colonisation, vascular occlusion, environmental persistence, and resistance to antimicrobial control measures. Consequently, biofilm formation is closely linked to the severity and epidemiology of many economically important bacterial plant diseases, including Pierce's disease, bacterial wilt, citrus canker, and bacterial soft rots. A deeper understanding of the molecular mechanisms underlying biofilm development in phytopathogens is essential for the design of more effective, sustainable disease management strategies, including anti-biofilm compounds, quorum-quenching agents, biocontrol approaches, and resistant crop varieties. Continued research into biofilm regulation and structure will be important for reducing the substantial agricultural losses caused by biofilm-forming bacterial pathogens worldwide.

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Digital Agronomy: Big Data, Crop Simulation Models, and Remote Sensing for Real-Time Farm Decisions

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Abstract

Digital agronomy has evolved to be a revolutionary strategy in modern agriculture in which advanced digital technologies and agronomic science are combined to inform farm management decisions. With the fast development of big data analytics, crop simulation models, remote sensing and ICTs technologies, agriculture has experienced huge advancements in its efficiency, productivity and sustainability. The integration of digital technologies in agriculture helps farmers and researchers monitor crop performance, assess the soil and environmental condition, predict the behavior of crops and the use of agricultural inputs, among others. Information collected from satellites, unmanned aircrafts, field sensors, weather stations and farm machines constitutes big data that can be analyzed for decision making. Crop simulation models predict the crop growth, yield, water consumption and nutrients dynamics, while remote sensing provides continuous monitoring of crops for their stress and health status. All the digital technologies discussed above have contributed to precision farming, minimized production risks and promoted sustainable agricultural development. This paper reviews digital agronomy including its concepts, applications, benefits, limitations and future possibilities, emphasizing on the integration of big data, crop simulation models and remote sensing in farm decision-making.

Introduction

There have been remarkable advancements in the agriculture due to the rapid developments of information technology, artificial intelligence, geographic information systems, cloud computing and sensors based monitoring systems. Agriculture was done using farmers' experiences, historical data and manual observation of crops and field conditions. However, nowadays agriculture is highly complex due to increased climate change, decreased natural resources, labor shortages and increased demand for foods. Digital agronomy has emerged as an innovative science that combines the knowledge of agronomic science and digital technologies to enhance crop productivity, resource efficiency and environmental sustainability.

Digital agronomy entails data collection, analysis, interpretation and use for informing farm management decisions through crop production cycle. Information collected from weather stations, soil sensors, satellite images, drones, farm machines, mobile applications and agricultural research databases gives insight into crop growth and field heterogeneity. The data collected informs about irrigation scheduling, fertilizer management, pests and diseases control, harvesting and yield estimation. Big data, crop simulation models and remote sensing technologies have transformed agricultural management and allow site-specific management of farms rather than general management. These technologies decrease uncertainties, increase production efficiency, reduce input wastes and promote sustainable agricultural systems. Therefore, digital agronomy has become an integral part of climate-smart agriculture and precision farming (Wolfert et al., 2017).

Digital Agronomy and its Importance

Digital agronomy involves the use of digital technologies and data analysis for improving agronomic decisions. The knowledge of crop science, soil science, meteorology, engineering, computer science and data analytics is used to optimize agricultural production. Contrary to conventional agriculture, digital agronomy involves the constant collection of real-time information from multiple sources during crop growing period. The information gathered gives an understanding of crop growth, environmental and management conditions. The information generated allows the identification of existing problems before they worsen, and thus reduces the risk of losses in production and increases the profitability. The application of digital agronomy also supports sustainable management of natural resources. Fertilizers, irrigation water, pesticides and energy are used according to needs of crops, and therefore, reduces costs and minimizes environmental pollution and greenhouse gases emission. Thus, digital agronomy contributes to economic viability, environmental conservation and food security.

Big Data in Modern Agriculture

Big data has become one of the most impactful elements of digital agriculture. Modern agricultural systems generate enormous amount of data from different sources including satellites, drones, field sensors, weather stations, agricultural experiments, farm machinery, mobile applications, market information systems and government databases. The data sets have high volumes, velocities, varieties and complexities. Through big data analytics, information is converted into practical recommendation using sophisticated statistical analysis, machine learning algorithms and predictive analytics.

Farmers can use the data analysis to know the performance of their crops, identify the limiting factors, environmental conditions and optimize farm management. The continuous collection of weather information allows the prediction of rainfall, drought, frost and heat stress, and thus, allows farmers to take action before crop damage.

Big data also supports long-term agricultural planning by the integration of historical weather records, soil characteristics, cropping histories and management practices. Researchers use these data sets to identify production trends, evaluate farming systems and develop improved crop management techniques. Big data supports governments and extension services in crop forecast, food security planning, disaster management and formulation of policies. Cloud computing has further enhanced the management of agricultural data by the ability to store and process large data sets. Mobile-based advisory platforms give location specific recommendations to farmers. Therefore, big data has become the basis of modern smart farming systems (Wolfert et al., 2017).

Crop Simulation Models

Crop simulation models are mathematical tools that simulate crop growth and development under various environmental and management conditions. These models include the knowledge of crop physiology, soil processes, weather variables and agronomic practices to simulate the growth and development of crops throughout their growing seasons. Some of the widely used models include the Decision Support System for Agrotechnology Transfer (DSSAT) and the Agricultural Production Systems Simulator (APSIM), which simulate crop growth and development, phenological development, biomass accumulation, water balance, nutrients dynamics and yield under different environmental and management conditions (Jones et al., 2003; Keating et al., 2003).

Crop simulation models can be applied to study how agriculture is affected by climate change. They help to estimate the effect of changes in temperature, precipitation, atmosphere CO₂ concentration, and extreme weather events on crop growth. The information can be used to design adaptation strategies such as new cultivars development, change in sowing dates, and effective water management. Moreover, crop simulation models contribute to irrigation scheduling and estimate crop water needs according to the weather, soil moisture, and plant growth information, which helps to increase water efficiency. Also, they support nutrient management since crop nutrient needs and soil nutrient availability can be estimated, which allows for optimizing fertilizer application and minimizes nutrient loss to the environment. Moreover, crop simulation models are commonly used for yield forecasting, which helps to estimate the crop production before the harvest.

Remote Sensing in Digital Agronomy

Remote sensing has become an important tool for monitoring agricultural systems over wide geographic areas. Remote sensing means the acquisition of crop and soil information without any physical contact with their help. The technologies include satellites, UAVs, airplanes, and ground-based sensors. Repeated observations during the whole growing season provided by satellite remote sensing allow assessing the state of the crops constantly. Spectral data from satellite sensors provide evaluation of vegetation growth, canopy development, chlorophyll content, biomass production, and crop stress. Vegetation indices, like Normalized Difference Vegetation Index, are used to assess the vigour of the crops and detect crop stress conditions.

The spatial resolution of drone-based remote sensing technologies is much higher, and this allows monitoring each field in detail. High-resolution pictures can detect nutrient deficiency, water stress, diseases, weeds, and pests before they become visible to the human eye. Early identification of problems leads to prompt reaction and minimizes yield losses. Remote sensing allows performing soil mapping and land use assessment. Differences in soil moisture, organic matter, texture, and other characteristics of the soil can be identified by spectral data. This information contributes to precision farming and site-specific nutrient management. The great advantage of remote sensing is its ability to monitor agricultural regions quickly and repeatedly. Satellite images are used by government agencies to estimate crop acreage, perform drought assessment and flooding monitoring, forecast crops production. Researchers combine remote sensing data with crop simulations to improve prediction accuracy and validate models (Zhang et al., 2002).

Integration for Real-Time Farm Decisions

The true power of digital agronomy lies in the integration of big data, crop simulation models, and remote sensing into one decision-support system. All information received from different sources is analyzed constantly and generates recommendations specific to particular crops, fields, and conditions. For instance, satellite images can show decreasing the health status of the vegetation in part of the field. Soil moisture sensors detect moisture deficiency, and the weather forecasts show that the weather is going to stay dry. Crop simulation models estimate the effect on yield if irrigation is delayed. Based on all this information, the farmer gets the recommendations concerning irrigation. The same way fertilizer recommendations become more accurate when they consider remote sensing information, soil test results, weather forecasts, and crop simulation models. The variable rate fertilizer application ensures the application of nutrients only where they are needed, which leads to better efficiency and minimization of environmental contamination. Digital agronomy also promotes the integrated pest and disease management since weather data, crop growth stage, and remote sensing data can indicate favourable conditions for disease development. Early warning

systems allow applying the timely preventative measures instead of routine pesticide application. Harvest planning has also been improved by digital technologies since crop maturity, weather forecasts, machinery availability, and predicted yields can be analyzed to develop the best harvesting schedule.

Benefits of Digital Agronomy

Digital agronomy has a lot of benefits for farmers, researchers, policymakers, and agriculture industry. It improves the accuracy of decisions due to real-time information, helps to increase crop productivity by optimizing management practices, and to become more profitable by minimizing unnecessary costs. Water, fertilizers, and pesticides precise application increases efficiency of usage and minimizes the environmental effects. Moreover, digital agronomy contributes to enhancing resilience against climate variability providing early warnings for drought, floods, heat waves, and pest outbreaks. Yield forecasting increases the accuracy of food security planning and agricultural marketing. Additionally, digital agronomy promotes sustainable farming since it helps to monitor soil condition, water resources, and crops performance.

Challenges and Future Prospects

Although digital agronomy has a huge potential, there are some challenges related to it. The high cost of investment, lack of digital infrastructure, lack of internet connection in rural areas, lack of technical expertise, data fragmentation, and problems with data ownership are significant barriers to digital adoption. Smallholder farmers in developing countries can face difficulties in adopting advanced technologies due to their financial and technical restrictions. The future developments of digital agronomy are expected to relate to artificial intelligence, machine learning, digital twin, robotics, autonomous farm machinery, IoT, blockchain, and cloud computing platforms. Their integration with crop simulation models and remote sensing will allow predicting crop growth, disease outbreaks, nutrient deficiency, and climate risks. The development of user-friendly mobile applications and decision support platforms will promote technology adoption by farmers. Cooperation of researchers, governments, technology companies, and extension services will be crucial to realize the full potential of digital agronomy.

Conclusion

Digital agronomy is a great innovation in agriculture, which combines data-driven technologies with traditional knowledge. Big data provides constant information from different agricultural sources, crop simulation models predict crop responses under different management practices, and remote sensing allows quick monitoring of crops and their environment. All these technologies help to make real-time decisions based on the evidence, which helps to increase productivity and profitability of the farm and to make the farm more sustainable. Their integration promotes the precision agriculture and optimization of water, fertilizers, pesticides, and other agricultural inputs usage, minimizes their environmental impact. Although there are some challenges connected to infrastructure, affordability, and technical capacity, technological innovations continue to make digital agronomy more accessible. With climate change, resource shortage, and increasing demands for food, digital agronomy will play an important role in development of resilient, efficient, and sustainable farming.

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Integrated Soil Health Management: Long-Term Impacts of Organic Manures, INM, and Microbial Consortia on Productivity

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Abstract

Soil health is important for sustainable agriculture, but long-term use of chemical fertilizers and intensive agricultural production have caused low soil fertility, organic carbon content, and degradation of biological activity of the soil. This review discusses three methods of improving soil health: organic manures, integrated nutrient management (INM), and microbial consortia. Organic materials such as farmyard manure, compost, vermicompost, poultry manure, and green manures contribute to the improvement of soil organic carbon content, aggregation, water-holding capacity, and microbial activity. INM is the integration of organic and inorganic sources of nutrients to ensure crop productivity and soil fertility. Beneficial microbial consortia, including nitrogen-fixing, phosphate solubilizing, and PGPR, increase the availability of nutrients and plant resistance. Field experiments demonstrate that combined application of these three components leads to the improvement of physical, chemical, and biological properties of soil, as well as sustained high crop yields in comparison with both organic and inorganic sources used separately. Although there are some challenges, such as limited availability of organic materials and inconsistency of microorganisms' activity, integrated management of soil health provides an efficient way to ensure sustainable crop production.

Introduction

The solution to these problems can be found through sustainable nutrient management, which includes the use of organic materials, mineral fertilizers, and beneficial microorganisms. Organic manures replenish soil organic carbon content and improve physical properties, while mineral fertilizers provide quickly available nutrients for high-yielding crops. Inoculants of microorganisms increase nutrient availability using nitrogen fixation and phosphorus solubilization. Combined application of these three methods leads to nutrient-use efficiency and long-term soil productivity.

Soil Health and its Components

Soil health means the ability of soil to work as a living ecosystem supporting crop growth and environmental quality. It depends on the interplay of physical, chemical, and biological properties. Physical properties include bulk density, aggregation, porosity, infiltration rate, and water-holding capacity, regulating root growth and water transport. Chemical properties include soil organic carbon content, pH, cation exchange capacity, and nutrient availability. Biological properties are related to microbial biomass, enzyme activities, and soil microorganisms involved in organic matter decomposition and nutrient cycling. These components are tightly correlated. Organic matter improves aggregation, increases nutrient retention, improves water holding, and provides energy for microorganisms. Thus, practices increasing soil organic carbon content influence soil physical structure, chemical fertility, and biological activity at the same time. Sustainable management of soil requires integrated interventions instead of single nutrient sources.

Organic Manures and their Long-Term Benefits

Organic manures continue to be among the best tools for improving degraded soils. Farmyard manure, compost, vermicompost, poultry manure, green manures, and crop residues provide organic carbon with gradual release of nutrients. Apart from improving fertility, they stimulate microbial activity and increase soil biological functions. Long-term experiments show that continuous application of organic manures decreases soil bulk density, increases porosity, improves aggregation, and enhances water infiltration and water-holding capacity. This leads to favourable conditions for root growth and increases drought resistance of crops. Organic materials increase soil organic carbon and nutrient availability due to gradual mineralization. Humic substances in compost and manure improve cation exchange capacity and buffering of soil pH, especially degraded soil. Moreover, organic materials provide energy for soil microorganisms, increasing their biomass and enzyme activities and accelerating nutrient cycling. Although organic manures have lower concentrations of nutrients compared to mineral fertilizers, their positive impact on soil health is substantial and long-lasting.

Integrated Nutrient Management

INM involves organic manures and inorganic fertilizers to increase nutrient-use efficiency and maintain soil fertility. Mineral fertilizers quickly provide nutrients necessary for crop growth but do not sustain soil organic matter and biological activity by themselves. On the contrary, organic manures improve soil quality but usually cannot meet the nutrient needs

of intensive agricultural systems without additional nutrients. INM integrates these two sources of nutrients to ensure sustainable productivity. Results of long-term fertilizer experiments convincingly show that INM is much more efficient than single-source fertilization. Long-term fertilization trials under the All India Coordinated Research Project on Long-Term Fertilizer Experiments have demonstrated that mineral fertilization without organic manures increases crop yields but gradually decreases soil organic carbon content and micronutrient availability. At the same time, integration of farmyard manure and recommended fertilizer doses maintains higher soil organic carbon content, microbial biomass, nutrient-use efficiency, and crop productivity over decades.

Moreover, long-term maize experiments reported by Abid et al. (2020) demonstrated that the combination of farmyard or poultry manure with mineral fertilizers greatly increased grain yield, biomass production, harvest index, and fertilizer-use efficiency compared with either organic or inorganic sources. Yield stability was improved due to water retention and nutrient availability facilitated by organic matter during the whole growing period. The better performance of INM can be explained by several factors. Organic matter improves physical properties of soil and water availability, thus increasing nutrient uptake efficiency. Decomposition of organic materials increases availability of phosphorus and micronutrients by providing organic acids. Meanwhile, mineral fertilizers provide easily available nutrients when there is a high demand of plants while organic materials gradually release nutrients, reducing the risk of their losses through leaching and volatilization. These synergetic effects make INM one of the most effective tools for maintaining soil fertility and crop productivity.

Microbial Consortia and Biofertilizers

Microbial consortia is the biological part of integrated soil health management. It consists of beneficial microorganisms such as nitrogen-fixing bacteria, phosphate- and potassium-solubilizing bacteria, and PGPR, including species of *Rhizobium*, *Azotobacter*, *Bacillus*, and *Pseudomonas*. They improve plant growth by biological nitrogen fixation, nutrient solubilization, phytohormone production, siderophore synthesis, and suppression of soil-borne pathogens. Recent studies are oriented towards the development of microbial consortia instead of single-inoculant microorganisms because they perform complementary functions. Such microbial consortia establish in rhizosphere more efficiently and provide consistent benefits in field conditions. They increase nutrient availability, stimulate root development, improve drought and salinity resistance, and decrease dependency on chemical fertilizers. Microbial inoculants are especially useful when used in combination with organic manures. Organic amendments supply carbon and energy necessary for the growth of microorganisms thus providing survival and functioning of introduced microorganisms. For that reason, microbial consortium should be viewed as an important element of integrated nutrient management rather than an alternative to organic and inorganic fertilizers.

Integrated Approach for Sustainable Soil Health

It is evident from long-term studies that a combination of organic manures, mineral fertilizers, and microbial consortia proves to be much more effective than use of any one component separately. Organic manures increase soil structure, water storage, and carbon sequestration; mineral fertilizers fulfill nutrient demands of plants immediately; microbial inoculants contribute to nutrient transformation, biological nitrogen fixation, and nutrient-use efficiency. An integrated approach leads to the increase of soil organic carbon, aggregation, microbial biomass, enzyme activity, nutrient availability and results in high and stable crop yields. Soil structure improvement helps roots grow better and increase water infiltration. On the contrary, biological activity improvement leads to the acceleration of nutrient cycles. As a result, plants become more resistant to drought and other adverse environmental factors. Integrated soil management also has numerous environmental benefits. Decreased use of synthetic fertilizers reduces emissions of greenhouse gases during the process of fertilizers production and minimizes losses of nutrients due to leaching and runoff. Moreover, the increase of soil organic carbon helps mitigate the effects of climate change due to carbon sequestration. Thus, integrated soil management allows supporting both agriculture production and environmental safety.

Challenges and Future Research

Despite the obvious advantages of integrated soil health management, there are a number of restrictions to the use of such practice. The amount of organic manures is often insufficient because of the lack of livestock population in certain regions. Transportation, storage and application of bulky organic amendments increase costs of production and labour input. What is more, the amount of nutrients in organic manures differs substantially according to its origin and technology of processing. Microbial consortia have their limitations too since the efficiency of their functioning depends on the type of soils, climate, crop species, and indigenous soil microorganisms. Commercially used biofertilizers should have more advanced formula, better quality control, stability of composition and better field activity. In future, research should pay attention to development of specific nutrient management according to the results of soil testing and crop needs. The progress in molecular biology, metagenomics, and microbiology will make it possible to create more effective microbial consortia for particular agro-ecosystems. The conductance of long-term field experiments will help to estimate the cumulative effects of integrated management on soil quality and productivity. Effective extension programs, farmer education and appropriate government policy are also required.

Conclusion

Long-term scientific data convincingly prove that soil fertility maintenance through use of only one type of nutrient sources is impossible. Organic manures help restore soil organic carbon and biological activity but do not completely fulfill the needs of intensive farming system. Mineral fertilizers help to provide plants with nutrients but deteriorate soil quality in case of long-term application. Microbial consortia improve nutrient cycling and plant development but depend on soils with proper organic content. Thus, integration of organic manures, mineral fertilizers, and beneficial microbial consortia is the best way to maintain soil fertility, increase nutrient use efficiency, crop productivity, and environmental resistance.

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Sea Buckthorn: A Gold Mine of the Cold Desert

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Introduction

Sea buckthorn (*Hippophae rhamnoides* L.) is a Himalayan shrub or tree popularly known as Siberian Pineapple, Sand Thorn, Sallow Thorn, Sea Berry, Wonder Plant, Golden Bush, Gold Mine. Sea buckthorn belongs to the family of *Elaeagnaceae*. It is a thorny willow-like plant species native to Europe and Asia. In ancient Greece, leaves of sea buckthorn were used as horse fodder for improving weight and shiny hair, thus gaining the sea buckthorn genus a Graeco-Latin name 'Hippophae' (Hippo - Horse; Phaos - to shine). It is a pioneer tree species for soil improvement, wind and soil and water conservation. It is an ancient miraculous plant of great interest because of its tenacity, rich in nutritionally active substances and biological activity. Every part of this plant (fruits, leaves, stems, branches, roots and thorns) has been traditionally used in medicine, nutritional supplement, soil and moisture conservation and for the establishment of wildlife habitats.

The leaves can be used as feed, particularly for ruminants. Due to its tolerance against strongly eroded, nutrient poor and sometime salty soils, the plant is also used for land reclamation or as shelterbelt. Due to its immense use, it has aptly been called a wonderful plant, magic plant, super food, functional food and bank of vitamins. The fruits are processed and then used in the food industry, in traditional medicine, as part of drugs or in the cosmetic industry. It is rich in antioxidants, anti-inflammatory, anti-carcinogenic and anti-atherosclerotic properties. With its late maturing attribute, sea buckthorn offers interest as an ornamental bush. Sea buckthorn contains nearly 200 nutritional and bioactive compounds and is known as a "natural vitamin treasure house"

and a "source of nutrition and health care".

It is recognized differently in different parts of the world for eg. 'Oblepicha in Russia', 'Sanddorn' in Germany, 'Argousier' in France, 'Espino Amarillo' in Spain. In India, it is known as 'Chharama' in Himachal Pradesh, 'Chuck', 'Dhurchuk' or 'Chuma' / 'Tarwa' in Uttaranchal, 'Tare' or 'Taroobo' in North East region (Sikkim and Arunachal Pradesh) and 'Tsestalullu' in Ladakh. In India, sea buckthorn naturally thrives in various regions, including Jammu and Kashmir, Himachal Pradesh, Uttarakhand, Sikkim and Arunachal Pradesh. In late 2023, the Geographical Indication Registry officially awarded the **GI tag to 'Ladakh Sea Buckthorn'**, making it the fourth product in Ladakh to receive this recognition for its unique regional origin, protect the "wonder plant" from counterfeit and enhance its market value. It also grows in several countries like China, Russia, Britain, Germany, Finland, Romania, France, Nepal, Bhutan and Pakistan at an altitude of 2500-4300 meters height.

Uses

1. Sea buckthorn berries are rich in beta-carotene, vitamins C, E and B12, offering anti-inflammatory properties and immune boosting benefits.
2. Consuming sea buckthorn juice is recommended during pregnancy for its vitamin content. While safe to eat raw, they're most flavorful when cooked.
3. They're versatile in the kitchen, used in purees, juices, jams, syrups and liquor. Dried berries make delicious tea or powder. Sea buckthorn oil, extracted from the berries, is popular in cosmetics.
4. Sea buckthorn is a very good fodder for sheep, goats and cattle as it contains many nutrients and bioactive substances.
5. Leaves and fruit residue used as supplementary food can promote growth of animals and poultry.
6. As fuel wood: In the Hindu-Kush Himalaya region, plant biomass is the most important source of energy.
7. Sea buckthorn has proved to be a popular green energy plant because of its quality biomass. It is a good source of firewood.

Importance of Sea Buckthorn

Sea buckthorn is a multipurpose fast growing species which is serving as a measure of biodiversity conservation, soil conservation, medicines, food, fodder and fuel wood. It has an extraordinary capacity to grow and survive under adverse conditions (-40 to 40° C). For the farmers living in the mountains it offers the opportunity to maintain a sustainable livelihood. Sea buckthorn berry is a very rich source of vitamins and is called treasure of bioactive substances, for these reasons, it is also called a wonderful plant.

Pharmaceutical Importance

About ten varieties of sea buckthorn drugs have been developed and are available in the form of liquid, powder, plaster, paste, pills, liniments, aerosols, etc. The most important pharmacological functions attributed to sea buckthorn oil are: anti-inflammatory, antimicrobial, pain relief, and promoting regeneration of tissues. Sea buckthorn oil is also touted as a treatment for oral mucositis, rectum mucositis, vaginal mucositis, cervical erosion, radiation damage, burns, scalds, duodenal ulcers, gastric ulcers, chilblains, skin ulcers caused by malnutrition and other skin damage.

Nutraceutical Importance

Sea buckthorn fruit consists of sugars, sugar alcohols, fruit acids, vitamins (C, E, and K), polyphenols, carotenoids, fiber, amino acids, minerals and plant sterols. Major sugars in sea buckthorn fruits are fructose and glucose, with total sugar content of 2.7-5.3 g/100 ml of juice. Typical sourness of the fruits is due to high content of malic acid (0.8-3.2 g/100 ml of juice) while astringency is related to quinic acid (1.2-2.1 g/100 ml of juice). Major sugar alcohol in fruit is L-quebrachitol (0.15-0.24 g/100 ml of juice). The concentration of vitamin C in sea buckthorn fruit, ranged from 100-300 mg/100 g fruit, which is higher than strawberry, kiwi, orange, tomato, carrot, and hawthorn. Additionally, fruits have high concentrations of carotenoids, vitamin E and vitamin K. The most prevalent dietary minerals in sea buckthorn fruits are potassium (300- 380 mg/100g), manganese (0.28-0.32 mg/100 g) and copper (0.1 mg/100 g).

Cosmetical Importance

Many kinds of sea buckthorn cosmetics have been developed and tested in hospitals. It is proved that sea buckthorn beauty cream has positive therapeutic effects on melanosis, skin wrinkles, keratoderma, keratosis, senile plaque, xeroderma, facial acne, recurrent dermatitis, chemical corrosion and ichthyosis, as well as freckles. Other sea buckthorn extracts can improve metabolism and retard skin maturation.

Socio-Economic Importance

Due to its unique biological features, sea buckthorn has been used in various ways to maintain the ecology of the Himalayas. In winter, the importance of sea buckthorn increases as it is almost the only food available for birds. Sea buckthorn provides long-term benefits in terms of maintaining the ecological equilibrium and improving the environment.

Nitrogen-Fixing Capacity

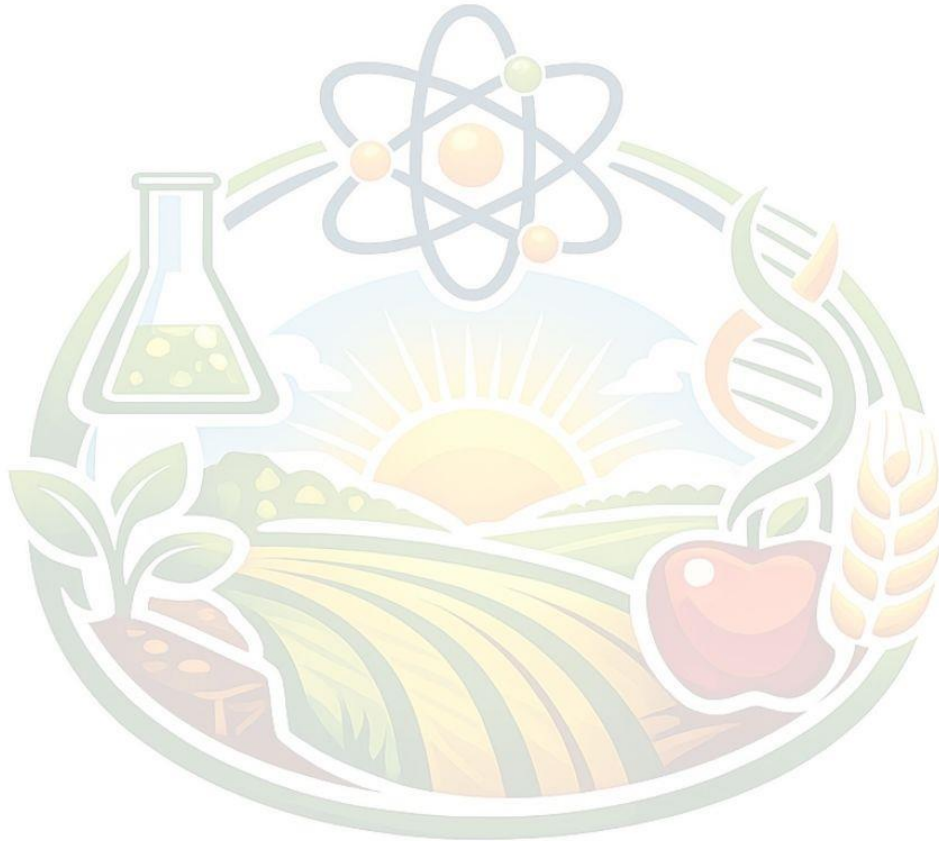
An 8 to 10-year old sea buckthorn forest can fix 180 kg of nitrogen/ha/year.

Conclusion

To conclude, further research will unlock its full therapeutic potential, particularly for conditions like ulcers and gastritis, integrating sea buckthorn into daily wellness routines offers a natural, versatile path to enhanced vitality.

		
Tree	Fruit	Seeds And Oil
		
Juice	Bark Powder	Dried Berries

 Plants	 Leaf Tea	 Root Extract



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Agronomic Biofortification: Fertilizer Strategies for Zinc, Iron, and Selenium Enrichment in Cereals

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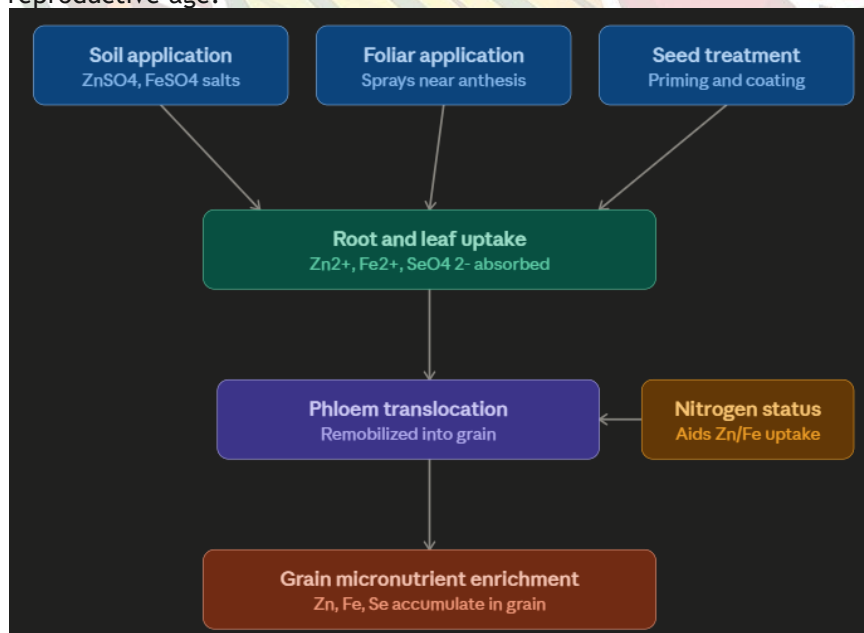
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Abstract

Micronutrient malnutrition, widely termed "hidden hunger," affects billions of people globally, with deficiencies of zinc, iron, and selenium among the most prevalent and clinically significant. Populations across South Asia and Sub-Saharan Africa are especially vulnerable because their diets are dominated by cereal staples such as wheat, rice, and maize, crops that are inherently low in bioavailable micronutrients when grown on deficient soils. Agronomic biofortification, the deliberate application of mineral fertilizers to soil, foliage, or seed to raise the concentration of target nutrients in edible plant tissue, has emerged as one of the fastest and most immediately deployable strategies for addressing this problem, complementing slower genetic biofortification approaches. This review synthesizes agronomic biofortification strategies for zinc, iron, and selenium enrichment in cereal crops. It examines the physiological basis of micronutrient uptake and grain loading, compares soil, foliar, and seed-based application methods, evaluates the role of fertilizer chemical form, timing, and combination with nitrogen, discusses emerging tools such as nanofertilizers and biofertilizers, and considers constraints limiting adoption among smallholder farmers. The evidence indicates that foliar application, particularly when timed near anthesis and combined with adequate nitrogen nutrition, is generally more efficient than soil application for zinc and iron enrichment, while both soil and foliar selenium fertilization are effective. Agronomic biofortification remains an indispensable, scalable tool for achieving sustainable micronutrient security through cereal-based food systems.

Introduction

Cereal crops, principally wheat, rice, and maize, constitute the primary source of dietary energy for most of the global population, particularly in low- and middle-income countries. Yet cereal grains are characteristically poor sources of zinc, iron, and selenium, especially when grown on soils that are themselves deficient in these elements. This mismatch between dietary dependence on cereals and their low micronutrient density underlies the global problem of hidden hunger, which manifests as impaired immunity, cognitive deficits, anemia, and stunted growth, particularly among children and women of reproductive age.



Two broad strategies address micronutrient deficiencies through the food system: genetic biofortification, which uses breeding or biotechnology to develop cultivars with intrinsically higher grain micronutrient content, and agronomic biofortification, which applies mineral fertilizers through soil, foliar, or seed treatments to increase micronutrient concentrations in edible plant parts. According to a systematic review of agronomic biofortification, this approach offers a readily accessible and expedient solution for enriching cereal grains with essential micronutrients, and is particularly

beneficial for the poorest rural communities that cannot afford mineral supplements or animal-derived foods (Kumar et al., 2025). Importantly, agronomic and genetic biofortification are complementary rather than competing approaches: even when cultivars with inherently higher grain zinc and iron content are developed, adequate fertilization remains necessary to realize their genetic potential under field conditions (Fageria et al., 2015). This review examines agronomic biofortification strategies for zinc, iron, and selenium in cereals, covering physiological mechanisms, application methods, fertilizer chemistry, emerging technologies, and practical constraints to adoption.

The Rationale for Agronomic Biofortification

Micronutrient malnutrition arises when diets supply sufficient calories but inadequate vitamins and minerals. Because cereal-based diets dominate in regions where hidden hunger is most severe, the micronutrient density of staple grains has an outsized influence on population health. Zinc deficiency affects roughly a third of the world's population and contributes to impaired growth and immune function, while iron deficiency remains the leading cause of anaemia worldwide. Selenium deficiency is geographically concentrated in regions with inherently selenium-poor soils, including parts of China, Europe, and Africa. Agronomic biofortification directly addresses this gap because it can be implemented rapidly using existing fertilizer supply chains and extension services, without the multi-year breeding cycles required for new cultivars. Agronomic biofortification is considered the easiest and quickest method for enriching cereal grains with zinc, iron, and other micronutrients in developing countries, especially in Asia and Africa where cereals form the dietary staple, and is regarded as one of the only approaches capable of reaching the poorest rural populations who lack access to alternative nutrient sources (Fageria et al., 2015).

Physiological Basis of Micronutrient Uptake and Grain Loading

Zinc is absorbed by roots mainly as the divalent cation Zn^{2+} , but in calcareous, alkaline soils typical of much of South Asia, zinc availability is severely restricted through precipitation and adsorption onto soil particles. Once absorbed, zinc must be remobilized through the phloem to the developing grain, a process that is comparatively inefficient in cereals, since zinc has limited phloem mobility relative to other nutrients. This bottleneck explains why foliar application timed near anthesis and grain filling, when phloem remobilization is active, tends to outperform soil application for enriching grain zinc. Iron presents similar, and arguably greater, challenges. In aerobic, calcareous soils, iron exists mainly as poorly soluble oxides and hydroxides, limiting root uptake regardless of total soil iron content. Iron transport to the grain relies heavily on phloem remobilization from vegetative tissues during senescence, and foliar-applied iron is often poorly translocated compared with zinc or selenium because of its tendency to form insoluble complexes on leaf surfaces and limited symplastic mobility once absorbed by leaf cells.

Selenium behaves quite differently from zinc and iron because it is taken up efficiently as selenate (SeO_4^{2-}) via sulfate transporters and is highly mobile in both the xylem and phloem, allowing efficient translocation to grain regardless of application method. This mobility explains why both soil and foliar selenium fertilization are effective, with sodium selenate generally more efficient than selenite forms due to superior root uptake and translocation. Nitrogen nutrition plays a critical facilitating role across all three micronutrients. Improved nitrogen nutrition enhances root uptake, root-to-shoot translocation, and remobilization of radiolabeled zinc (^{65}Zn) in durum wheat, demonstrating that nitrogen supply increases both the initial acquisition of zinc by roots and its subsequent retranslocation from vegetative tissue into the grain during senescence (Erenoglu et al., 2011). This finding underlies the now widely adopted practice of combining nitrogen and micronutrient fertilization strategies to maximize grain enrichment.

Fertilizer Application Methods

1. Soil Application: Soil application of zinc sulfate, iron sulfate, or iron chelates is the traditional method of micronutrient fertilization and can be effective in correcting severe deficiencies, particularly when residual effects across multiple growing seasons are considered. However, soil-applied zinc and iron are prone to fixation, especially in calcareous and high-pH soils, meaning that only a small fraction of the applied nutrient becomes available for plant uptake, and larger quantities are typically required to achieve meaningful grain enrichment compared with foliar methods.

2. Foliar Application: Foliar application bypasses soil fixation entirely by delivering nutrients directly to leaf tissue, from which they can be translocated to the grain via the phloem. Foliar application of zinc and iron fertilizers is considered more effective and requires substantially lower quantities than soil application, making it both agronomically and economically attractive, particularly for zinc where post-anthesis foliar sprays reliably raise grain concentrations (Kumar et al., 2025). Field experiments across multiple maize cultivars and locations have confirmed that foliar treatments effectively increase grain concentrations of zinc, iron, and selenium simultaneously, alongside measurable improvements in the bioavailability of zinc and iron in the harvested grain (Xue et al., 2023). These same experiments, along with related work in wheat and rice, showed that foliar iron enrichment is generally less pronounced than for zinc or selenium, reflecting iron's poorer mobility within leaf and phloem tissue even when applied directly to the canopy.

Seed Treatment and Combined Strategies

Seed priming or coating with micronutrient solutions represents a lower-cost supplementary method, useful primarily for improving seedling vigor and early micronutrient status rather than substantially raising final grain concentrations. In practice, the most effective agronomic biofortification programs combine soil-applied basal fertilization to correct underlying deficiencies with one or more foliar sprays timed at critical growth stages, an approach that has been widely validated in wheat, rice, and maize systems across diverse agroecological zones, including numerous options available to smallholder farmers in Sub-Saharan Africa based on chemical fertilizers such as zinc sulfate, iron sulfate, and iron chelates alongside traditional nutrient sources including farmyard manure, compost, and cereal-legume intercropping systems.

Selenium-Specific Considerations

Selenium biofortification differs mechanistically from zinc and iron enrichment because of selenium's high mobility once absorbed. Both soil and foliar applications have proven effective for selenium enrichment, with sodium selenate identified as the more efficient chemical form due to its superior solubility and uptake efficiency compared with selenite (Kumar et al., 2025). National-scale selenium fertilization programs, most notably in Finland, where selenium was added to compound fertilizers beginning in the 1980s, demonstrated that systematic agronomic selenium enrichment can shift an entire population from selenium deficiency toward adequate status, offering a policy template for other selenium-deficient regions.

Emerging Technologies: Nanofertilizers and Biofertilizers

Recent research has expanded agronomic biofortification beyond conventional inorganic salts toward nanoparticle-based fertilizers and microbial biofertilizers. Nanoscale zinc and iron formulations offer potentially greater surface area and controlled release, which may improve uptake efficiency and reduce total fertilizer input, though field-scale evidence remains more limited than for conventional foliar sprays. Plant growth-promoting microbes and mycorrhizal associations have also been explored as biofertilizer strategies capable of enhancing micronutrient solubilization and root uptake, representing a lower-cost, more agroecologically compatible option, particularly relevant for resource-constrained farming systems where synthetic fertilizer access is limited.

Constraints and Adoption Challenges

Despite strong agronomic evidence supporting fertilizer-based biofortification, adoption remains limited in many developing regions. Major bottlenecks include the low availability of micronutrient-specific fertilizers, limited farmer awareness of biofortification benefits, and constrained financial capacity among smallholders to purchase additional fertilizer inputs beyond standard nitrogen-phosphorus-potassium regimes. Current trends in Sub-Saharan African agriculture increasingly support agroecological approaches using local micronutrient sources, such as compost tea, organic manure, and cereal-legume intercropping, as more accessible alternatives to purchased mineral fertilizers.

Conclusion

Agronomic biofortification offers a rapid, flexible, and complementary approach to addressing zinc, iron, and selenium deficiencies through cereal-based diets. Foliar application, particularly when timed near anthesis and supported by adequate nitrogen nutrition, generally outperforms soil application for zinc and iron enrichment, while both soil and foliar methods are effective for selenium. Realizing the full benefit of this approach requires continued attention to fertilizer accessibility, farmer education, and integration with genetic biofortification programs to achieve durable improvements in global micronutrient security.

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Banking Carbon Underground: How Green Manuring Turns a Farmer's Field into a Climate Investment

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Abstract

Sustainable agriculture requires soil management practices that enhance productivity while minimizing environmental degradation. Green manuring, the practice of incorporating fresh plant biomass into the soil, has emerged as an effective strategy for improving soil fertility, enhancing soil biological activity, and reducing dependence on synthetic fertilizers. Leguminous green manure crops contribute substantial amounts of biologically fixed nitrogen while increasing soil organic matter and improving soil physical, chemical, and biological properties. This review examines the agronomic principles of green manuring, its effects on soil health and crop productivity, environmental benefits, implementation challenges, and future prospects. Evidence from recent studies indicates that green manuring significantly improves nutrient availability, soil structure, microbial diversity, water-holding capacity, and crop yields while supporting climate-smart and sustainable agricultural systems. Despite challenges such as land availability and additional management requirements, green manuring remains an economically viable and environmentally friendly practice that contributes to long-term agricultural sustainability.

Keywords: Green manuring; Sustainable agriculture; Soil fertility; Nitrogen fixation; Organic matter; Soil health.

A Second Harvest You Cannot See

Every season, a farmer invests in seeds, labour, water, and fertilizers with the expectation of one visible return from a healthy standing crop and a profitable harvest. Green manuring asks for one additional investment a few weeks of land and a fast-growing legume or grass crop that is incorporated back into the soil before it reaches maturity. Unlike a harvested crop, its reward is not immediately visible. Instead, it delivers a second, hidden return by storing carbon beneath the soil, a benefit that becomes evident only through a soil test.

Yet this invisible return is far more valuable than it often appears in conventional extension advice. Soil is the world's largest terrestrial carbon reservoir, storing roughly twice as much carbon as the atmosphere. Even small increases in soil carbon stocks can have significant consequences for climate change mitigation while also improving soil fertility, water retention, and nutrient availability. For farmers, these changes can translate into lower fertilizer requirements, greater resilience to drought, and reduced production costs over time.

This article reframes green manuring from that perspective, not simply as another soil health practice, but as a climate-smart investment in carbon banking. By viewing soil as a long-term asset that can accumulate carbon while sustaining productivity, farmers can better evaluate the true returns of green manuring alongside familiar costs such as diesel, urea, irrigation, and labour.

What Actually Happens When You Plough a Green Crop Under

Two separate carbon deposits are made the moment a green manure crop is incorporated. The first is fast-cycling: sugars, root exudates, and soft leaf tissue that soil microbes consume within weeks, releasing nitrogen, phosphorus, and sulphur for the following crop. The second is slow-cycling: lignified stems and root fragments that resist microbial breakdown and are gradually converted into stable, mineral-bound organic carbon that can persist in the soil for decades. A field's long-term carbon balance depends on the second pool, not the first which is exactly why the choice of species, biomass quantity, and stage of incorporation changes the outcome as much as the decision to green-manure at all.

According to Fan *et al.* (2024), a cross-crop synthesis across wheat, maize, rice, and tobacco systems demonstrated that green manure incorporation significantly improved soil health by increasing SOC sequestration by 64%, reducing nitrate leaching by 44%, and enhancing soil N, P, and K contents by 8-13% compared with unmanaged fallow. That is a materially larger effect than the fertility-only framing of most extension advice suggests the nitrogen story and the carbon story are two returns on the same investment, not one.



Fig: Incorporation of Dhaincha (*Sesbania aculeata*) by ploughing

The Carbon Clock: Why Patience Changes the Payoff

1. Roughly half of the total soil-carbon gain from a sustained green-manuring programme is typically realised within the first 20 years, with accumulation continuing at a diminishing rate for up to a century (a pattern widely reported in long-term soil-carbon literature, e.g. Poeplau & Don, 2015).
2. A 2025 meta-analysis of Indian regenerative-agriculture trials found the same shape at a shorter scale: rapid SOC gains in the first 5-10 years, followed by a plateau consistent with the soil approaching "carbon saturation" - a ceiling on how much stable carbon a given soil type can hold.
3. Practical reading: do not judge green manuring on one or two seasons. Track soil organic carbon every 3-5 years and expect the curve to bend, not the crop to fail.

Not All Green Manures Bank Carbon Equally

Extension advice has traditionally ranked green manure crops by nitrogen contribution alone. A climate-smart lens adds a second axis how much of the incorporated biomass survives as stable carbon rather than being fully mineralised and lost as CO₂ within a season. Yield improvements vary depending on crop species, climate, soil characteristics, and management practices; however, long-term experiments consistently report positive responses.

Table 1. Nitrogen Contribution and Key Benefits of Common Green Manure Crops:

Green Manure Crop	Nitrogen Contribution (kg N ha ⁻¹)	C: N Ratio	Major Benefits	Citation
Sunn hemp (<i>Crotalaria juncea</i>)	80-120	15-12	Rapid biomass production, fixes nitrogen, suppresses weeds, improves soil organic matter	(FAO, 2020; ICAR, 2018)
Dhaincha (<i>Sesbania aculeata</i>)	60-100	18-25	Improves soil fertility, suitable for paddy fields, enhances soil structure	(FAO, 2020)
Cowpea (<i>Vigna unguiculata</i>)	50-90	14-20	Nitrogen fixation, weed suppression, drought tolerant	(FAO, 2020)
Green gram (<i>Vigna radiata</i>)	30-60	12-18	Improves soil fertility and microbial activity	(ICAR, 2018)
Black gram (<i>Vigna mungo</i>)	30-60	16-18	Adds organic matter and improves soil health	(ICAR, 2018)
Berseem (<i>Trifolium alexandrinum</i>)	60-100	12-16	Improves soil structure and increases organic matter	(FAO, 2010)
Sesbania (<i>Sesbania rostrata</i>)	100-150	12-18	Very high nitrogen fixation, ideal for rice ecosystems	(FAO, 2010)

The Fine Print: Trade-offs Worth Knowing Before You Commit

1. Calcareous and arid soils can lose the soil inorganic carbon even as organic carbon rises, because root-driven acidification slowly dissolves carbonates; net carbon storage in such soils still favours green manuring, but the inorganic-carbon side of the ledger is worth monitoring rather than ignoring (Geoderma, 2025).
2. In flooded rice systems, green-manured plots have shown a rise in methane emissions relative to unmanured fallow—a real cost that needs to be weighed against the SOC and yield gains, and one that timing and water management can partly offset.
3. Land and time taken out of a marketable crop remain the most tangible cost for smallholders; the carbon and fertility return accrue over years, while the land-opportunity cost is felt in the very first season.

From One Field to Global Insights

Green manuring's climate relevance is not confined to any one farm. The '4 per mille' initiative, launched at the COP21 climate conference in 2015, set out an aspirational target of growing the world's agricultural soil-carbon stock by 0.4 percent a year—an amount that, if achieved, could offset a substantial share of annual fossil-fuel emissions. Long-term Indian field data cited in that literature—including a 19-year rice-wheat trial where green manuring combined with balanced NPK sustained measurable carbon gains to 60 cm depth are part of the evidence base for that target (Majumder *et al.*, 2008). Separately, modelling work suggests that if roughly 15 percent of global cropland adopted green manure within its rotation, the additional carbon sequestered could offset one to two percent of annual fossil-fuel emissions on its own. No single field moves that needle, but the direction of every well-timed green-manure crop is the same direction the global target requires.

A Practical Decision Guide

The right green manure crop depends on what a specific field needs most nitrogen, carbon banking, salinity relief, or simple drought tolerance. Use the table below as a starting filter, then confirm with a local soil test.

Your field situation	Recommended green manure direction	Why
Priority is nitrogen self-sufficiency	Legumes: sunnhemp, dhaincha, cowpea, green/black gram	Rhizobium symbiosis delivers 30-150 kg N ha ⁻¹ depending on species and biomass
Priority is banking carbon in dry, calcareous, or degraded soil	Non-legume or mixed system: sorghum-sudan grass, or legume + grass combinations	Higher lignin, higher C:N residues resist mineralisation longer and build stable SOC faster
Saline or sodic soil reclamation	Multi-species green manure mixtures rather than a single crop	Mixed residues reported to raise SOC more consistently than mono-cropped legumes on salt-affected land
Puddled / lowland rice	<i>Sesbania rostrata</i> or <i>S. aculeata</i> (dhaincha)	Stem-nodulating <i>Sesbania</i> tolerates flooding and fixes N efficiently under anaerobic conditions
Water-short, rainfed tract	Short-duration, drought-tolerant legumes (cowpea, green gram) timed to available moisture	Limits the biomass-loss risk that insufficient moisture otherwise creates

Farmer's Guide to Sustainable Practices

1. Get a baseline soil test (organic carbon, pH, EC) before starting a green-manuring programme, and repeat every 3-5 years to see the real trend, not season-to-season noise.
2. Match the crop to the goal: legumes for nitrogen, non-legume or mixed systems for faster carbon banking on poor or calcareous soils.
3. Incorporate at 45-60 days, at or near flowering, when biomass and nutrient accumulation peak.
4. In flooded rice fields, manage water carefully after incorporation to limit the methane trade-off.
5. Budget for the land-opportunity cost honestly the fertility and carbon returns are real, but they are not instant.
6. Where feasible, alternate or mix legume and non-legume green manures across seasons to capture both nitrogen and carbon benefits.

Conclusion

Green manuring has always been sold to farmers as a fertility practice. The evidence gathered over the last three years reframes it more precisely: it is a carbon-banking practice with a fertility bonus attached, and the size of both returns depends on deliberate crop choice, not just the decision to green-manure at all. For a farmer weighing whether the land and weeks are worth it, the honest answer is that the return is real, measurable, cumulative over decades, and

increasingly recognised as part of a global climate strategy that begins in exactly the kind of field being plowed under this season.

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Heavy Metal Contamination- Its Impact on Aquaculture Farming Systems

Article ID: 74406

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Introduction

Aquaculture plays a crucial role in ensuring food security for many nations globally, thus one of the fastest- growing food production systems which serves as an important source of protein and livelihood for millions of households. Pollution is one of the key factors that has been hindering the growth of the sector, of which heavy metal is a part, which as a pollutant is one of the most persistent and non-biodegradable, thus affecting the system for a very long period. The heavy metal accumulates in the bottom sediments of the ponds and water bodies, in the fish body as well as in other aquatic organisms. In the Aquaculture system, the main heavy metals that pollutes the water and stands as risk to health are Cadmium (Cd), Lead (Pb), Arsenic (As), Chromium (Cr), Copper (Cu) and Mercury (Hg). Hence, evaluation and removal of heavy metals is very essential. The heavy metals gradually build-up in the animal tissue due to the comparatively higher intake rate than the rate of elimination. This is called bioaccumulation. Bioaccumulation is a continuous process, increasing the total concentration of the harmful substances in the tissue over time. So, removing or decreasing the heavy metals from the environment has become of paramount importance. Heavy metals, along with the disruption of fish growth, reproductive health and weakened immunity, are a serious risk to human health. When humans consume fish contaminated with heavy metals, the heavy metals transfer through the food chain by the process of biomagnification. These inorganic contaminations may originate from nature or due to anthropogenic activities. In this article, we will discuss how these pollutants affect fisheries and aquaculture.

Routes of Heavy Metal Contamination and its Sources

In general, natural as well as anthropogenic pathways are major pathways through which heavy metals contaminate the aquatic environment. Naturally heavy metal occurs in the soils by weathering process of the igneous and sedimentary rocks which may be released into the soil as a result of erosion, volcanic eruption, leaching, biological processes, etc. Anthropogenic activities that lead to the accumulation of heavy metals are industrial effluents, agricultural runoff, leaching, contaminated feed and supplements, mining and smelting, fossil fuel combustion, etc. Untreated wastewater discharge from the industries contains huge amounts of heavy metals that mix with the clean water bodies and contaminate them. Fertilizers containing heavy metals like cadmium, and other pesticides which are used during the cultivation of crops may be washed off by rain draining into ponds and rivers. Leaching is the process where toxic heavy metals dissolve from solid materials (soil, e-waste, etc.) into water, seepage from nearby landfills or old piping system, mining, etc. causing serious, long-term environmental and water contamination. Low quality feed and other supplements supplied to the aquatic organisms may sometimes be contaminated with Lead or Mercury, which will get bioaccumulated in the organisms and eventually affect the ecosystem. Several studies reported that the industrial and agricultural runoff are the major contributors to the presence of toxic heavy metals that are known to be the non-point source pollution with potentially serious implications to human health as well as aquatic life. Therefore, proper actions required to control the anthropogenic sources of heavy metal contamination by creation of specific policy frameworks.

Physiological Impacts of Heavy Metal on Aquatic Organism

The toxicity of heavy metals is influenced by the water quality parameters such as pH, water hardness, temperature, etc. which also is important for the well being of aquatic organisms. The primary physiological impacts on these organisms are the respiratory distress, reproductive failure, hematological changes, skeletal deformities, enzymatic inhibition and many more. Heavy metals like copper, iron, mercury can stress the fishes leading to excessive secretion of mucus in the gills which results in the coagulation of the gill lamellae, thus respiratory distress otherwise known as asphyxiation. Chronic exposure to toxic heavy metals can affect the gonads which will lead to reduced fecundity, poor egg quality, thus lower production rate. Even in the larval stages, due to the toxicity of heavy metal, mortality rates become very high. A few metals may bind to the active sites of some essential enzymes in the metabolic pathways of activities related to kidneys and liver and disrupt the normal functioning of the organisms. Anemia is a condition of decreased red blood cell which can be caused by the heavy exposure to Lead that can decrease the hemoglobin content in fish.

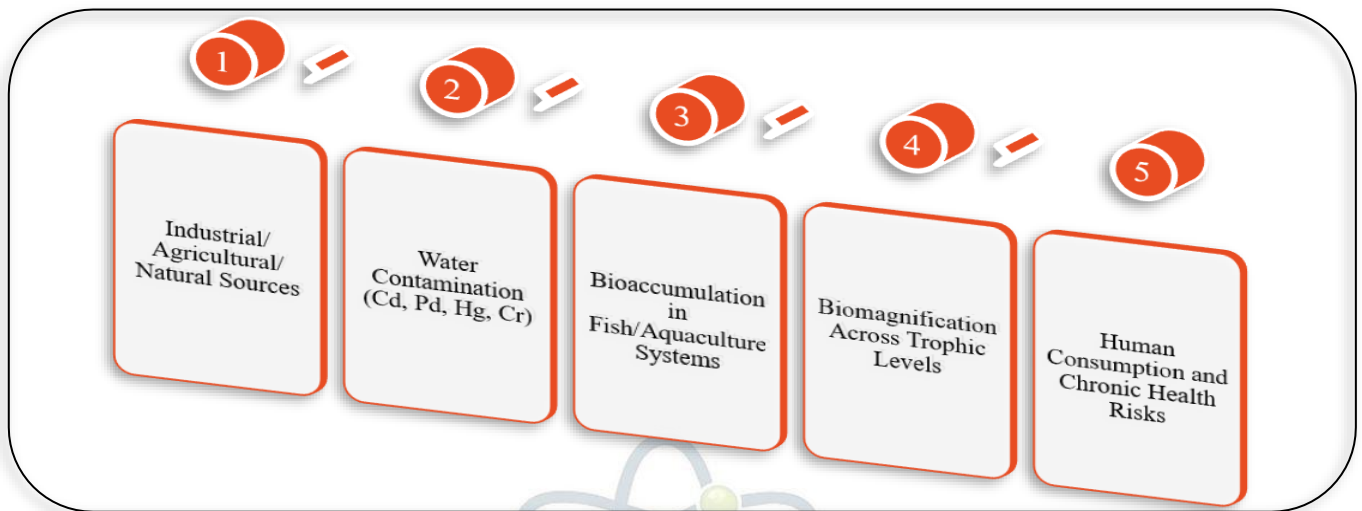


Figure: Flowchart representing the Pathway of Heavy Metals from Source to Humans through Biomagnification
(Source: Created by Author)

Bioaccumulation and Impacts of Heavy Metal on Human Health

The gradual build-up of any toxic materials in tissues of organism overtime is called bioaccumulation. Aquatic organisms accumulate heavy metals through different routes like the gills, skin and oral pathway from contaminated food and water which are not excreted very easily and concentrate in the tissues for a long period harming its health. The food chain with each tropic level aggregates more toxin and there is an increase in the total concentration of toxic substances, highest accumulation being in the predators as they consume multiple contaminated prey. This process of increase in the concentration of toxin in higher tropic level is called biomagnification. Human being omnivorous consume all kind of organisms of which some may be contaminated with Mercury, Cadmium, Lead like toxic heavy metals that can cause chronic conditions like *Minamata* disease (Hg) affecting the nervous system or *Itai-itai* disease (Cd) affecting bone density. Foods contaminated with even minor amount of this pollutants slowly accumulating in the human body as lead to bigger issues related to reproduction and heart diseases.

Table 1: Comparison between Bioaccumulation and Biomagnification:

Aspects	Bioaccumulation	Biomagnification
Mechanism	Intake> Elimination	Predators eat contaminated prey
Time scale	Continuous exposure	Successive transfer between organisms
Occurrence	Single organism	Across trophic levels (food chain)

Source: Compiled by authors based on standard literature understanding

Management and Mitigation Strategies

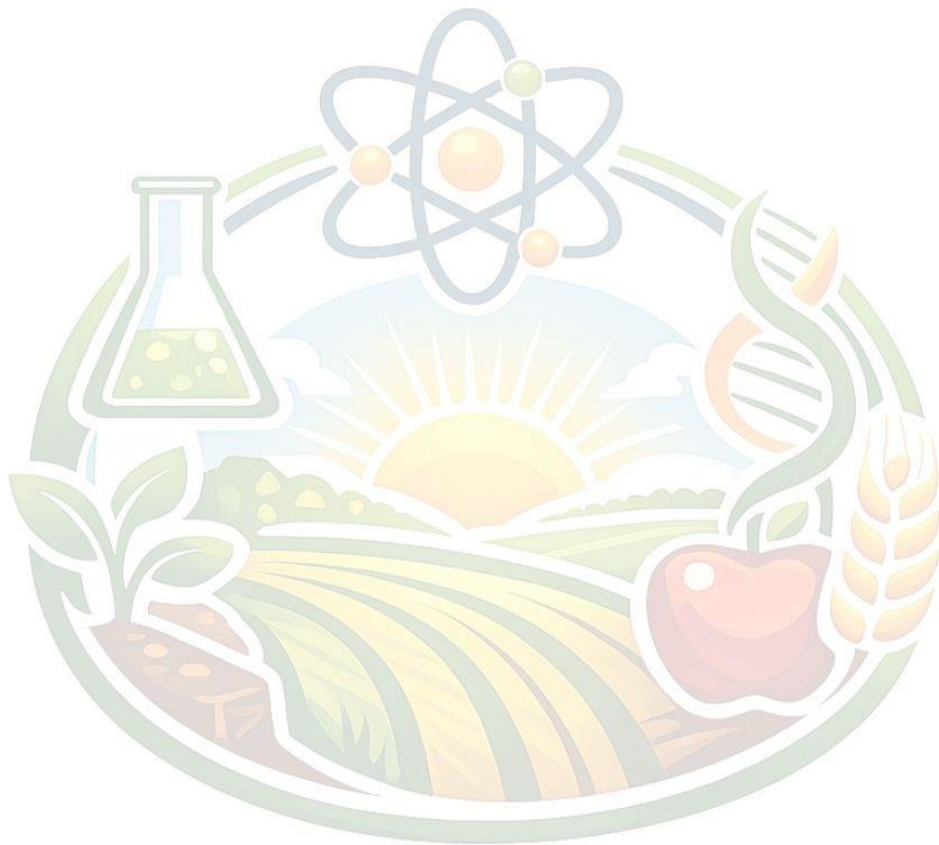
The persistent accumulation of heavy metals in global ecosystems, being non-biodegradable are highly toxic, causing irreversible negative physiological affects to human through consumption of crops and aquatic organisms. To maintain a sustainable and safe aquaculture venture, a few measure that can be practically applied are:

1. Application of lime and alum can precipitate many heavy metals which will sink to the bottom as sludge, thus remediating water.
2. Removal of the bottom sludge that contains high concentration of heavy metals along with other toxic substances periodically can improve the quality of water, beneficial for the aquatic organisms.
3. Testing the water quality parameters periodically to ensure that the parameters are under optimal limit.
4. EDTA (Ethylenediaminetetraacetic acid) coagulate the heavy metal ions and destroy their reactive nature making it non-toxic to fish as it no longer can get absorbed through gills.
5. Phytoremediation is one of the processes wherein the plants bioaccumulate metabolites or less toxic form from the environment. In water bodies, plants like *Eichhornia crassipes* (Water Hyacinth) or *Lemna minor* (Duckweed) suck metals out of water. Many other processes like, phytovolatilization, phytoaccumulation or phytoextraction, rhizofiltration, etc., takes place naturally to reduce toxic substances.

Conclusion

Heavy metals are silent threat not only to the aquaculture sector, but it impacts human as well. Its has now become one of the major issues potentially harmful to health. Biological or anthropogenic sources are the predominant reasons for

their availability in the environment which are adversely affecting aquatic as well as terrestrial ecosystem. Over the period, microorganisms and plants have evolved its mechanism to breakdown and reduce the toxicity of these pollutants, but aquaculture sector is facing challenges in managing these heavy metals. Protecting the aquatic ecosystem from pollutants like heavy metal toxicity is vital not only for the economic success of the aquaculture sector but also for the long-term health management and well-being of the global population.

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Lead Bank Scheme and Its Effectiveness: Strengthening Inclusive Banking and Rural Development

Article ID: 74407

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Introduction

One of the basic necessities for achieving sustainable economic development is access to credit that is both timely and affordable. In a country such as India, in which a large part of the population relies on agriculture and related activities for their living, financial inclusion has always been a national priority. Even though the banking sector has expanded greatly since independence, rural and underdeveloped areas have still had inadequate access to institutional finance. In order to overcome these inequalities, the Lead Bank Scheme (LBS) was launched in 1969 in accordance with the recommendations of the Gadgil Study Group. The scheme was intended to enhance cooperation between banks, government departments, and development agencies so as to achieve balanced regional development by means of effective credit planning (Reserve Bank of India [RBI], 2023). Over the years the Lead Bank Scheme has developed into an important institutional arrangement for promoting financial inclusion, extending banking infrastructure, supporting government-supported development programmes, and enabling lending in the priority sectors. It still serves a crucial role in improving access to banking services, especially in rural and semi-urban areas. Over the years the Lead Bank Scheme has become an important institutional arrangement for promoting financial inclusion, for extending banking infrastructure, for supporting government-sponsored development programmes and for aiding lending in the priority sectors. It still plays a vital role in improving access to banking services, especially in rural and semi-urban areas.

What is the Lead Bank Scheme?

The Lead Bank Scheme is a form of banking coordination at district level whereby one commercial bank is appointed as the Lead Bank for a given district. The Lead Bank is given the task of coordinating the activities of all the banks and financial institutions working in the district and works in close cooperation with the district administration, the various line departments, the development agencies and all other stakeholders in order to assess credit requirements and to draw up district credit plans. The main aim of the scheme is to make sure that institutional credit goes to all the productive parts of the economy, especially those relating to agriculture, micro, small and medium enterprises (MSMEs), self-help groups (SHGs), rural artisans, and the economically weaker sections of society (RBI, 2023).

Objectives of the Lead Bank Scheme

The Lead Bank Scheme seeks to achieve several developmental objectives, including:

1. Extending banking services to rural and urban areas that are currently not well served.
2. Promoting financial inclusion within vulnerable and marginalized communities.
3. Improving access for agriculture, MSMEs, and the related sectors to institutional credit.
4. Coordinating the development programmes carried out by banks and government agencies.
5. Keeping an eye on the implementation of lending in the priority sector.
6. Helping create jobs and encourage people to start businesses.
7. Decreasing the imbalances between regions in the distribution of banking and credit.

These objectives are in close agreement with India's wider vision of achieving inclusive and sustainable economic development.

Major Functions of the Lead Bank

Within its district the Lead Bank has a number of duties. It carries out surveys in order to identify gaps in banking, evaluates the credit potential of various sectors, draws up district credit plans and helps to put into effect different government-sponsored credit schemes. The bank also arranges financial literacy programmes, keeps an eye on banking outreach and holds meetings of both the District Consultative Committee (DCC) and the District Level Review Committee (DLRC) in order to examine the progress of banking activities. The Lead Bank also collaborates with various government departments in order to enhance the flow of credit for use in agriculture, rural infrastructure, education loans, housing finance, and the development of small businesses. Continuous monitoring is carried out to make sure that banking services are delivered efficiently to the intended beneficiaries.

Contribution to Financial Inclusion

A major achievement of the Lead Bank Scheme has been its role in promoting financial inclusion. With the guidance of the Reserve Bank of India and the Government of India, the Lead Banks have actively backed initiatives such as:

1. Opening bank accounts as part of financial inclusion programmes.
 - a. Setting up more banking branches in villages where there was no bank before.
 - b. Advancement of the Business Correspondent (BC) services.
2. Campaigns aimed at improving financial literacy and financial awareness.
3. The implementation of Direct Benefit Transfer (DBT).
4. Digital payment adoption.
5. The linking of credits for Self-Help Groups (SHGs).

These measures have greatly increased access to formal financial services, which as a result has reduced rural households' reliance on informal moneylenders and improved their financial security (Government of India, 2024).

Role in Agricultural Development

Agriculture is still one of the priority areas within the Lead Bank Scheme; the Lead Bank ensures that crop loans, investment credit, dairy loans, fisheries financing, horticultural development, farm mechanization and other related agricultural activities are made available in a timely manner. It works in cooperation with the agriculture departments, cooperative institutions and banks in order to improve the flow of credit and promote the use of better farming technologies. District Credit Plans, when drawn up under the scheme, identify investment opportunities which are specific to each sector on the basis of the resources available in the area, thus encouraging diversified agricultural development and rural employment.

Impact on Rural Entrepreneurship

The Lead Bank Scheme has made a significant contribution to the promotion of entrepreneurship by providing credit to Micro, Small and Medium Enterprises (MSMEs), women entrepreneurs, young people, artisans, and start-up enterprises; various government programmes are carried out as a result of co-ordinated action between Lead Banks and the district-level agencies. Because of credit support, a large number of first-generation entrepreneurs have been able to set up small manufacturing units, service enterprises, food processing industries, and rural businesses, thus creating job opportunities and increasing household incomes.

Achievements of the Lead Bank Scheme

Since its introduction, the Lead Bank Scheme has recorded several notable achievements:

1. Banking services have been extended to almost all districts of the country.
2. There has been an improvement in the flow of institutional credit to the agriculture sector and to other priority sectors.
3. Banks and government departments need to work together more closely.
4. Promoting greater financial inclusion by means of universal banking programmes.
5. An improved implementation of credit schemes sponsored by the government.
 - a. Encouraging the use of digital banking and cashless transactions.
6. Enhancing credit planning and monitoring at the district level.
7. There has been an improvement in outreach to Self-Help Groups and Farmer Producer Organizations (FPOs).

Challenges Facing the Lead Bank Scheme

Even though there has been a great deal of progress, some difficulties still have an effect on the effectiveness of the Lead Bank Scheme. In many districts there is poor coordination between the various institutions involved, which causes delays in the implementation of development programmes. Differences still exist between regions with regard to banking infrastructure, especially in remote and tribal areas. In some regions credit absorption capacity stays low because of a lack of awareness, low levels of financial literacy and a shortage of entrepreneurial skills.

Other Important Challenges Include

1. A rise in non-performing assets (NPAs).
 - a. There is a shortage of properly trained banking staff in the rural branches.
 - b. The uptake of digital financial services remains slow in some areas.
2. There is poor supervision of the district credit plans.

- a. There is a duplication of efforts among the various agencies.
3. There is only a limited degree of integration of technology for the purpose of real-time monitoring.

Future Outlook

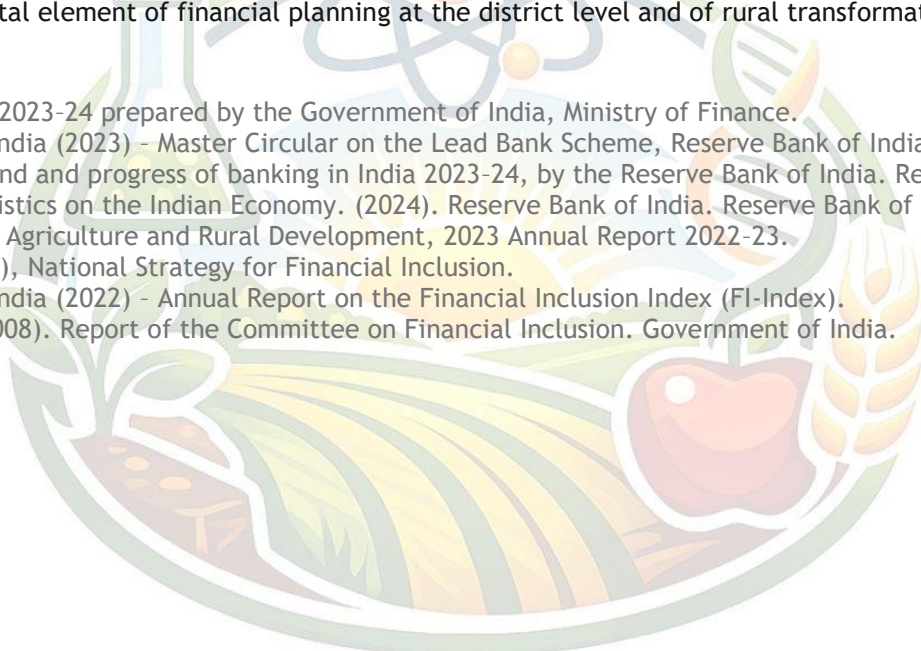
The financial system in India is rapidly undergoing change thanks to digital banking, the Unified Payments Interface (UPI), Aadhaar-enabled services, artificial intelligence, and innovations in the field of fintech. The Lead Bank Scheme is expected to take on an even more important role by incorporating these technologies into financial planning at the district level. The future should see a focus on digital financial inclusion, financing for sustainable agriculture, climate-resilient investments, women's entrepreneurship, support for Farmer Producer Organizations, and the promotion of rural start-ups. Improved coordination among institutions will aid in achieving the aims of inclusive economic growth and financial empowerment.

Conclusion

The Lead Bank Scheme has always been one of India's most successful methods of coordinating banking development at the district level. It has made a significant contribution to socio-economic development by improving access to institutional credit, promoting financial inclusion, supporting agriculture and rural entrepreneurship, and helping to carry out government development programmes. Even though problems concerning coordination, monitoring, and regional disparities still persist, continuous reforms, digital innovations, and greater institutional cooperation can greatly improve its effectiveness. As India moves forward with inclusive and sustainable development, the Scheme will keep acting as a fundamental element of financial planning at the district level and of rural transformation.

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From Farm to Fortune: How One-Woman Entrepreneur is Transforming Bihar's Banana Industry Through Innovation

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Adding Value, Empowering Communities, and Redefining Rural Entrepreneurship

In the heart of Bihar's fertile Vaishali district, where banana cultivation has sustained farming families for generations, an inspiring story of innovation is reshaping the future of agriculture. While countless farmers continue to depend solely on selling fresh bananas, one woman entrepreneur has chosen a different path—one that transforms an ordinary fruit into extraordinary opportunities.

Meet **Ms. Abha Kumari**, the founder of **Hajipur Alpan Banana**, a thriving rural enterprise located in Mohabbatpur village, Hajipur. Cultivating banana on just one acre of land, she has demonstrated that the true potential of agriculture lies not merely in production but in value addition, entrepreneurship, and sustainable innovation.



Her journey represents a new generation of Indian farmers—individuals who are no longer satisfied with producing raw agricultural commodities but are creating branded products, generating employment, reducing waste, and building resilient rural businesses. Today, Hajipur Alpan Banana stands as an inspiring example of how a single agricultural enterprise can create economic opportunities while contributing to environmental sustainability and women's empowerment.

The Challenge Behind Traditional Banana Farming

India is one of the world's largest producers of bananas, yet many growers continue to face significant economic challenges. Fresh bananas have a short shelf life, making them highly vulnerable to spoilage during transportation and storage. During peak harvest seasons, markets become oversupplied, forcing farmers to sell their produce at low prices. For many farming families, months of hard work often translate into uncertain incomes. Fruits that cannot be sold quickly become waste, resulting in financial losses and reduced profitability.

Recognizing these challenges, Ms. Abha Kumari envisioned a new approach. Instead of treating bananas as a single marketable commodity, she saw them as the foundation for a wide range of value-added products capable of generating income throughout the year.

A Vision Beyond Cultivation

As a member of the **Shaurya Jeevika Self Help Group**, Abha Kumari believed that farming could become more profitable through innovation, processing, and entrepreneurship. With determination, skill development, and continuous learning, she established **Hajipur-Alpan Banana**, a small-scale processing unit dedicated to producing high-quality banana-based products.



Her philosophy is simple yet powerful:

"Every part of the banana plant has value, and nothing should go to waste."

This vision transformed her farm from a conventional cultivation unit into a diversified agribusiness that combines food processing, eco-friendly manufacturing, branding, and rural employment.

Turning Bananas into Premium Products

Today, Hajipur Alpan Banana manufactures a remarkable range of innovative products designed to meet the growing demand for nutritious foods and sustainable alternatives.

Innovative Banana Products

Today, the farm produces a diverse range of banana-based products that appeal to different consumer groups.

Banana Chips

Banana chips are among the most popular products. Carefully selected bananas are sliced, seasoned, and processed to create a crispy, flavorful snack. The product enjoys steady demand in local markets as well as among tourists and retailers.



Banana Flour

Green bananas are processed into flour, which is increasingly recognized as a nutritious ingredient for baking, baby food, and health-conscious diets. Banana flour is naturally rich in resistant starch and dietary fiber, making it attractive to consumers seeking healthier food options.



Banana Powder

Banana powder is used in beverages, bakery products, nutritional supplements, and infant foods. Its long shelf life makes it suitable for storage and transportation.



Banana Jam and Jelly

Ripe bananas are transformed into delicious spreads that provide consumers with a unique alternative to conventional fruit jams. These products demonstrate how even fully ripened bananas can be utilized effectively.



Banana Candy and Snacks

Healthy banana candies and dried banana snacks have become attractive products, especially among children and young consumers looking for natural alternatives to processed sweets.



Banana Fiber

One of the most innovative ventures involves extracting fiber from banana stems. Banana fiber is biodegradable, strong, and environmentally friendly. It can be used to produce ropes, handicrafts, bags, mats, decorative items, and even sustainable textiles.





Banana Stem and Banana Blossom Products

The farmer will also explore products made from banana stems and blossoms, including pickles and food items valued for their nutritional benefits. This ensures that nearly every part of the banana plant contributes to income. Through diversification, the farmer has transformed a single crop into multiple revenue streams.



Each product undergoes hygienic processing and careful packaging, ensuring high quality and consumer satisfaction. By extending the shelf life of bananas, these products reduce post-harvest losses while opening access to new and more profitable markets.

The enterprise has also embraced changing consumer preferences by offering healthier, natural, and minimally processed food options that appeal to health-conscious buyers.

Nothing Goes to Waste

One of the most remarkable features of Hajipur Alpan Banana is its commitment to zero-waste agriculture. After harvesting the fruit, banana stems are processed to extract natural fibres materials that were once discarded as agricultural waste but are now transformed into environmentally friendly products.

These include:

- Eco-friendly shopping bags
- Handmade greeting cards
- Decorative handicrafts
- Gift articles
- Sustainable fibre products

The initiative reflects the principles of the circular economy, where agricultural residues become valuable raw materials rather than environmental burdens. By utilizing almost every component of the banana plant, the enterprise demonstrates that sustainable farming can also be economically rewarding.

Empowering Women Through Enterprise

Beyond its commercial success, Hajipur Alpan Banana has become a symbol of women's empowerment. Working through the Shaurya Jeevika Self Help Group, the enterprise provides opportunities for rural women to participate in:

1. Food processing
2. Packaging
3. Product labelling
4. Quality control
5. Marketing
6. Handicraft production

These activities generate additional household income while helping women develop entrepreneurial skills, financial confidence, and leadership abilities. The enterprise illustrates how Self-Help Groups can evolve beyond savings and credit activities to become engines of rural industrial development.

Overcoming Challenges

Building a successful agribusiness was not without obstacles.

Like many first-generation entrepreneurs, Ms. Abha Kumari faced numerous challenges, including limited financial resources, high investment requirements for processing equipment, lack of consumer awareness about value-added banana products, branding difficulties, and restricted market access. Instead of allowing these obstacles to discourage her, she embraced continuous learning through agricultural training programmes, entrepreneurship workshops, exhibitions, and interactions with experts.

Her willingness to innovate and improve gradually transformed these challenges into opportunities.

Creating Economic and Social Impact

The impact of Agri-Hajipur Banana extends far beyond the farm.

The enterprise has:

1. Increased profitability from banana cultivation.
2. Reduced post-harvest losses.
3. Diversified income sources.
4. Generated employment for rural women and youth.
5. Encouraged environmentally responsible production.
6. Inspired neighbouring farmers to adopt value addition.
7. Demonstrated the commercial potential of banana-based enterprises.

By processing locally grown bananas into premium products, the business contributes to strengthening the agricultural value chain while promoting inclusive rural development.

A Model for the Future

With rising consumer demand for healthy snacks, gluten-free flours, natural food products, and eco-friendly alternatives, enterprises like Hajipur Alpan Banana are well positioned for future growth. Expanding into e-commerce platforms, obtaining quality certifications, participating in national exhibitions, collaborating with Farmer Producer Organizations (FPOs), and exploring export markets could further enhance the enterprise's reach.

As India continues to promote food processing, women-led enterprises, and sustainable agriculture, the Hajipur Alpan Banana model offers valuable lessons for farmers across the country.

An Inspiration for Rural India

The journey of Ms. Abha Kumari proves that innovation begins with a simple idea the courage to see possibilities where others see limitations. By transforming bananas into a diverse portfolio of nutritious foods and eco-friendly products, she has shown that modern agriculture is not only about cultivation but also about creativity, entrepreneurship, sustainability, and community development.

Her story is a testament to the power of rural innovation, demonstrating that with determination, skill, and vision, even a one-acre farm can become the foundation of a successful enterprise. As more farmers embrace value addition and sustainable processing, the future of Indian agriculture will be defined not merely by higher production but by greater value creation, stronger rural economies, and empowered farming communities. The success of Hajipur Alpan Banana stands as a shining example that every harvest holds the potential to create prosperity, employment, and lasting social change.

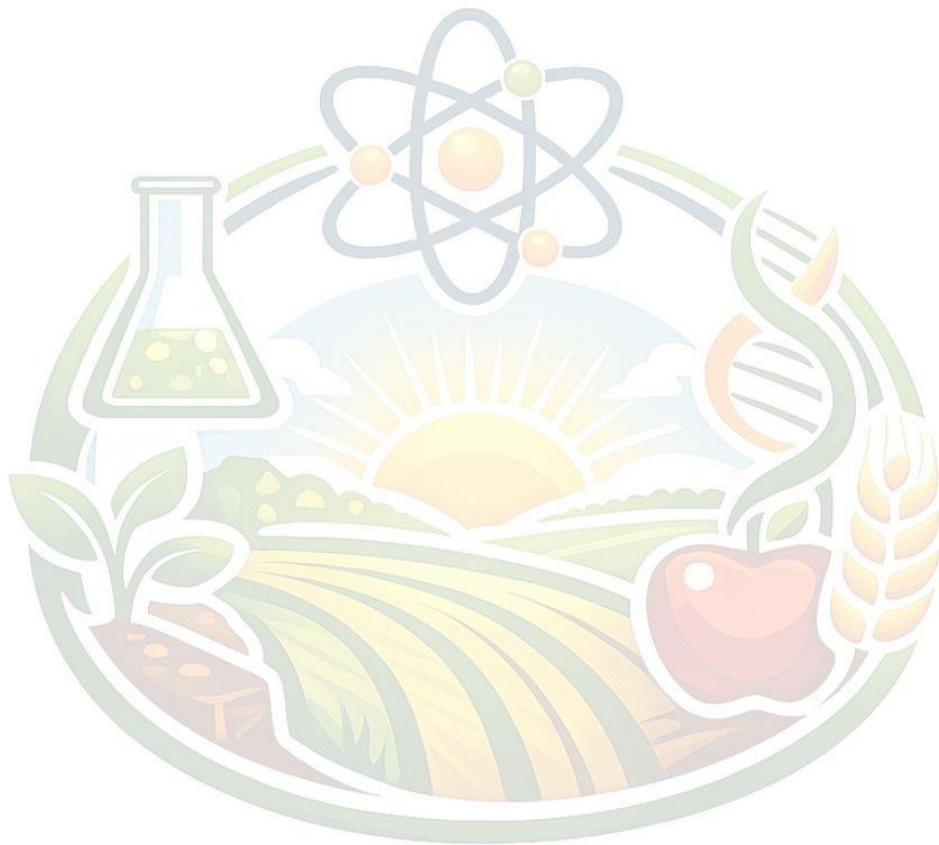
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Conclusion

The entrepreneurial journey of **Ms. Abha Kumari** illustrates how innovation and value addition can transform traditional farming into a sustainable agribusiness. Through **Hajipur Alpan Banana**, she has successfully converted a one-acre banana farm into a diversified enterprise producing nutritious food products and environmentally friendly banana fibre handicrafts.

Her work reflects the immense potential of rural women entrepreneurs in strengthening agricultural value chains, promoting sustainable livelihoods, and creating employment opportunities. By demonstrating that every part of the banana plant has economic value, she has set an inspiring example for farmers across India.

The story of **Hajipur Alpan Banana** is not merely about producing banana products—it is about resilience, innovation, women empowerment, and building a greener rural economy that benefits both farmers and society.



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Role of Artificial Intelligence in Entomology

Article ID: 74409

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Artificial Intelligence (AI) is revolutionizing entomological research by enhancing precision, scalability and decision-making in pest management and ecological monitoring. Its integration into entomology enables automated identification of insect species through image recognition, accelerates data analysis from field and laboratory trials and supports predictive modeling of pest population dynamics. Machine learning algorithms, particularly convolutional neural networks (CNNs), have shown high accuracy in classifying morphologically similar species, aiding rapid diagnostics and biodiversity assessments. In agricultural entomology, AI-driven systems facilitate real-time surveillance of pest outbreaks, optimize trap placement, and forecast infestation risks based on climatic and crop data. These capabilities are instrumental in developing site-specific Integrated Pest Management (IPM) strategies, reducing pesticide use, and improving crop protection outcomes. Furthermore, natural language processing (NLP) tools assist in synthesizing vast entomological literature, while decision support systems (DSS) powered by AI help stakeholders make informed interventions. Despite its promise, challenges remain in data standardization, model interpretability, and field-level validation. Nonetheless, AI offers transformative potential for entomologists, especially in resource-constrained settings, by enabling scalable, cost-effective, and adaptive pest control solutions. As the discipline evolves, interdisciplinary collaboration between entomologists, data scientists, and agronomists will be critical to harness AI's full potential in advancing sustainable pest management and ecological resilience.

Keywords: Artificial Intelligence (AI), Entomological research, Pest management, Ecological monitoring, Integrated Pest Management (IPM), Agricultural entomology, Machine learning, Convolutional neural networks (CNNs).

Modern agriculture is grappling with significant challenges. As the industry becomes increasingly competitive and global in nature, farmers and those supplying agricultural inputs must navigate a complex landscape shaped by environmental variations and international economic and political dynamics (Demirel and Kumral 2021). According to the Food and Agriculture Organization, pests are responsible for reducing global crop yields by 20 to 40 percent annually. Pest outbreaks lead to an estimated annual loss of \$220 billion to the global economy, with invasive insect species alone accounting for about \$70 billion. While pesticides have helped mitigate crop losses, their prolonged and excessive use has triggered serious problems such as pest resistance, (Weller, S., *et al.*, 2014). The contributions of pesticides to pest management in meeting the global need for food production by 2050, resurgence of secondary pests, deterioration of plant immunity, environmental pollution, and increased health risks for consumers. To address these concerns, it's essential to manage resources like water, energy, fertilizers, and pesticides with precision and care. This underscores the urgent need for advanced technological solutions in agriculture that can detect pest infestations early and minimize unnecessary pesticide usage. Smart farming has recently emerged as a way to incorporate artificial intelligence (AI), digital technologies, and wireless communication systems—such as the Internet of Things (IoT)—into every aspect of agriculture. This approach enables precise monitoring and control of crop health, pest and disease management, fertilization, and irrigation across farm fields. Conventional methods of manually identifying insect pests are often slow, costly, and labour-intensive. Therefore, combining artificial intelligence with entomological research can significantly enhance the timely detection, prediction, and control of pest and disease outbreaks, leading to more efficient agricultural management.

Applications of AI in Agricultural Entomology

1. Taxonomic studies: *Identifying and classifying insects* helps organize biodiversity and understand species relationships. Quantifying phenotypes reveals variations in traits like size or behavior. These insights support the study of evolutionary differences, showing how insects adapt over time. Together, they form a foundation for entomological research and ecological understanding.

2. Ecological studies: *Studying insect ecology* involves tracking their spatial and temporal patterns to understand distribution dynamics. Researchers monitor changes in population mass and assess species richness to gauge biodiversity and ecosystem health. By analyzing dietary habits and ecological roles, scientists uncover how insects interact within food webs. Evaluating habitat characteristics further reveals the environmental factors shaping insect behavior and survival.

3. Pest management: *Effective pest management* begins with detecting and accurately categorizing pest species to understand their behavior and impact. Tracking their activity and spread over time enables timely interventions through targeted control measures. By establishing early warning systems, researchers can anticipate outbreaks and respond proactively. Forecasting pest trends further enhances biosecurity, helping safeguard crops and ecosystems from emerging threats.

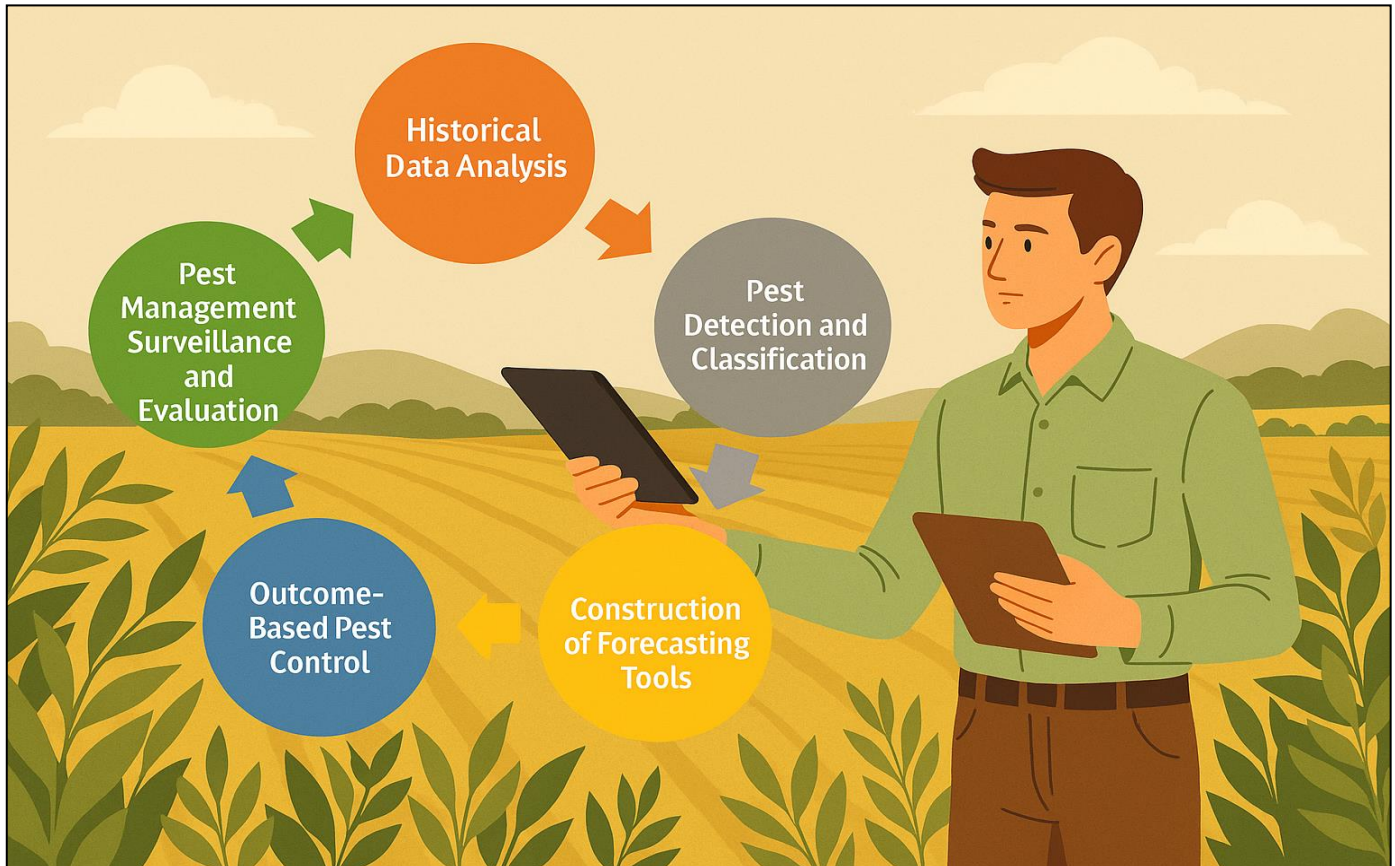


Fig 1.1: AI-driven model for real-time pest detection and management

Table 1: Illustrative uses of artificial intelligence and machine learning in entomological studies:

Crop	Insect Pests	Recognitions model	Research Parameter	References
Coffee	Coffee berry borer (CBB) <i>Hypothenemus hampei</i> (Ferrari)	Using swarm intelligence for proliferation simulation and machine learning like Random Forest to assess factors influencing CBB density.	Recognition and Classification	Lee and Tardaguila (2023)
Cabbage	Diamond back moth (DBM) <i>Plutella xylostylella</i> (Linnaeus)	AI-CABB System: This is a recent AI-enabled system that uses a YOLOv5-based detection model trained on a dataset of four insect classes, including DBM, found on cabbage.	Predicting Population Density	Kaur et al. (2022)
Tomato	Whitefly, <i>Bemisia tabaci</i> (Gennadius)	YOLO is one of the most widely adapted object detection algorithms for whitefly monitoring	Evaluating and recognizing developmental phases	Lutz and Coradi (2022)

		due to its speed and high accuracy.		
Soyabean	Aphid, <i>Aphis glycines</i> (Matsumura)	Convolutional Neural Networks (CNNs): These models, such as one developed by researchers in 2017, can count aphids on soybean leaves in greenhouse settings with high accuracy.	Fluctuations in Species Numbers and Distribution	Murmu et al. (2022)
Cotton	Whitefly, <i>Bemisia tabaci</i> (Gennadius)	Modified versions of the You Only Look Once (YOLO) deep learning model are commonly used for the detection and counting of tiny whiteflies in images captured from leaves or traps	Recognize signs of stress, environmental influences, and morphological details	Toscano-Miranda et al. (2022)
Brinjal	Brinjal shoot and fruit borer, <i>Leucinodes orbonalis</i> (Guenee)	S: One study used a CNN based on the VGG-16 architecture to detect four insect classes: brinjal shoot and fruit borer larvae and adults, and Epilachna beetle grubs and adults.	Recognition, Labelling Categorization	Saikumar et al. (2023)

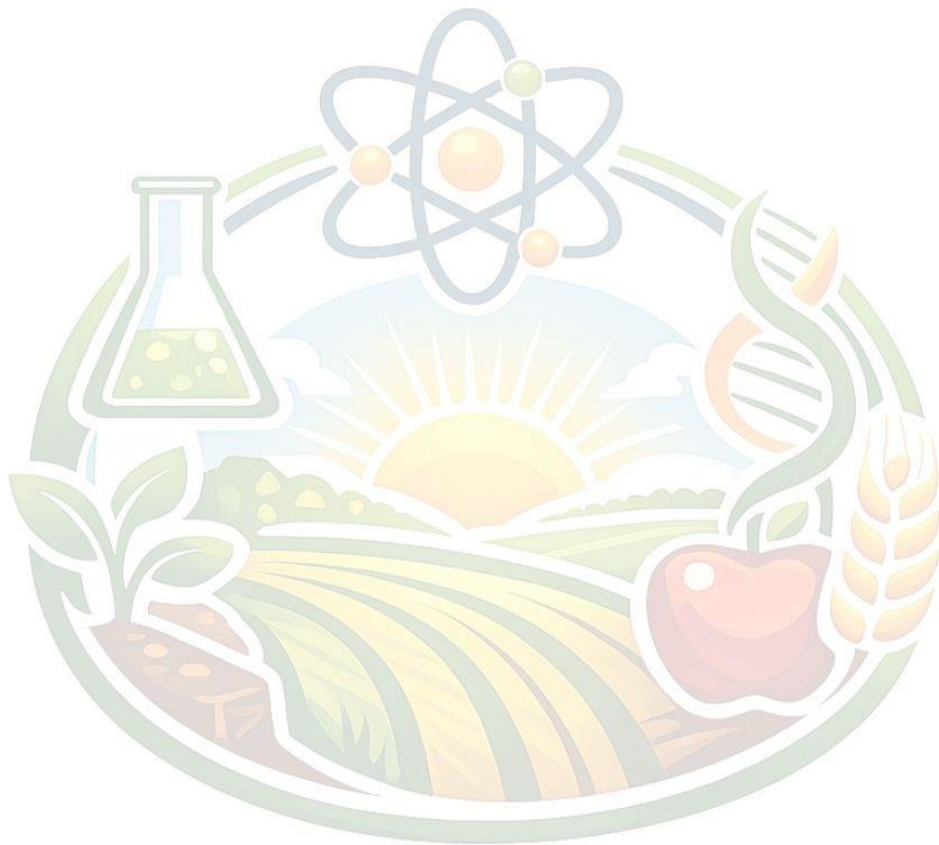
Summary

Pest management is inherently a prolonged and multifaceted process, often requiring continuous monitoring, timely interventions, and adaptive strategies. Traditional approaches, while effective to an extent, can be labour-intensive and reactive rather than predictive. Integrating artificial intelligence (AI) into pest management systems offers a transformative shift toward precision and efficiency. AI-driven tools can analyze vast datasets from field observations, climatic conditions, and crop phenology to forecast pest outbreaks, optimize control measures, and reduce reliance on chemical inputs.

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From Plate to Farm: How Western Food Trends Are Reshaping Indian Agriculture

Article ID: 74410

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Abstract

Changing food preferences driven by globalization, urbanization, rising incomes, and evolving lifestyles are transforming Indian agriculture. Growing demand for Western-style foods has expanded markets for high-value horticultural crops, strengthened food processing industries, and created new opportunities for farmers through improved value chains and digital marketing platforms. However, this transition also presents challenges such as biodiversity loss, monocropping, rising production costs, and increasing dependence on processed foods. The article highlights the need to balance modern consumer demand with conservation of indigenous crops, sustainable farming practices, and nutrition-sensitive agriculture. By integrating innovation, climate-smart technologies, and traditional agricultural wisdom, Indian agriculture can meet changing market demands while ensuring long-term environmental sustainability and food security.

Keywords: Western food trends; Indian agriculture; consumer preferences; crop diversification; food processing; protected cultivation; sustainability; biodiversity; value chains; climate-smart agriculture.

Introduction

Food habits are closely linked to culture, yet they continue to evolve with changing lifestyles and economic development. In India, the growing influence of Western food choices has altered consumer demand, encouraging farmers to diversify production and adopt new technologies (Pingali, 2007). While these changes offer promising market opportunities, they also raise concerns about agricultural sustainability and the preservation of traditional food systems. This article examines both the opportunities and challenges associated with this transition.

Changing Food Choices, Changing Farms

Changing consumer preferences are transforming cropping patterns, markets, and farming practices. For centuries, Indian agriculture has evolved in harmony with the country's rich food traditions. Although food habits are generally rooted in culture, they have undergone significant changes in recent decades. Economic development, technological advancements, globalization, and industrialization have increased the demand for processed foods and introduced new tastes. Western-style food habits, once confined to metropolitan cities, are now influencing consumers across the country. This dietary transition is not only changing menus but also redefining agricultural production and marketing.

According to a consumer survey conducted by Franchise India (2012), the growing popularity of eating away from home reflects changing consumer behaviour. Today, fast-food restaurants, supermarkets, online food delivery platforms, and processed food industries have become an integral part of urban and semi-urban life. Consequently, the demand for crops such as lettuce, broccoli, sweet corn, mushrooms, potatoes, herbs, avocados, dragon fruit, kiwi, and other exotic vegetables has increased substantially. Many of these crops, once largely imported, are now cultivated commercially by Indian farmers, reflecting a broader transformation in agricultural markets and production systems. This trend reflects the broader diversification of Indian agriculture towards high-value horticultural crops driven by increasing domestic demand and export opportunities (Jha *et al.*, 2019).

Did You Know?

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1. Demand for exotic vegetables and fruits has increased rapidly in urban India.
2. The food processing sector is creating new opportunities for value addition and rural employment.
3. Traditional crops such as millets and native pulses are witnessing renewed consumer interest owing to their nutritional value.

New Opportunities for Farmers

Improved living standards and higher incomes have changed people's eating habits. Modern farmers are adopting new technologies and cultivating crops that cater to evolving consumer preferences. The expansion of food processing industries has strengthened value chains involving grading, packaging, cold storage, transportation, and processing. Digital marketplaces, e-commerce platforms, and contract farming arrangements have enabled farmers to connect directly with organized retailers and food service companies (Bhat and Mayya, 2025).

Many high-value vegetables such as coloured capsicum, lettuce, cucumber, cherry tomato, and herbs are increasingly being cultivated under protected structures, allowing year-round production of premium-quality produce. For example,

farmers in peri-urban regions around Bengaluru, Pune, and Delhi have diversified into exotic vegetables to meet the growing demand from supermarkets, hotels, and restaurant chains.

Challenges Beside the Changing Plate

While Western food trends have opened new markets, they have also introduced several challenges. Increasing preference for a limited number of commercial crops can reduce the cultivation of traditional cereals, pulses, millets, and indigenous vegetables, threatening agricultural biodiversity and valuable local germplasm.

Commercial production of exotic crops often requires higher investments in irrigation, fertilizers, protected cultivation, and cold-chain infrastructure, making adoption difficult for small and marginal farmers. Monocropping may accelerate soil nutrient depletion, increase pest and disease pressure, and reduce ecosystem resilience (IPBES, 2019). Likewise, increasing consumption of highly processed foods raises nutritional and public health concerns.

Balancing Tradition with Modern Markets

The transformation of India's food system should not be viewed simply as the replacement of traditional diets with Western foods. Instead, it represents an opportunity to diversify agricultural production while preserving indigenous crops and food heritage. Growing consumer interest in millets, traditional rice varieties, native pulses, organic foods, and functional foods demonstrates that traditional agriculture continues to offer significant market potential.

Climate-smart agriculture can help farmers respond to changing consumer demand while conserving natural resources. Precision farming, micro-irrigation, integrated nutrient management, protected cultivation, and digital advisory services can improve productivity, resource-use efficiency, and resilience under changing climatic conditions.

Export Opportunities

The expanding production of high-value horticultural crops also offers export opportunities. Improving quality standards, traceability, post-harvest management, and food safety compliance can help Indian farmers access premium domestic and international markets.

The Way Forward

The future of Indian agriculture will increasingly be shaped by changing consumer preferences. Policy support should encourage crop diversification, strengthen cold-chain infrastructure, promote Farmer Producer Organizations (FPOs), improve market access, and invest in research on both traditional and emerging crops. Nutrition-sensitive agriculture should become a central objective alongside productivity and profitability.

Key Takeaways

1. Changing food habits are reshaping crop choices and agricultural markets.
2. High-value horticultural crops provide new income opportunities.
3. Protected cultivation and value addition can enhance farm profitability.
4. Climate-smart and diversified farming systems are essential for sustainability.
5. Traditional crops remain important for food, nutrition, and biodiversity.

Conclusion

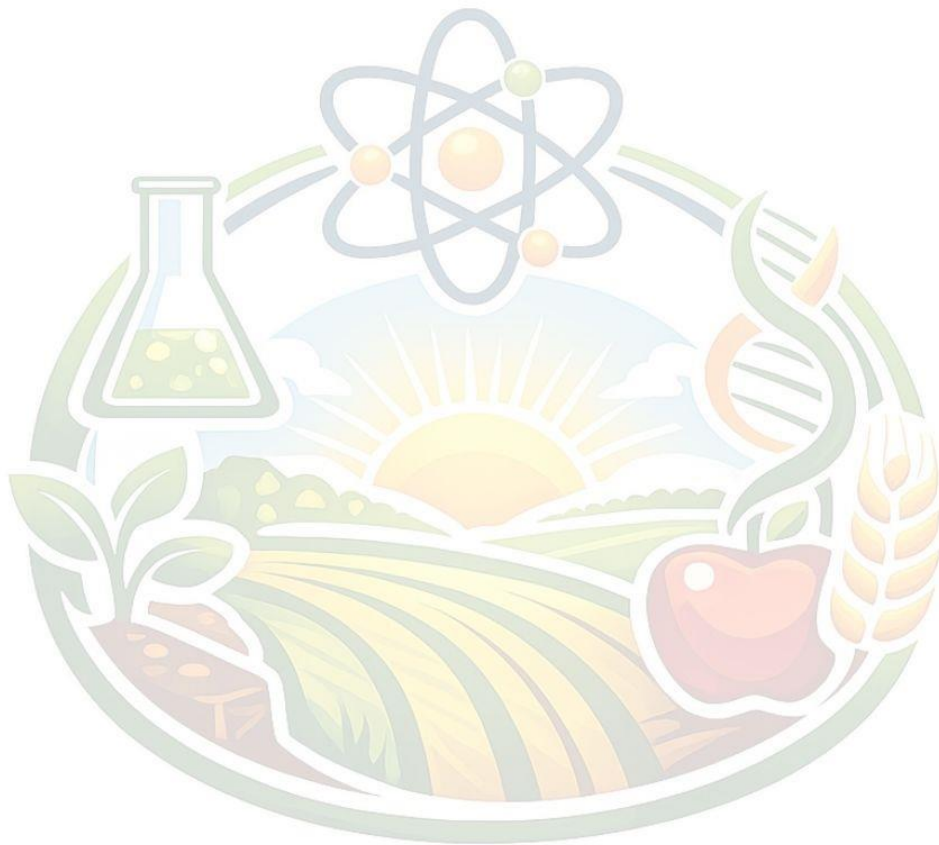
Western food trends are reshaping Indian agriculture by influencing crop choices, value chains, and market opportunities. The future lies not in choosing between tradition and modernity but in integrating both. By combining innovation, sustainable farming practices, and the conservation of indigenous crops, Indian agriculture can meet evolving consumer preferences while safeguarding biodiversity, environmental health, and the nation's agricultural heritage for future generations.

"The future of Indian agriculture lies not in choosing between tradition and modernity, but in integrating both to build resilient, profitable, and sustainable farming systems."

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Reserve Mobilization in Plants: Nature's Strategy for Growth and Survival

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Introduction

Plants are remarkable living organisms that produce their own food through photosynthesis. However, they cannot rely solely on daily photosynthesis throughout their life cycle. During seed germination, flowering, fruit development, drought, salinity, flooding, or other stressful conditions, plants require an internal source of energy and nutrients. To meet these demands, plants store food reserves in various organs and later transport these reserves to growing tissues through a process known as reserve mobilization.

Reserve mobilization is one of the most important physiological processes in plants because it ensures continuous growth, successful reproduction, and survival under unfavorable environmental conditions. Without efficient reserve mobilization, seeds may fail to germinate, young seedlings may not establish properly, and crops may produce poor yields.

What is Reserve Mobilization?

Reserve mobilization refers to the breakdown and movement of stored food materials from storage tissues to actively growing or metabolically active tissues where they are needed. Simply put, reserve mobilization is the conversion of stored nutrients into usable forms that supply energy and building materials for plant growth and development.

Why Do Plants Store Food?

Plants store food because photosynthesis cannot always meet their energy and nutrient requirements throughout their life cycle. Environmental conditions such as drought, low light intensity, extreme temperatures, or seasonal changes can reduce photosynthetic activity, while certain developmental stages require large amounts of energy and nutrients. Therefore, plants accumulate reserve food during favorable conditions and utilize these reserves whenever the demand exceeds the supply from current photosynthesis.

Stored food reserves play a crucial role during seed germination and early seedling establishment, when young seedlings are not yet capable of producing sufficient food through photosynthesis. These reserves provide the energy and building materials needed for cell division, root and shoot development, and the establishment of healthy seedlings.

As plants continue to grow, stored reserves support important developmental processes such as flower initiation, fruit development, and grain filling. During these stages, the demand for carbohydrates, proteins, and other nutrients is extremely high. Reserve mobilization ensures a continuous supply of assimilates to developing flowers, fruits, and seeds, thereby improving reproductive success and final crop yield.

Food reserves are also essential for plant survival during dormancy and under various environmental stresses such as drought, salinity, flooding, and extreme cold or heat. During these adverse conditions, photosynthesis is often reduced due to limited water availability, stomatal closure, or damage to the photosynthetic machinery. Plants rely on stored reserves to maintain respiration, cellular metabolism, tissue repair, and other vital physiological processes until favorable conditions return.

Major Storage Organs in Plants

Sr.	Storage Organ	Stored Reserves	Examples	Importance / Function
1	Seeds	Starch, proteins, oils	Wheat, Rice, Maize, Pigeonpea, Chickpea, Soybean	Most common storage organs; provide nutrients and energy for seed germination and early seedling growth.
2	Roots	Mainly carbohydrates (starch and sugars)	Carrot, Beetroot, Sweet potato, Cassava	Store food reserves that support regrowth, flowering, and survival during unfavorable conditions.
3	Tubers	Starch	Potato	Underground modified stems that store large amounts of starch for vegetative propagation and future growth.
4	Rhizomes	Carbohydrates (mainly starch)	Ginger, Turmeric	Underground stems that store reserves for perennial growth and vegetative reproduction.

5	Bulbs	Carbohydrates and minerals	Onion, Garlic	Modified underground buds that store food to support rapid growth during the next growing season.
6	Stems	Sugars (mainly sucrose) and carbohydrates	Sugarcane, Bamboo	Store carbohydrates that are remobilized during flowering, grain filling, and stress conditions.
7	Leaves	Carbohydrates and water	Aloe vera, Agave	Succulent leaves store food and water, helping plants survive drought and other environmental stresses.

Type of Stored Reserve

Types	Stored Form / Examples	Major Functions
Carbohydrates	Stored as: Starch, Sucrose, Fructans, Hemicellulose	Energy production, Cell wall synthesis, Growth and development, Respiration
Proteins	Storage proteins: Albumins, Globulins, Prolamins, Glutelins	Protein synthesis, Enzyme production, Formation of new tissues during germination
Lipids	Found mainly in oilseed crops: Groundnut, Mustard, Sunflower, Soybean, Castor	High-energy reserve, converted into carbohydrates during germination, Membrane synthesis, supports seedling growth
Minerals	Stored nutrients: Phosphorus (P), Potassium (K), Calcium (Ca), Magnesium (Mg), Iron (Fe), Zinc (Zn)	Enzyme activation, Cell division and metabolism, Nutrient supply during seedling establishment, Structural and physiological functions

Source-Sink Relationship

Reserve mobilization is closely associated with the source-sink relationship in plants. Mature leaves, stored reserves, and stem tissues act as sources, supplying carbohydrates and other assimilates. Growing organs such as young leaves, flowers, pods, fruits, seeds, roots, and developing embryos function as sinks, where these nutrients are utilized for growth and development. Efficient transport of assimilates from source to sink is essential for achieving higher crop productivity.

Reserve Mobilization Under Drought

During drought stress, stomatal closure reduces photosynthesis and limits the production of new assimilates. To overcome this shortage, plants remobilize stored carbohydrates and nutrients from stems, roots, and older leaves. These reserves help maintain respiration, support reproductive growth, facilitate grain filling, contribute to osmotic adjustment, and improve survival under prolonged water deficit. Consequently, crop varieties with efficient reserve mobilization generally exhibit better drought tolerance and higher yields.

Reserve Mobilization During Grain Filling

Grain filling is one of the most critical stages of crop development, during which the demand for carbohydrates is extremely high. Since current photosynthesis may not fully meet this demand, stored carbohydrates accumulated in stems are remobilized and transported to developing grains. This process significantly enhances grain weight, yield, and grain quality, particularly in high-yielding cereal crops such as wheat.

Reserve Mobilization in Legumes

In leguminous crops such as pigeonpea, chickpea, lentil, and soybean, reserve mobilization primarily involves the remobilization of nitrogen and proteins. Storage proteins in leaves are degraded into amino acids and transported to developing seeds, where they contribute to protein synthesis. Efficient remobilization therefore plays an important role in improving both seed yield and nutritional quality.

Reserve Mobilization Under Nutrient Deficiency

When essential nutrients become limited in the soil, plants efficiently recycle nutrients from older tissues to younger, actively growing organs. Nutrients such as nitrogen, phosphorus, potassium, and magnesium are remobilized from senescing leaves and transported to developing tissues. This internal nutrient recycling enables plants to sustain growth and survive under nutrient-deficient conditions.

Reserve Mobilization During Senescence

Leaf senescence is a well-regulated physiological process that enables plants to recycle valuable nutrients before leaves are shed. During senescence, chlorophyll, proteins, and starch are degraded, while minerals and nitrogen are transported

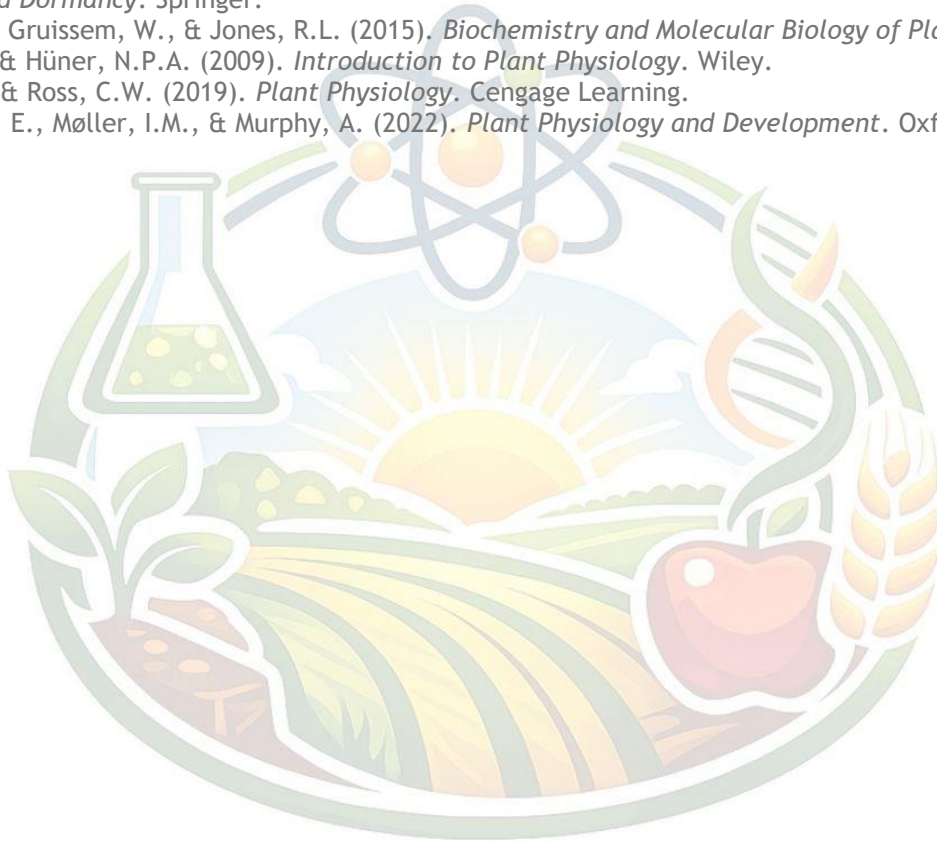
from older leaves to developing seeds and other growing organs. This nutrient recycling enhances seed development and improves reproductive success.

Conclusion

Reserve mobilization is a fundamental physiological process that enables plants to convert stored food reserves into usable energy and nutrients during periods of high demand or environmental stress. It supports seed germination, seedling establishment, flowering, grain filling, and survival under adverse conditions. Efficient reserve mobilization enhances crop productivity, stress tolerance, and resource-use efficiency. As agriculture faces the challenges of climate change and a growing global population, understanding and improving reserve mobilization will remain an important strategy for developing resilient, high-yielding crop varieties and ensuring sustainable food production.

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Chlorophyll Fluorescence Sorting Machine: A New Era in Precision Seed Quality Assessment

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Abstract

Seed quality is traditionally evaluated through germination, vigour, moisture content, physical purity and seed-health tests. Although these methods are essential, many require considerable time and generally provide information at the seed-lot level. The development of non-destructive optical technologies has created new opportunities for rapid assessment of individual seeds. Chlorophyll fluorescence (CF) sorting is one such technology that uses residual chlorophyll in developing seeds as an indicator associated with maturity and physiological quality. During seed maturation, chlorophyll is progressively degraded, resulting in a decline in fluorescence. This signal can be measured rapidly and used to classify individual seeds. The concept was developed into a seed-sorting system by Jalink, enabling seeds to be separated according to their fluorescence characteristics. Research in cabbage, soybean, pepper and other crops has demonstrated the potential of CF sorting to improve selected seed fractions. However, fluorescence is an indirect indicator of seed quality, and its effectiveness varies with crop, genotype and seed-lot characteristics. Integration of fluorescence with machine vision, hyperspectral imaging, robotics and artificial intelligence could further advance precision seed processing. Thus, chlorophyll fluorescence sorting represents a promising step towards faster, non-destructive and individual-seed-based quality assessment.

Keywords: Chlorophyll fluorescence, seed sorting, seed quality, seed maturity, seed vigour, non-destructive testing, optical sensing.

Introduction

Seed quality is one of the most important determinants of successful crop establishment. High-quality seed should germinate rapidly and uniformly and produce vigorous seedlings capable of establishing successfully under field conditions. Conventional seed testing provides essential information through germination, vigour, moisture, physical purity and seed-health tests. However, many of these tests require several days and generally provide information about a representative sample rather than every individual seed.

The development of non-destructive seed assessment technologies is therefore attracting increasing attention. Techniques such as digital imaging, X-ray imaging, spectroscopy, hyperspectral imaging and chlorophyll fluorescence can obtain information from intact seeds without destroying them (Rahman and Cho, 2016).

Among these technologies, chlorophyll fluorescence is particularly interesting because it exploits a natural characteristic of developing seeds. Seeds may retain chlorophyll during maturation, and its progressive degradation is associated with the transition towards maturity. This change can be detected optically and used as a rapid indicator of seed maturity and, in several crops, seed performance (Jalink et al., 1998; Jalink et al., 1999).

The technology has now progressed beyond fluorescence measurement alone. Chlorophyll fluorescence sorting machines can analyse individual seeds and automatically separate them according to their fluorescence characteristics, providing a potential tool for precision seed processing.

The Science Behind Chlorophyll Fluorescence

Chlorophyll fluorescence is the weak light emitted by chlorophyll molecules after absorbing excitation light. Developing seeds may retain chlorophyll, particularly in the seed coat, which progressively disappears as the seed matures. Consequently, immature seeds generally exhibit higher chlorophyll fluorescence, while mature seeds show lower fluorescence (Jalink et al., 1999). This natural change provides the basis for using fluorescence as an optical indicator of seed maturity. Importantly, fluorescence does not directly measure viability or germination; rather, it provides information associated with chlorophyll retention that can be related to seed performance. Jalink et al. (1998) demonstrated in Brassica oleracea that seeds with lower fluorescence generally exhibited better germination and normal seedling development, supporting the potential of chlorophyll fluorescence as a rapid and non-destructive indicator of seed maturity and quality.

From Fluorescence Measurement to Seed Sorting

The major development in chlorophyll fluorescence technology was the transition from simply measuring fluorescence to using it for individual-seed sorting. Jalink (1997) developed a method and apparatus for determining seed maturity and quality based on chlorophyll fluorescence and separating seeds according to their fluorescence characteristics.

Unlike conventional grading, which mainly relies on physical attributes such as size, shape, weight, density and colour, fluorescence sorting introduces a physiological characteristic into seed processing. Thus, seeds can potentially be separated not only by how they appear, but also by the optical signal associated with their maturity and physiological status.

How Does a Chlorophyll Fluorescence Sorting Machine Work?

- 1. Seed Feeding:** Seeds are dropped or shaken from a **feeder hopper** (often equipped with a **vibrator mechanism**) onto a chute or conveyor system to slide down in a single-file, controlled line.
- 2. Light Excitation:** As individual seeds pass through a dedicated **optical measurement zone**, they are exposed to a high-intensity excitation light source. This is typically a specific wavelength spectrum (like **blue or red LEDs/lasers**).
- 3. Fluorescence Detection:** Chlorophyll inside the seeds absorbs this light energy. Since unstable energy is re-emitted at a lower, longer wavelength, the seed emits a **red/far-red fluorescence glow**. High-sensitivity **optical sensors or cameras accompanied by special bandpass optical filters** capture only this specific wavelength while blocking out the ambient or background light.
- 4. Signal Processing & Classification:** The detected optical brightness is sent to an **industrial computer (master control system)**, converting the signal into precise numerical data. The system compares the numerical intensity against a **predefined threshold value**. Higher fluorescence usually indicates an immature seed containing too much residual chlorophyll.
- 5. Mechanical Separation:** Depending on the reading, the computer triggers a precise **pneumatic air compressed blast/ejector** or blower nozzle. It shoots an air stream to deflect rejected seeds into one fraction bin, while allowing accepted prime seeds to fall naturally into a separate high-quality fraction bin.

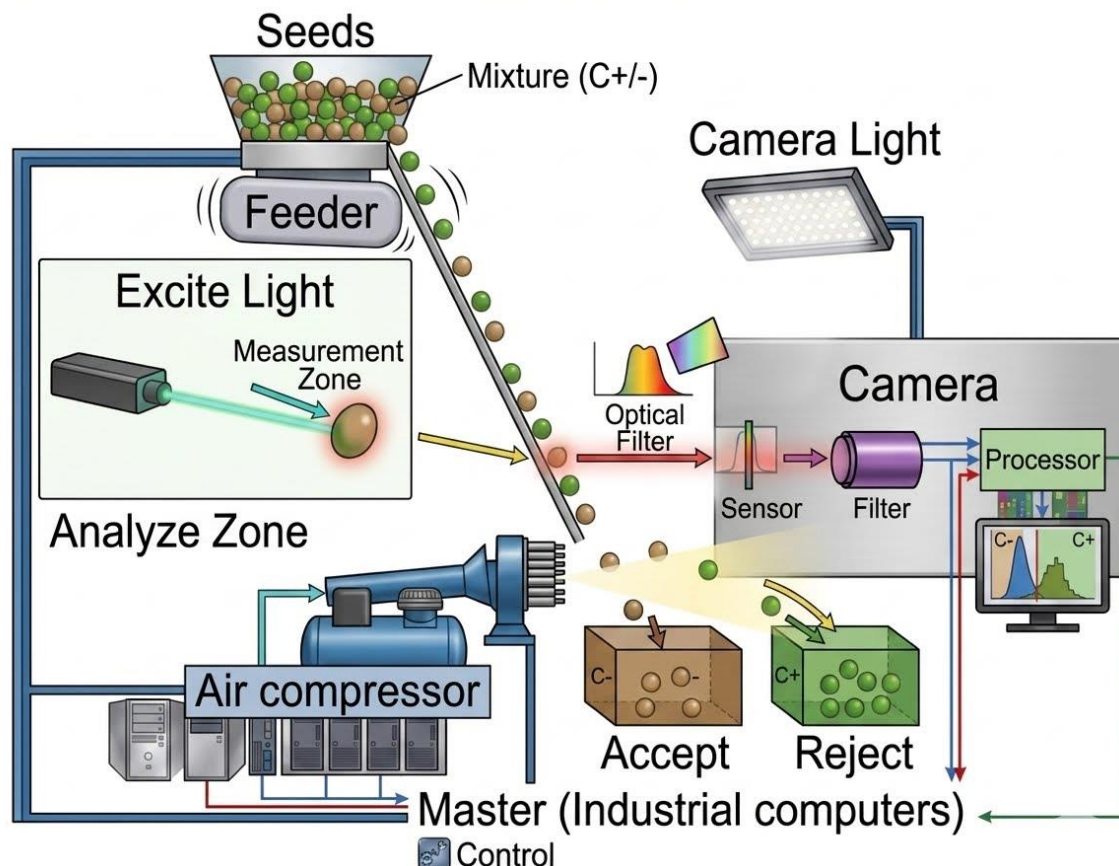


Fig. Schematic Layout of an Automated Chlorophyll Fluorescence Seed Sorting Machine

Evidence from Seed Research

The potential of chlorophyll fluorescence sorting has been demonstrated in several crops. In Brassica oleracea, Jalink et al. (1998) reported that seeds with lower fluorescence generally showed better germination and normal seedling development, indicating the potential for removing high-fluorescence seeds to improve the quality of the remaining fraction. Further studies demonstrated its application to deteriorated cabbage seed lots, suggesting that fluorescence sorting could also be useful for upgrading stored seed (Dell'Aquila et al., 2002). In soybean, Cicero et al. (2009) showed that fluorescence could effectively identify green seeds associated with incomplete chlorophyll degradation, allowing

high-fluorescence seeds to be separated from the lot. In pepper, Kenanoglu et al. (2013) reported improvements in germination, emergence and seedling vigour following fluorescence sorting, particularly in seed lots produced from less mature fruits. Together, these studies demonstrate that chlorophyll fluorescence sorting can be particularly valuable where residual chlorophyll is closely associated with seed maturity and physiological performance.

Why is Fluorescence Sorting Important?

The importance of chlorophyll fluorescence sorting lies in its potential to upgrade seed lots by identifying differences among individual seeds. A seed lot is rarely completely uniform; seeds can vary in maturity, physiological age, vigour and storage history, while conventional testing generally provides an overall estimate of the lot. Fluorescence sorting offers the possibility of detecting and separating individual seeds based on their optical characteristics, which may be particularly valuable for high-value vegetable seeds, hybrid seed production and crops where uniform emergence is essential. By moving from lot-level assessment towards individual-seed characterisation and classification, the technology represents an important step towards precision seed processing.

Advantages of Chlorophyll Fluorescence Sorting

1. Non-destructive: Seeds remain intact during measurement.
2. Rapid: Fluorescence can be measured within a very short period, making high-throughput screening possible.
3. Individual-seed assessment: Individual seeds can be classified rather than relying only on a lot average.
4. Objective measurement: Fluorescence provides a quantitative signal rather than depending on visual colour assessment.
5. Maturity-related information: Residual chlorophyll provides useful information about seed developmental status.
6. Potential for seed-lot upgrading: Poorer or immature fractions can potentially be removed from a seed lot.
7. Automation: Optical detection can be integrated with mechanical seed sorting.
8. Compatibility with other technologies: Fluorescence can be combined with imaging and spectroscopic methods for more comprehensive seed assessment.
9. The combination of speed, sensitivity and non-destructive measurement was one of the major attractions of the original fluorescence sorting concept (Jalink et al., 1998).

Limitations and Challenges

Despite its potential, chlorophyll fluorescence sorting has several limitations.

1. Indirect quality indicator: Fluorescence mainly reflects residual chlorophyll and maturity; it does not directly measure germination or viability.
2. Crop-specific response: The relationship between fluorescence and seed quality may vary among crops and genotypes.
3. Need for calibration: Fluorescence thresholds must be established using germination, vigour and field-emergence data.
4. Not all poor seeds are high-fluorescence seeds: Seeds may lose quality because of ageing, mechanical injury, pathogens or other factors that are not necessarily reflected by chlorophyll fluorescence.
5. Equipment requirements: Sensitive optical detectors and automated sorting systems require specialised equipment.
6. Cost: Commercial-scale systems may involve considerable initial investment.
7. Need for standardisation: Measurement conditions and fluorescence thresholds must be standardised for reliable application.

Therefore, CF sorting should currently be considered a complementary seed-quality technology rather than a replacement for conventional seed testing.

The Future: From Fluorescence Sorting to Intelligent Seed Sorting

The future of chlorophyll fluorescence sorting lies in its integration with advanced technologies such as machine vision, hyperspectral imaging, X-ray imaging, robotics and artificial intelligence. While fluorescence provides information related mainly to residual chlorophyll and seed maturity, combining it with characteristics such as seed size, shape, colour, internal structure and chemical composition could provide a more comprehensive assessment of individual seeds. Artificial intelligence could integrate these multiple signals to predict seed quality and classify seeds according to their potential performance. Such systems could transform conventional seed processing into individual-seed precision phenotyping, moving from simple physical grading towards intelligent, quality-based seed sorting.

Research Priorities

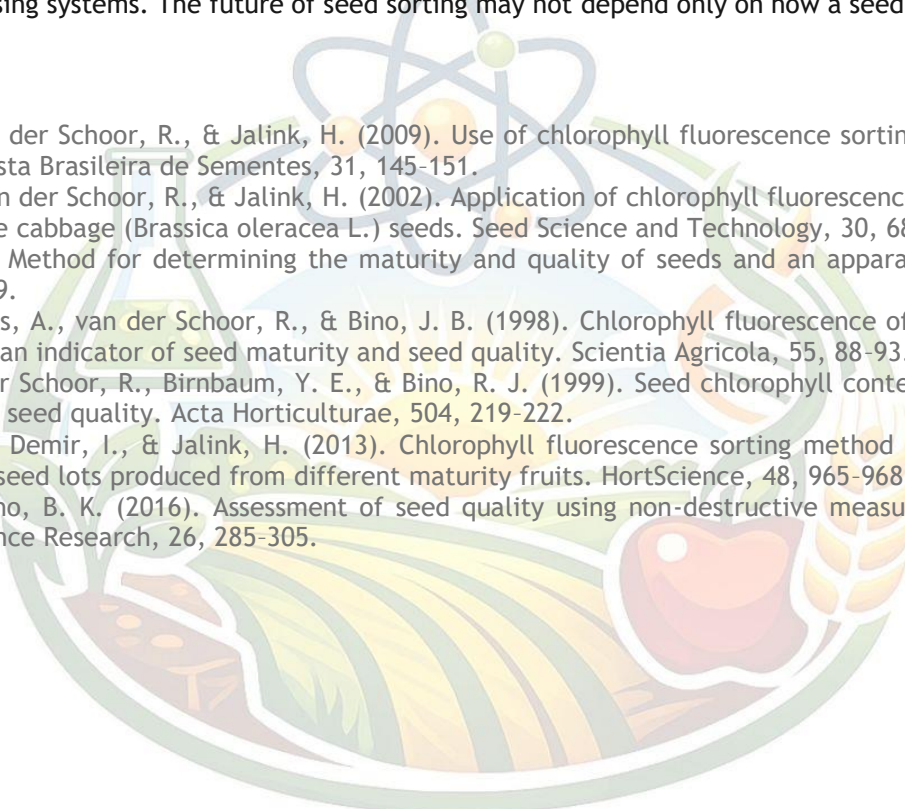
Before large-scale adoption, crop- and genotype-specific fluorescence thresholds need to be established and validated against germination, vigour and field-emergence performance. Further research is also required to understand the influence of seed development, environmental conditions and storage on fluorescence-quality relationships. In addition, the economic feasibility and standardisation of measurement procedures across instruments and laboratories will be essential for reliable commercial application.

Conclusion

Chlorophyll fluorescence sorting is a promising advancement in modern Seed Science and Technology, offering a rapid and non-destructive approach for identifying seed fractions based on residual chlorophyll and maturity. Studies in cabbage, soybean and pepper have demonstrated its potential to improve selected seed fractions (Jalink et al., 1998; Cicero et al., 2009; Kenanoglu et al., 2013). However, its effectiveness varies with crop, genotype and seed-lot characteristics, and it should complement rather than replace conventional seed-quality tests. With integration of imaging, spectroscopy, robotics and artificial intelligence, fluorescence sorting could contribute to a new generation of precision seed-processing systems. The future of seed sorting may not depend only on how a seed looks, but on what its light reveals.

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Seed Priming: A Sustainable Seed Enhancement Technology for Improved Germination and Crop Establishment

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Abstract

Rapid, uniform and successful crop establishment is a major determinant of crop productivity, particularly under conditions of environmental stress. Seed priming is a physiological seed enhancement technique in which seeds are partially hydrated under controlled conditions to initiate pre-germinative metabolic processes without allowing radicle protrusion. Different approaches, including hydropriming, osmopriming, halopriming, hormonal priming, biopriming and nanopriming, have been developed to improve germination performance and seedling vigour. Priming can accelerate germination, improve germination uniformity, enhance seedling growth and activate mechanisms associated with tolerance to drought, salinity, temperature extremes and other stresses. At the cellular level, these benefits are associated with improved membrane repair, activation of hydrolytic enzymes, mobilisation of stored reserves, regulation of reactive oxygen species, enhancement of antioxidant defence and modulation of hormonal and molecular signalling. Biopriming additionally exploits beneficial microorganisms to improve plant growth and stress resilience. Despite its potential, variability in treatment conditions, crop and cultivar specificity, difficulties in maintaining the benefits during storage and limited standardisation remain important constraints. Future research should focus on developing crop-specific protocols, understanding priming-induced molecular memory and integrating seed priming with precision seed treatment and climate-resilient crop production systems.

Keywords: seed priming, seed enhancement, seed vigour, germination, biopriming, antioxidant defence, crop establishment, abiotic stress.

Introduction

Successful crop production begins with successful seed establishment. Although seed is often considered merely the starting material for crop production, its physiological quality determines how effectively a crop can establish under field conditions. Germination percentage is an important measure of seed quality; however, seeds with similar germination percentages may differ considerably in their rate of germination, uniformity of emergence and ability to withstand environmental stress. These characteristics are collectively associated with seed vigour.

Seed vigour is particularly important during the early stages of crop establishment because the germinating seedling must rapidly transition from dependence on stored reserves to active growth and resource acquisition. Delayed or non-uniform emergence can result in uneven crop stands, increased competition among plants and reduced resource-use efficiency. The problem becomes more pronounced under suboptimal conditions such as drought, salinity, low or high temperature and fluctuating soil moisture.

Seed priming has emerged as one of the important approaches for improving seed performance. It provides a physiological “head start” to the seed by initiating several metabolic processes before sowing while preventing completion of germination. Recent reviews describe seed priming as a relatively low-cost and environmentally favourable approach for improving germination, seed vigour and tolerance to biotic and abiotic stresses.

What is Seed Priming?

Seed priming is a controlled pre-sowing treatment in which seeds are exposed to a suitable hydration environment for a defined period. The treatment allows water uptake and activation of early germination-associated metabolic events but is terminated before visible radicle emergence.

During normal germination, dry seeds first undergo imbibition, followed by activation of metabolism, repair of cellular structures, synthesis and activation of enzymes, mobilisation of stored reserves and eventually radicle protrusion. Priming essentially allows several of these preparatory processes to occur before the seed is placed in the field (Jatana et al., 2024).

After the priming treatment, seeds are generally brought back to an appropriate moisture content before handling or sowing. Consequently, when the primed seed encounters favourable conditions again, it can proceed more rapidly towards germination (Ntshalintshali et al., 2025). This physiological advantage is particularly valuable when the interval between sowing and emergence is critical.

Different Approaches to Seed Priming

Seed priming is not a single technique. Different priming approaches have been developed according to the crop, seed characteristics, environmental conditions and intended application.

Hydropriming: The concept of hydropriming was reported by Bodsworth and Bewley (1981). Hydropriming is the simplest form of seed priming and involves controlled hydration of seeds using water. Since it does not require specialised chemicals, it is relatively inexpensive and environmentally friendly. Its effectiveness depends on hydration duration, temperature, seed-to-water ratio and initial seed quality. Excessive hydration may result in radicle protrusion or deterioration, whereas insufficient hydration may not adequately activate the desired physiological processes. Therefore, treatment conditions require careful optimisation (Bodsworth & Bewley, 1981; Diya et al., 2024).

Osmopriming: The concept of osmopriming was introduced by Heydecker et al. (1973). Osmopriming involves hydration of seeds using solutions with controlled osmotic potential. Polyethylene glycol (PEG) and selected salt solutions can regulate water uptake and prevent premature radicle emergence. By controlling the rate and extent of hydration, osmopriming allows pre-germinative metabolic processes to proceed under controlled conditions (Heydecker et al., 1973; Bradford, 1986).

Halopriming: The use of osmotic salts for seed conditioning was described by Bradford (1986). Halopriming involves the use of inorganic salts as priming agents. Salts such as potassium nitrate (KNO_3), potassium chloride (KCl) and calcium chloride ($CaCl_2$) can influence germination and subsequent seedling performance. However, the concentration and duration of treatment are critical, as excessive salt exposure may impose osmotic or ionic stress and adversely affect seed quality (Bradford, 1986; Jatana et al., 2024).

Hormopriming: The concept of physiological seed conditioning using plant growth regulators was discussed by Khan (1992). Hormopriming involves the use of plant growth regulators or signalling molecules to influence germination and early seedling development. Hormones such as gibberellins, abscisic acid, auxins and cytokinins regulate dormancy, germination and seedling growth. Hormopriming can modulate these hormonal pathways and consequently influence germination behaviour and early plant development (Khan, 1992; Diya et al., 2024).

Biopriming: The concept of biological seed priming was demonstrated by Callan et al. (1990). Biopriming involves the association of beneficial microorganisms with seeds during the priming process. Microorganisms such as *Bacillus*, *Pseudomonas* and *Trichoderma* have been investigated for their ability to promote plant growth, improve nutrient availability, suppress pathogens and enhance tolerance to environmental stresses. Recent studies have particularly highlighted the potential of biopriming in legume crops for improving germination, seedling growth and stress resilience (Callan et al., 1990; Diya et al., 2024; Ntshalintshali et al., 2025). Biopriming therefore represents an important interface between seed technology and beneficial microbial biotechnology.

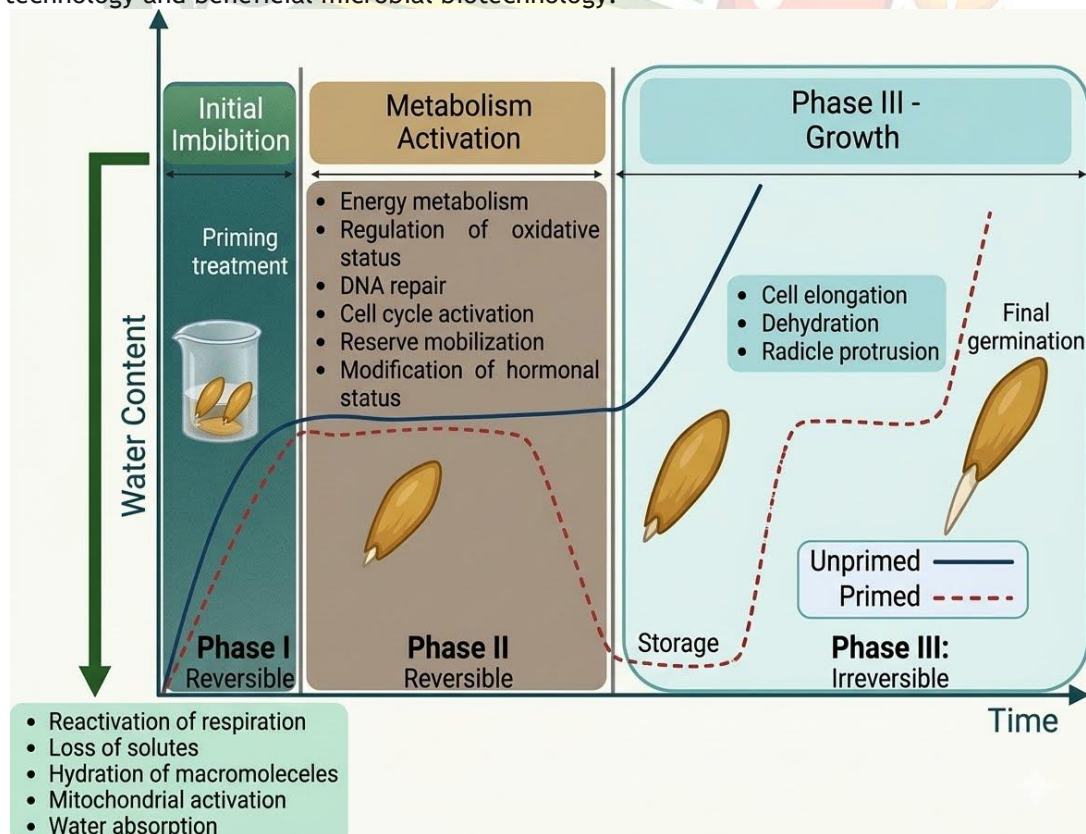


Fig. Triphasic Water Uptake and Physiological Dynamics During Seed Priming

What Happens Inside a Primed Seed?

The visible effect of priming- faster germination is only the final outcome of a series of physiological and biochemical changes.

1. Activation of metabolism: Dry seeds have very low metabolic activity. Once water enters the seed, cellular metabolism begins to increase. Priming allows this activation to progress without completing germination. Enzymes involved in carbohydrate and protein metabolism become active, providing the energy and building blocks required for subsequent seedling growth.

2. Mobilisation of stored reserves: Seeds contain carbohydrates, proteins and lipids that provide energy and nutrients to the developing embryo. During priming, the machinery responsible for mobilisation of these reserves can become activated. Faster mobilisation following sowing can contribute to more rapid radicle and shoot development.

3. Membrane repair: Membranes are particularly vulnerable during seed ageing and rehydration. Controlled hydration during priming facilitates repair of membrane structures and restoration of cellular organisation. Improved membrane integrity can reduce leakage of cellular solutes and contribute to better physiological performance.

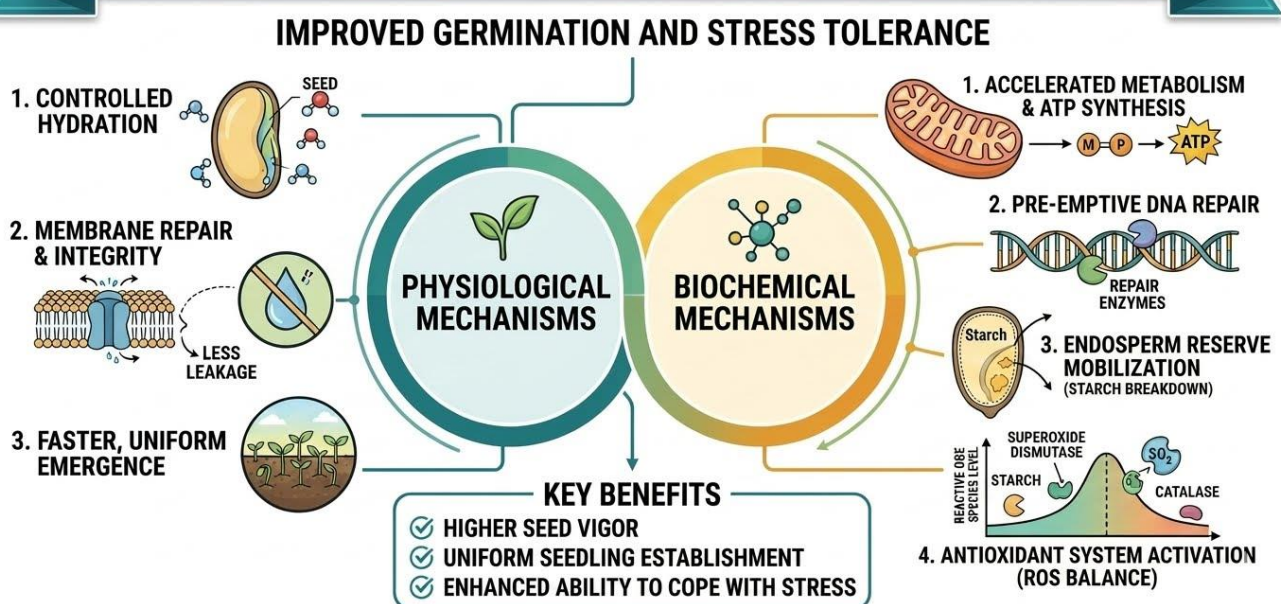
4. Antioxidant defence: Reactive oxygen species (ROS) are naturally generated during seed imbibition and germination. At appropriate levels, ROS can act as signalling molecules; however, excessive accumulation can cause oxidative damage. Priming can enhance antioxidant systems involving enzymes such as superoxide dismutase, catalase and peroxidases. This helps maintain an appropriate balance between ROS production and detoxification.

Recent reviews identify antioxidant regulation as one of the important mechanisms through which priming contributes to stress tolerance.

5. Cellular and molecular repair: Seed deterioration is associated with damage to cellular structures, proteins, membranes and nucleic acids. Priming can stimulate repair-related processes before the seed is exposed to the stresses associated with germination and field establishment.

This is one reason priming is increasingly being investigated not simply as a method for increasing germination percentage, but as a technology for improving the physiological readiness of the seed.

PHYSIOLOGICAL AND BIOCHEMICAL MECHANISMS OF SEED PRIMING



Seed Priming and Stress Tolerance

Agricultural crops increasingly face drought, salinity, temperature extremes and irregular rainfall, which can impair germination and seedling establishment. Seed priming can improve seed performance under such conditions by enhancing antioxidant defence, osmotic adjustment, membrane stability and water relations. However, the magnitude of these benefits may vary with crop, genotype and environment, and results obtained under controlled conditions may not always translate directly to the field (Ntshalintshali et al., 2025).

The Emerging Role of Biopriming

Biopriming combines seed enhancement with beneficial microorganisms. Plant growth-promoting rhizobacteria (PGPR) can produce growth-promoting substances such as indole-3-acetic acid, produce siderophores, solubilise nutrients, stimulate root development and enhance plant defence. Thus, biopriming can establish a beneficial plant-microbe association from the early stages of crop development. However, its effectiveness depends on microbial strain, inoculum density, host genotype and environmental conditions, making strain- and crop-specific optimisation essential.

Priming and Seed Ageing

A major challenge in seed priming is storability. Although priming can improve germination and seedling vigour, activation of metabolism during hydration and subsequent drying may influence seed longevity. Therefore, priming protocols must be evaluated not only for immediate performance but also for their effects on post-treatment storage. The benefits of priming should ideally remain stable until the treated seed reaches the farmer.

Need for Standardisation

There is no universal priming protocol applicable to all crops and varieties. Treatment efficiency depends on seed quality, genotype, seed size, hydration temperature and duration, priming agent and concentration, drying conditions and storage environment. Therefore, crop- and cultivar-specific protocols are essential for obtaining consistent and reproducible results.

From Laboratory to Farmers' Fields

The practical value of seed priming depends on its successful translation from laboratory research to field conditions. For farmers, the technology should be simple, affordable, reproducible and compatible with existing sowing practices. Commercial adoption will also require appropriate seed-coating systems, quality assurance and adequate storage stability. Field validation under diverse agro-environments is therefore essential before large-scale recommendation.

Future Prospects

Future research is moving towards mechanism-based and precision seed enhancement, including studies on molecular signalling, antioxidant regulation, metabolic reprogramming and stress memory. Emerging technologies such as nanopriming, microbial consortia, precision seed coating, advanced seed phenotyping and molecular diagnostics may further improve seed performance. However, their biological effectiveness must be balanced with economic feasibility, environmental safety, scalability and storability.

Conclusion

Seed priming provides an important link between seed physiology and sustainable crop production. By initiating key metabolic processes before sowing, it can improve germination, seedling vigour and stress tolerance. Hydropriming offers simplicity, while osmopriming, halopriming and biopriming provide additional opportunities for targeted seed enhancement. However, successful adoption requires crop-specific optimisation, adequate storage stability and field validation. The future of seed enhancement lies not simply in developing more treatments, but in developing reliable, economical and field-ready technologies that give every seed a better start.

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Role of Melatonin Seed Treatment in Mitigating Abiotic Stress

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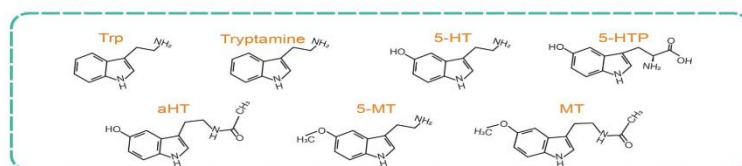
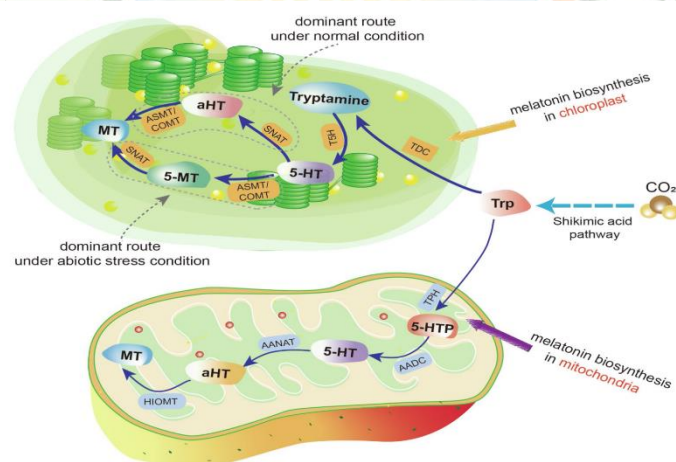
Abstract

Seed quality and seedling establishment are highly vulnerable to adverse environmental conditions such as drought, salinity, heat, and cold stress. Melatonin (N-acetyl-5-methoxytryptamine), a naturally occurring indoleamine, has recently been recognized as a multifunctional molecule in plants, regulating growth, development, and stress responses. Exogenous melatonin application, particularly as seed treatment, has emerged as a promising strategy to mitigate abiotic stress effects during seed germination and early seedling growth. Melatonin enhances antioxidant defense systems, stabilizes membranes, improves osmotic adjustment, and regulates gene expression related to stress tolerance. Studies across cereals, legumes, and horticultural crops reveal that melatonin-primed seeds show improved germination rate, seedling vigour, and resilience under unfavorable environments. This article reviews the mechanisms by which melatonin alleviates abiotic stress in seeds, highlights its regulatory pathways, and discusses its potential applications in seed technology and sustainable agriculture.

Keywords: Melatonin, Seed treatment, Abiotic stress, Germination, Antioxidant defense.

Introduction

Seed germination and early seedling establishment are critical phases in the plant life cycle. However, these stages are highly sensitive to abiotic stresses such as drought, salinity, high and low temperatures, and heavy metals. Stress conditions often lead to reduced seed germination, poor vigour, and lower crop establishment, ultimately affecting productivity (Hussain et al., 2019).



Melatonin, a low-molecular-weight indoleamine, was first discovered in animals but later identified in plants, where it functions as a growth regulator and stress modulator (Arnao & Hernández-Ruiz, 2014). Unlike conventional plant hormones, melatonin exhibits pleiotropic roles, including regulation of circadian rhythms, antioxidant defense, and signaling pathways involved in stress tolerance. Seed priming or coating with melatonin has recently gained attention as an eco-friendly approach to enhance seed quality and improve crop resilience under stress.

Chemistry and Biosynthesis of Melatonin in Plants

Melatonin (C₁₃H₁₆N₂O₂) is synthesized from tryptophan through a multi-step pathway involving tryptophan decarboxylase, tryptamine 5-hydroxylase, serotonin N-acetyltransferase, and hydroxyindole-O-methyltransferase (Back et al., 2016). It shares biosynthetic intermediates with auxin (indole-3-acetic acid), indicating potential cross-talk between melatonin and auxin-mediated pathways.

Mechanisms of Melatonin Action in Seeds under Abiotic Stress

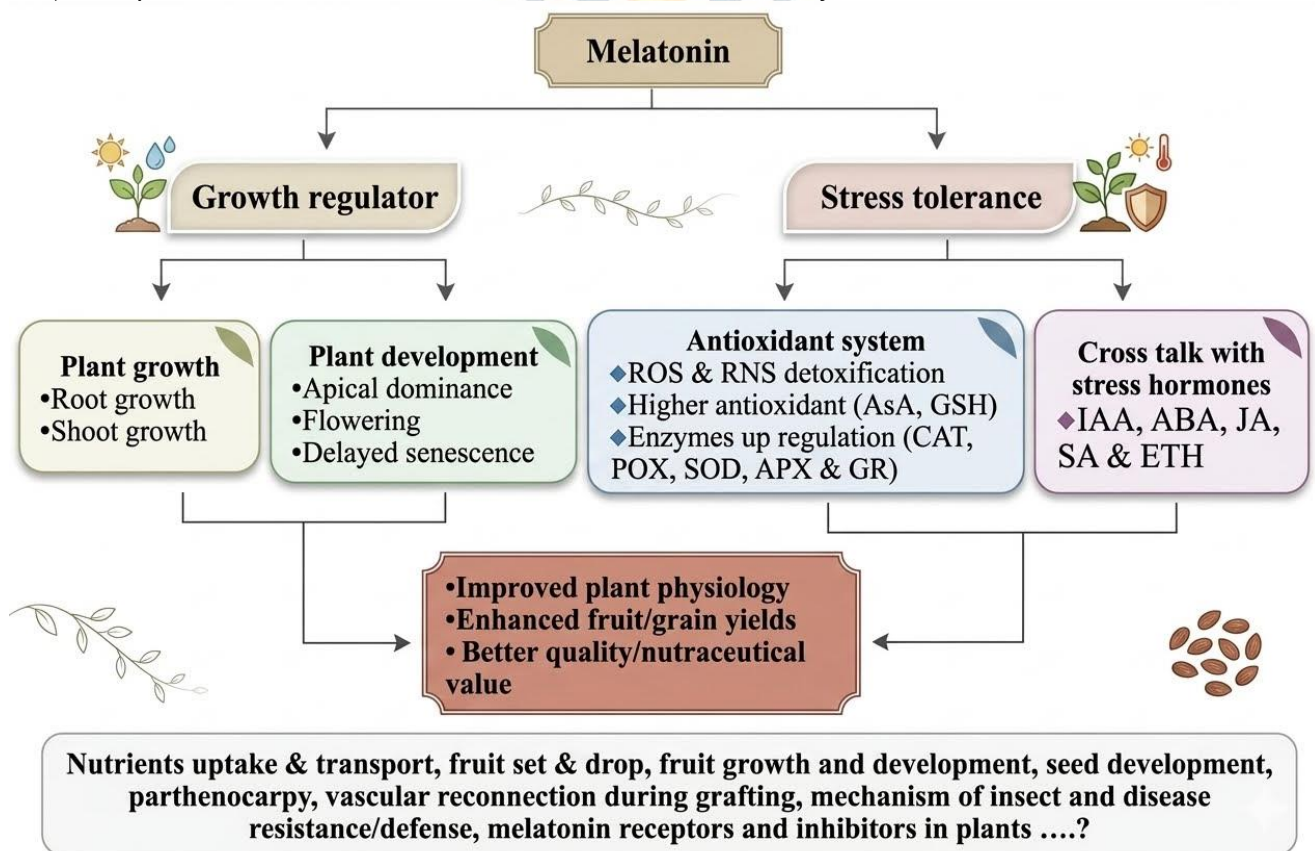
1. Antioxidant Defense and ROS Scavenging: Abiotic stresses generate excessive reactive oxygen species (ROS), leading to oxidative damage of lipids, proteins, and nucleic acids. Melatonin directly scavenges ROS and upregulates antioxidant enzymes such as superoxide dismutase (SOD), catalase (CAT), and peroxidases (POD) (Tan et al., 2012). This dual action protects seed membranes and enhances germination under stress.

2. Membrane Stabilization: Melatonin maintains membrane integrity by reducing lipid peroxidation and electrolyte leakage (Zhang et al., 2014). Seeds treated with melatonin exhibit lower malondialdehyde (MDA) content, a marker of oxidative stress.

3. Osmotic Adjustment and Water Relations: Under drought and salinity, melatonin-treated seeds accumulate higher levels of osmolytes such as proline, glycine betaine, and soluble sugars, helping to maintain water balance and cell turgor (Liang et al., 2019).

4. Hormonal Crosstalk: Melatonin interacts with abscisic acid (ABA), gibberellins (GA), and auxin during seed germination. It reduces ABA accumulation, thereby releasing seed dormancy, while promoting GA biosynthesis to enhance germination (Wei et al., 2015).

5. Gene Expression and Stress Signaling: Melatonin modulates the expression of stress-related genes, including heat shock proteins (HSPs), dehydration-responsive element-binding (DREB) factors, and antioxidant-related genes (Meng et al., 2014). This primes seeds to tolerate harsh conditions more efficiently.



Physiological Roles of Melatonin in Higher Plants

Evidence of Melatonin's Role in Mitigating Specific Abiotic Stresses

Drought Stress: Melatonin seed priming has been shown to improve germination and seedling vigour in wheat and maize under water-deficit conditions by enhancing antioxidant activity and osmotic balance (Hussain et al., 2021).

Salinity Stress: In rice and cucumber, melatonin-treated seeds exhibited higher germination rates and improved Na^+/K^+ homeostasis under saline conditions (Li et al., 2017).

Temperature Stress: Melatonin priming alleviates chilling injury in cucumber and tomato seeds by enhancing antioxidant enzyme activities and heat shock protein expression (Zhao et al., 2019). It also confers tolerance to high-temperature stress by modulating ROS levels.

Heavy Metal Stress: Seed treatment with melatonin reduces cadmium and aluminum toxicity by enhancing phytochelatin synthesis and metal chelation, thereby improving germination and seedling growth (Arnao & Hernández-Ruiz, 2019).

Application in Seed Technology

- 1. Seed Priming:** Soaking seeds in melatonin solution for a defined period improves germination uniformity and stress tolerance.
- 2. Seed Coating:** Melatonin can be incorporated into seed coats or polymer-based coatings for slow release during imbibition.
- 3. Integration with Other Treatments:** Combining melatonin with PGPR or osmopriming may further enhance seedling resilience under multiple stresses.
- 4. Potential Marker for Seed Vigour:** Melatonin content in seeds could serve as a biochemical marker for vigour and storability.

Future Perspectives

Despite promising results, melatonin seed treatment research is still in its infancy. Standardization of treatment concentrations, soaking duration, and crop-specific protocols are needed. Further studies on melatonin transporters, receptors, and signaling pathways will help in optimizing its application. Genomic and transcriptomic analyses could reveal natural variation in melatonin biosynthesis among crop species, offering new breeding targets for stress-resilient seeds.

Conclusion

Melatonin is emerging as a versatile regulator of plant stress physiology. Its application as a seed treatment offers an efficient, eco-friendly strategy to enhance seed germination, vigour, and tolerance to abiotic stress. By strengthening antioxidant defenses, stabilizing membranes, and modulating gene expression, melatonin ensures better crop establishment under adverse conditions. Integration of melatonin-based seed treatments into seed technology and crop management practices holds significant potential for sustainable agriculture in the face of climate change.

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ABB Bananas: A Hidden Treasure for Climate-Resilient and Nutritious Banana Production

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Introduction

Banana (*Musa* sp.) is an economically important fruit grown in several tropical countries with a high demand in global markets. In 2021, approximately 100 million tons of bananas were supplied from across over 130 tropical nations (FAO, 2021). Banana has a high nutritional value and numerous health benefits. It is rich in dietary fiber, potassium, antioxidants, vitamins B6 and C, and phytonutrients. Bananas are widely consumed fresh and processed to produce sun dried bananas, banana flour, banana starch, and various snacks (Rotchanapreeda et al., 2016). Edible banana cultivars are largely derived from interspecific hybridization involving the two wild progenitors, *Musa acuminata* (A genome) and *Musa balbisiana* (B genome), resulting in diverse genomic groups such as AAA, AAB and ABB, as well as less common polyploid forms. The triploids (AAA and AAB cultivars) are cultivated globally and play a significant role in the global economy (Ploetz, 2015). The ABB cultivar originated in South-East Asia and India and is divided into nine subgroups: Bluggoe, Monthan, Ney Mannan, Pisang Awak, Peyan, Pelipita, Saba, Kalapua, and Kloe Teparod (Cenci et al, 2021).

Origin and Genomic Constitution of ABB Bananas

It is commonly accepted that triploids have been generated by spontaneous hybridizations of edible AA or AB plants with various sources of the additional A or B genome (other edible AA or *M. acuminata*, and *M. balbisiana*). However, the studies cited above point up the genomic complexity of allotriploid cultivars, suggesting the occurrence of backcrosses with parental species through residual fertility in some allotriploid cultivars (De Langhe et al., 2010).

Among the allotriploids, the ABB genomic group comprises starchy bananas that are used for cooking, dessert and beer production (Karamura et al., 1998). They are reported as being resistant to weevils, nematodes and black leaf streak (Karamura et al., 1998) and tolerant of drought (Thomas et al., 1998; De Langhe, 2002; Vanhove et al., 2012; Ravi et al., 2013; Kissel et al., 2015; van Wesemael et al., 2019). They originate from two regions: India and surrounding regions, and South-East Asia (De Langhe et al., 2009; Perrier et al., 2011).

Table 1. Geographic distribution of the principal ABB banana cultivars

Sub-group	Cultivar	Type of fruit	Distribution
Pisang Awak	Pisang Awak, Fougamou, Bom, Pisang Kepok, Ducasse, Gia Hui, Muisa Tia, Kanthali, Chinia, Karpuravalli, Amrithapani, Octoman, Bankela, Ladisan	Dessert	Thailand, India, East Africa, Philippines
Bluggoe	Bluggoe, Matavia, Cacambou, Bararay, Burro, Bangrier, Bungan, Kanchikela, Sakkai, Chakkia, Gauria, Kapur, Nepali Chinia	Cooking	All continents (tropical and subtropical areas)
Pelipita	Pelipita	Cooking	Philippines, Latin America
Saba	Saba	Cooking	Philippines, Indonesia, Malaysia
Peyan	Peyan	Dessert/Cooking	India
Monthan	Monthan, Ashy Batheesa, Sambrani Monthan, Birbutia, Goukar, Chetty, Peykunnan, Karibale	Cooking	India, particularly southern India
Ney Mannan	Ney Mannan, Blue Java, Ice Cream	Dessert/Cooking	India and Southeast Asia; also cultivated in other tropical regions
Kalapua	Kalapua, Kalapua Large, Dwarf Kalapua	Cooking	Papua New Guinea and the Pacific region
Kloe Teparod	Kloe Teparod, Kluai Tiparot, Balonkawe	Dessert/Cooking	Thailand and the Philippines

Morphological Description and Fruit Characteristics of ABB Bananas

ABB bananas are generally vigorous, robust and medium to tall growing plants, although considerable variation in plant stature occurs among subgroups and cultivars. The pseudostem is commonly medium green to green and waxy, with variable pigmentation, and plants often develop a relatively stout pseudostem and strong suckering ability. Morphological characterization of South Indian banana cultivars has indicated that ABB cultivars are commonly distinguished by a medium-green, waxy pseudostem, closed petiolar canal with overlapping or inward curved margins, colourless petiolar margins and an auriculate rounded leaf base. Male flowers commonly show pinkish pigmentation. The inflorescence characters are also variable among ABB cultivars; the rachis may be vertically hanging, and in Monthan, the banana descriptor system records a distinctive small bunch of neutral or hermaphrodite flowers immediately above the male bud.

The fruit component traits of ABB bananas are highly variable, reflecting the diversity of their nine recognized subgroups. Fruits may range from relatively short to very long, and from straight to curved, with shapes including cylindrical, angular, plump or somewhat flattened forms. The fruit apex may be rounded, pointed or distinctly elongated. For example, Pisang Awak has been described as having straight fruits with a lengthily pointed apex, green peel when immature and yellow peel at maturity; fruits were reported at approximately 7-9 cm long with 10-14 fruits per hand in one morphological characterization. In contrast, Monthan produces relatively large, plump or stocky fruits, commonly about 18-20 cm long and 18-20 cm in girth, with thick peel and mealy pulp. The peel of ABB fruits is generally thick and may be green, waxy or ash coated at the immature stage, changing to yellow or ash yellow during ripening depending on the cultivar. The pulp is typically firm, mealy and starchy in cooking types, whereas dessert oriented ABB cultivars such as Karpuravalli and some Pisang Awak types may develop a softer, sweet and aromatic pulp at full ripeness. ABB bananas are consequently used for cooking, dessert consumption and, in some regions, processing into flour, chips and dried products. Cenci et al. (2021) describe ABB bananas broadly as starchy bananas used for cooking, dessert and beer production.

In terms of fruit quality components, ABB cultivars generally have appreciable dry matter and starch at the mature green stage, with starch progressively hydrolysed to soluble sugars during ripening. The balance between starch, soluble sugars, pulp firmness, peel thickness and pulp to peel ratio differs substantially among cultivars and determines their suitability for cooking or dessert use. Monthan, is particularly valued as a cooking banana because of its starchy, mealy pulp and thick peel, while Karpuravalli/Pisang Awak types are valued for their palatable, sweet pulp when ripe. Fruit number per hand and bunch, fruit length and girth, pedicel dimensions, peel thickness, pulp weight, pulp to peel ratio and flesh firmness are among the quantitative horticultural traits commonly used to characterize ABB cultivars.

Genomic Structure and Diversity of ABB Bananas

Molecular markers have shown that some ABB cultivars were erratically classified (Sardos et al., 2016; Christelová et al., 2017). Furthermore, the genomic composition of the Saba subgroup, coming from the Philippines, has been debated for years as some authors have suggested it consists of B genomes only (Valmayor et al., 1999).

The ABB genomic group comprises a morphologically diverse assemblage of cooking, dessert and beer bananas. Cenci et al. (2021) demonstrated extensive intergenomic recombination between the A and B subgenomes, with 34 of 36 ABB accessions showing at least one homologous exchange region. A normal ABB banana is expected to have approximately A:B = 1:2, whereas it was detected that regions where this expected ratio was altered because pieces of A and B genomes had exchanged/recombined. They described these as homologous exchanges (HEs). In 34 of 36 ABB genotypes, such A0:B3 or A2:B1 regions were detected. Bluggoe and Monthan were associated with HE pattern 1a (A0:B3 region in chr04 and chr11, A2:B1 region in chr09, additional A2:B1 region in chr04), whereas Peyan and Ney Mannan showed pattern 1b A0:B3 region in chr04 and chr11, A2:B1 region in chr09, lack of this additional A2:B1 region in chr04), supporting a common Indian origin for these four subgroups. Pisang Awak exhibited two distinct genomic patterns, suggesting at least two independent founding events. Pelipita and Klue Teparod showed exceptionally high B-genome contributions, with Pelipita characterized by extensive A-chromosome substitutions and Klue Teparod by several completely B-derived chromosomes. Saba accessions showed contrasting genomic patterns, indicating heterogeneous ancestry and arguing against a uniform BBB classification. Kalapua was recognized as an ABB subgroup but was not represented among the accessions analyzed in the study.

Bluggoe: Bluggoe is one of the most widely distributed ABB subgroups and is predominantly cultivated as a cooking banana. It includes cultivars such as Matavia, Cacambou, Bararay and Burro. Plants are generally vigorous, with stout pseudostems, and produce relatively large, firm and thick skinned fruits with starchy, mealy pulp. Bluggoe type bananas are cultivated widely throughout tropical and subtropical regions and are valued for cooking and processing.

Monthan: Monthan is an important cooking banana of India, particularly southern India. Plants are vigorous and robust, with relatively large bunches and thick, firm fruits. The fruits generally have a thick peel and starchy, mealy pulp and are mainly consumed after cooking. Monthan is also valued for its adaptability and suitability for different culinary preparations.

Ney Mannan: Ney Mannan is an ABB subgroup associated mainly with India and Southeast Asia. It includes cultivars such as Ney Vannan and related Blue Java or Ice Cream types. Depending on the cultivar, the fruits may be consumed as

dessert when fully ripe or used for cooking. Plants are generally vigorous, with medium to large bunches and relatively firm fruits.

Peyan: Peyan is predominantly associated with southern India and is mainly used as a cooking banana. It is characterized by vigorous plant growth and relatively firm, starchy fruits. The fruits are generally medium to large in size and are commonly consumed after cooking. Peyan is an important traditional banana type in parts of South India.

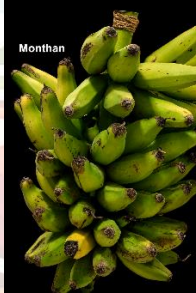
Pisang Awak: Pisang Awak is one of the most widely distributed ABB subgroups and occurs in Thailand, India, Southeast Asia, East Africa and the Philippines. It includes cultivars such as Fougamou, Bom, Pisang Kepok and Ducasse. Fruits are generally medium sized, with firm pulp when mature green and a sweet, aromatic pulp on ripening. Depending on the cultivar and stage of ripening, they are used both as dessert and cooking bananas. Pisang Awak types are also important in local food systems and smallholder production.

Pelipita: Pelipita is an important cooking banana, particularly associated with the Philippines and Latin America. Plants are generally vigorous and produce relatively large, firm fruits with thick peel and starchy pulp. The fruits are primarily cooked before consumption and are also suitable for processing. Pelipita has been particularly important in banana growing regions of Latin America as a cooking and staple food banana.

Saba: Saba is an important cooking banana subgroup widely cultivated in the Philippines, Indonesia and Malaysia. Plants are vigorous and produce large bunches with relatively thick-skinned, firm and starchy fruits. The fruits are generally consumed after cooking and are used in a variety of traditional dishes and processed products. Saba is particularly important as a staple cooking banana in the Philippines.

Kalapua: Kalapua is a traditional ABB subgroup associated mainly with Papua New Guinea and the Pacific region. It is primarily utilized as a cooking banana and forms part of the diverse traditional banana germplasm of the Pacific. Cultivars within this subgroup can vary considerably in plant stature, bunch characteristics and fruit morphology, reflecting the diversity of Pacific Musa germplasm.

Klue Teparod: Klue Teparod is associated mainly with Thailand and the Philippines and includes traditional cultivars such as Kluai Tiparot. It may be used both as a dessert and cooking banana, depending on cultivar and fruit maturity. Plants are generally vigorous, and fruits are characterized by firm pulp and distinctive fruit shape and flavour. Klue Teparod represents an important component of Southeast Asian banana diversity.

				
Karpooravalli (Pisang Awak sup group)	Peyan	Saba	Monthan	Blue Java (Ney Mannan sub group)
				
Pelipita	Kothia (Bluggoe subgroup)	Klue teparod	Kalapua	

Agronomic Adaptation and Stress Tolerance

ABB bananas are recognized as an important source of adaptation to drought and other abiotic stresses, with the greater contribution of the *Musa balbisiana* genome generally associated with enhanced stress tolerance compared with predominantly A-genome bananas. Ravi et al. (2013), based on field evaluation of banana germplasm at ICAR-NRCB and earlier observations, reported that ABB genotypes were generally more tolerant to drought than other genomic groups and identified traits such as relative water content (RWC), stomatal conductance, cell membrane stability, leaf emergence rate, delayed leaf senescence and bunch yield under soil-moisture deficit as useful indicators for drought screening. Their work also emphasized that bunch yield under drought stress is a particularly important criterion, as

physiological tolerance alone may not necessarily translate into productivity. Earlier field observations further indicated variation in drought response among ABB cultivars, with Pisang Awak and Bluggoe showing relatively good adaptation to water deficit, while Monthan displayed intermediate responses. Subsequent research have confirmed the importance of ABB germplasm as a source of drought adaptive traits and emphasized the need for systematic screening because drought tolerance is a complex, genotype and environment dependent trait. Thus, ABB bananas represent a valuable genetic resource for developing climate-resilient cultivars with improved water use efficiency, physiological stability and yield under moisture-limited conditions.

Nutritional and Biochemical Composition

ABB bananas, particularly cooking types, are nutritionally important because of their high carbohydrate and starch content, with substantial variation among cultivars and stages of fruit development. Studies on culinary ABB bananas such as 'Kachkal' and 'Cardaba' showed that starch is a major component of the developing fruit, while soluble sugars increase during ripening as starch is hydrolysed; potassium is generally the predominant mineral, accompanied by appreciable levels of other minerals. Green ABB fruits are also important sources of resistant starch, with Pelipita reported to have particularly high total starch content (up to 80.6% in the pulp) and cooking bananas generally showing high resistant-starch levels. In addition to carbohydrates, ABB fruits contain dietary fibre, protein, minerals, vitamin C, phenolic compounds and other antioxidant constituents, although their concentrations vary with genotype and ripening stage. In Cardaba, ripening was associated with increases in protein, fat, fibre, ash and vitamin C, while carbohydrate and tannin contents declined. Studies of ABB and other banana genotypes have also demonstrated considerable variation in phenolics, minerals and resistant starch, highlighting the potential of cooking bananas such as Pelipita and other ABB germplasm as sources of nutritionally valuable traits for food, functional food development and biofortification oriented breeding.

Food, Culinary and Processing Importance

ABB cooking bananas are important staple and food security crops in many tropical regions, where the mature green fruits are traditionally consumed after boiling, steaming, roasting or frying. Important ABB cooking cultivars such as Saba, Cardaba, Bluggoe, Fougamou and Pelipita are also used for processing into chips, flour, starch and other value added products. The high starch content of green ABB fruits makes them particularly suitable for flour and starch production, while their relatively firm pulp facilitates slicing and frying. Cardaba has been investigated as a raw material for flour, with flour from different maturity stages showing potential applications as binders, thickeners, emulsifiers, bakery ingredients and complementary food formulations. Resistant starch from ABB cultivars such as Bluggoe and Pisang Awak also provides potential for functional food applications. Processing of green cooking bananas into flour, chips and other shelf stable products can additionally reduce postharvest losses, extend product availability and enhance the economic value of ABB bananas. Recent work continues to explore green banana flour processing and starch modification for improved functional and nutritional properties, indicating further potential for ABB bananas in functional foods and value added product development.

Breeding Constraints and Opportunities

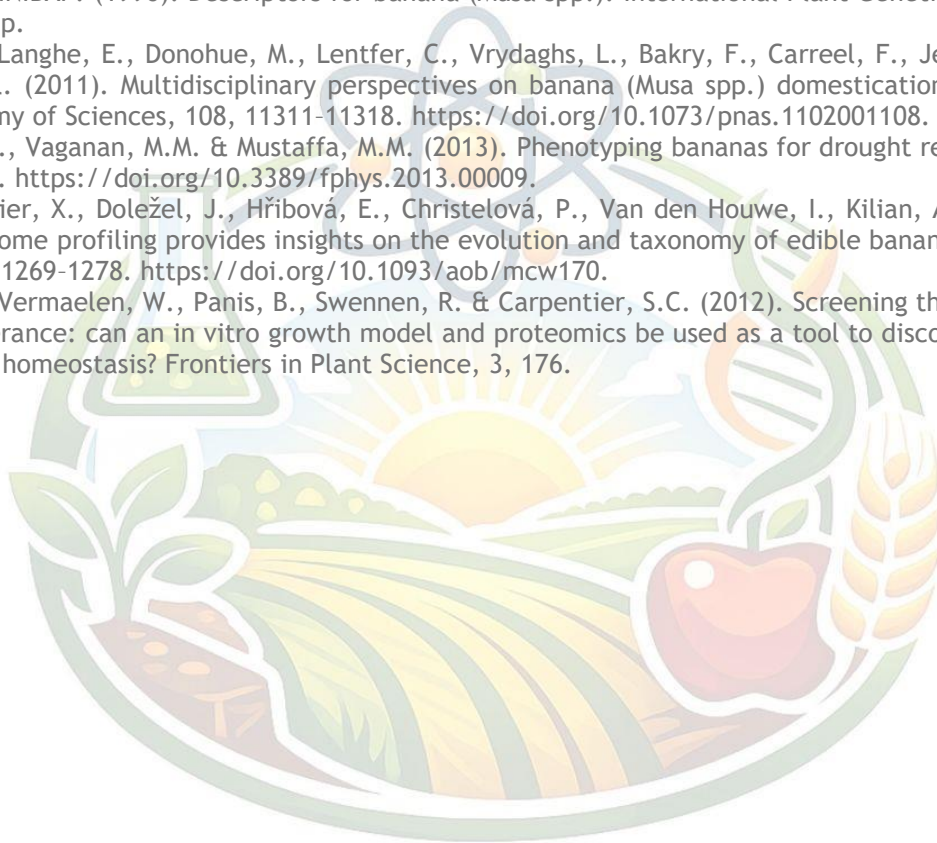
The utilization of ABB bananas in breeding is constrained by their triploid nature, low fertility, irregular meiosis and limited seed production, which restrict the efficiency of conventional crossing and selection. Banana breeding is further complicated by complex inheritance of quantitative traits and the frequent co-inheritance of undesirable plant or fruit characteristics with useful traits. Nevertheless, ABB germplasm provides valuable alleles for drought tolerance, stress adaptation, disease resistance and fruit quality improvement. The integration of conventional hybridization with molecular markers, genomics, marker assisted selection and other biotechnological approaches offers opportunities to efficiently exploit this genetic diversity and develop climate resilient banana cultivars.

Conclusion

ABB bananas represent a diverse and valuable group of cooking bananas, with considerable variation in plant characteristics, fruit quality, nutritional composition, culinary uses and adaptation to different environments. Their *Musa balbisiana* genome contributes useful traits such as drought adaptation, plant vigour and stress tolerance, making ABB germplasm particularly important in the face of climate change. At the same time, their triploid nature and low fertility present challenges for conventional breeding. Greater exploration and utilization of ABB genetic diversity, supported by modern molecular and genomic tools alongside conventional breeding, can help develop improved banana varieties with enhanced stress tolerance, productivity, nutritional value and consumer preferred fruit quality. Thus, conserving and effectively utilizing ABB germplasm is essential for the future sustainability, food security and resilience of banana production.

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Export Scenario of the Food Processing Products from India

Article ID: 74416

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Introduction

The food processing sector is one of the largest sectors in India in terms of production, growth, consumption, and export. India's food processing sector covers fruit and vegetables, spices, meat and poultry, milk and milk products, alcoholic beverages, fisheries, plantations, grain processing, and other consumer product groups like confectionery, chocolates and cocoa products, soya-based products, mineral water, high protein foods, etc.

Since liberalization in August 1991, proposals for projects have been proposed in various segments of the food and agro-processing industry. Besides this, Govt. has also approved proposals for joint ventures, foreign collaboration, industrial licenses and 100% export-oriented units envisaging an investment.

Table no -1 India's exports of Processed Food in 2024-25

Items	Rs. USD Millions
Miscellaneous Preparations	1476.71
Cereal Preparations	933.78
Processed Vegetables	897.07
Pulses	854.96
Groundnuts	794.99
Processed Fruits, Juices & Nuts	721.86
Guargum	568.97
Jaggery & Confectionary	406.92
Alcoholic Beverages	353.17
Cucumber and Gherkins (Prepd. & Presvd.)	306.72
Cocoa Products	295.55
Milled Products	192.2
Mango Pulp	80.4
Other Oil Cake/Solid Residues	3.32

Source: DGCIS

India's exports of Processed Food in 2024-25 were Rs. 7,886.62 USD Millions in 2024-25, which is as above.

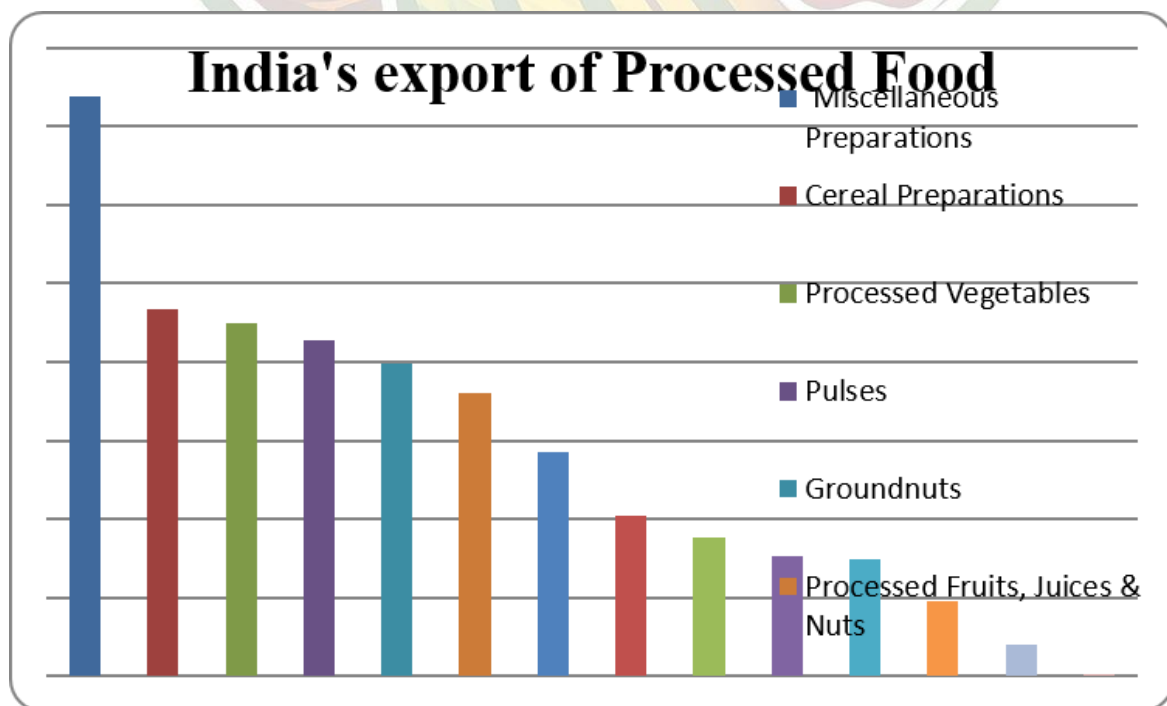




Table no-2 Major Export destination of different Processed Food for 2024-25:

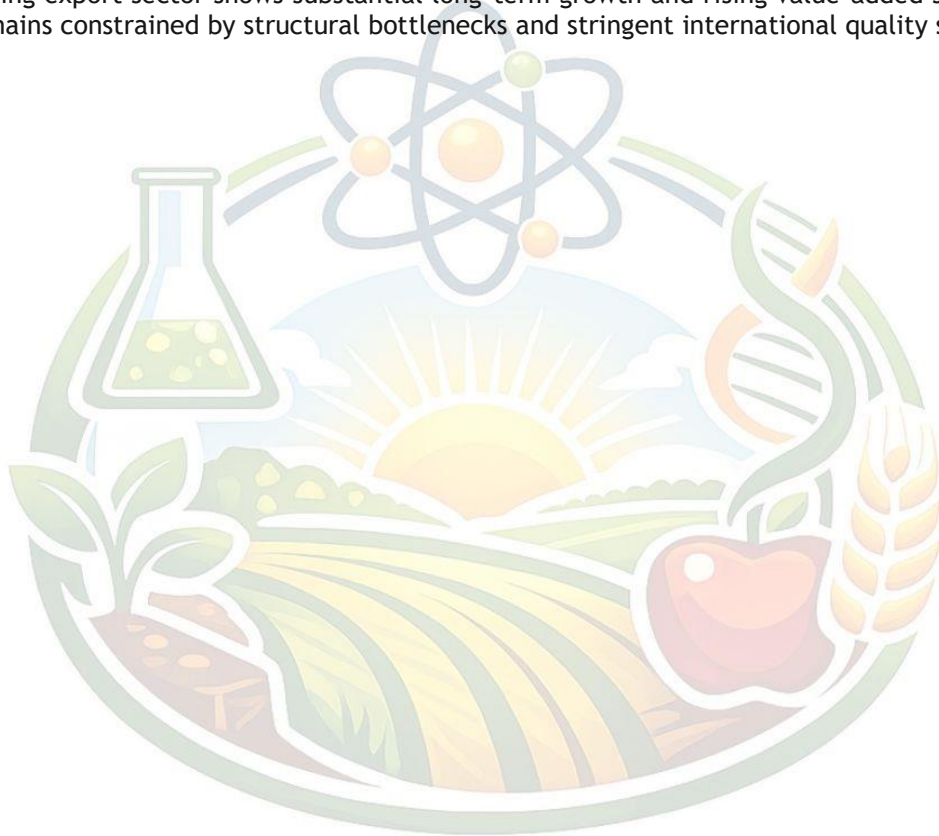
Sr no	Item	Rs. USD Millions	US \$	Major Export Destination for 2024-25
1	Cucumber And Gherkins (Pre. & Pres)	289594.37	306.72	U.S.A, Germany, France, Russia and Spain.
2	Processed Vegetables	614,979.19	897.13	U.S.A, U.K, Philippines, UAE and Indonesia
3	Mango Pulp	63,253.19	80.34	Saudi Arabia, USA, UK, Germany and Canada.
4	Processed Fruits, Juices & Nuts	503,300.22	721.93	U.S.A, Netherland, Saudi Arab, United Arab Emts and Russia.
5	Pulses	793,291.51	854.89	Bangladesh, China, UAE, U.S.A and Sri Lanka.
6	Ground Nuts	746,303.19	794.97	Indonesia, Vietnam, Philippines, Malaysia and Thailand.
7	Jaggery And Confectionery	471,057.29	406.84	Indonesia, USA, UAE, Nigeria and Nepal.
8	Guar Gum	453,612.57	568.96	U.S.A, Germany, Russia, Norway and China.
9	Cocoa Products	45,489.28	295.58	U.S.A, Netherland, UAE, Indonesia, and Nepal.

10	Cereal Preparations	594,596.64	933.75	U.S.A, United Arab Emts, U.K, Canada and Nepal.
11	Alcoholic And Non-Alcoholic Beverages	221,821.72	353.13	United Arab EMTs, Singapore, Tanzania, Netherland, and Ghana.
12	Milled Products	267,768.04	192.16	USA, United Arab Emts, U.K, Canada and Saudi Arab
13	Other Oil Cake/Solid Residues	15,163.63	3.34	Vietnam, Spain, Nepal, U.K and France
14	Miscellaneous Preparations	1,005,318.37	1,476.70	U.S.A, United Arab EMTs, Malaysia, U.K and Australia.

(Source: DGCIS)

Conclusion

India's food processing export sector shows substantial long-term growth and rising value-added shipments, but its full global potential remains constrained by structural bottlenecks and stringent international quality standards.



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Winged Bean - A Forgotten Crop with Remarkable Potential

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Introduction

With the growing global demand for food and improved nutrition, diversification of crop production and dietary sources has become increasingly important for achieving food and nutritional security. Among the many underutilized crops, winged bean (*Psophocarpus tetragonolobus* (L.) DC.) stands out for its remarkable nutritional and agricultural potential. It is a tropical legume traditionally cultivated in parts of Asia and other humid tropical regions (Alalade *et al.*, 2016), but its cultivation has largely remained limited to small-scale and backyard production. Despite receiving attention as a promising crop for the future, its potential has yet to be fully realized.

Winged bean is valued for its multiple edible parts, including green pods, immature and mature seeds, leaves and tuberous roots making it an exceptionally versatile crop. Its nutrient-rich seeds are particularly notable for their high protein content, while its ability to fix atmospheric nitrogen further adds to its importance in sustainable agriculture (Bassal *et al.*, 2020). With growing interest in nutritious foods, crop diversification and sustainable farming, winged bean offers an opportunity to transform an overlooked crop into a valuable source of food and nutrition.

A Multi-Purpose Crop

Winged bean is unique because it can provide different food products from a single crop. Young pods are used as a vegetable, while immature seeds are eaten for their pleasant, pea-like flavour. Mature seeds can be boiled or roasted and are also suitable for processing into flour and other food products. The crop also offers edible leaves, flowers and tuberous roots. Leaves may be consumed as a leafy vegetable, flowers can be used in salads or cooked and tubers can be boiled, steamed, baked or fried (Sambudi and Buckle, 1991). This wide range of uses gives winged bean an advantage over crops where only one or two plant parts are commonly utilized.

This ability to offer multiple food products from one crop makes winged bean truly versatile and gives it considerable potential for food diversification and household nutrition.

Nutritional Value

Winged bean is a nutrient-rich legume, particularly valued for its high protein content. Studies on different varieties have reported 33.4-39.7% protein, 16.5-20.6% fat, 10.8-12.9% fibre and 25.1-33.1% carbohydrates in the seeds on a dry-weight basis (Tanzi *et al.*, 2019). Its protein is also a valuable source of essential amino acids, while the seeds provide considerable energy, making winged bean a promising plant-based food for improving dietary quality.

The nutritional value extends beyond protein, with winged bean containing vitamins, minerals and bioactive compounds such as phenolics and flavonoids. Different plant parts also show nutritional variation, with tubers, leaves and flowers contributing additional nutrients to the diet. This combination of protein, fibre, energy and micronutrients makes winged bean a promising crop for dietary diversification and nutrition security, particularly where affordable plant-based protein sources are needed.

Multiple Uses

Winged bean offers a wide range of uses at different stages of growth. Tender pods are consumed as vegetables, while immature seeds have a pleasant, pea-like flavour and can be used in soups and other dishes. Mature seeds can be boiled or roasted and are also used to prepare flour. Leaves and flowers can be consumed as vegetables or incorporated into salads, while the tuberous roots can be boiled, steamed, baked or fried (Adegboyega *et al.*, 2019).

Its versatility also extends to food processing and product development. Research has explored winged bean for flour, snacks, sprouts, tofu, tempeh, bean milk, fermented foods and nutrient-enriched products. Seed and tuber flours have also been used to improve the nutritional quality of products such as cookies.



Fig 1. Different edible parts of winged bean

Benefits to Farmers

Winged bean can offer farmers an opportunity to diversify their production and obtain different food products from a single crop. Its green pods, immature seeds, tubers and mature seeds can be harvested for different purposes, while the crop has traditionally been grown on a small-scale in home gardens and sold in local markets. This flexibility can provide both household food and opportunities for local income generation.

The crop also has potential as a low-input option, particularly in systems where reducing dependence on external inputs is important. Its nitrogen-fixing ability can support soil fertility, while the development of improved cultivars and value-added products could increase its market appeal and economic value. However, reliable production and market information are still limited, highlighting the need for further research and better market development.

Benefits to Soil

Winged bean has an important advantage as a legume because of its ability to form root nodules with *Rhizobium* bacteria and fix atmospheric nitrogen. This allows the crop to obtain part of its nitrogen requirement naturally and makes it suitable for low-input farming systems. Studies have also shown that winged bean can nodulate and grow across a range of tropical soil types, including relatively poor soils (Kaur *et al.*, 2025; Alalade *et al.*, 2016). By contributing biologically fixed nitrogen to the farming system, winged bean can support better soil fertility and more sustainable crop production, while reducing dependence on external nitrogen inputs. This makes its inclusion in diversified cropping systems particularly valuable where sustainable nutrient management is a priority.

Food and Value Addition

Winged bean has considerable scope for commercial processing because of the functional properties of its seed proteins and oil. Protein concentrates and isolates have shown good water-holding, oil-binding, emulsifying and foaming properties, making them suitable for incorporation into different food formulations. Its seed oil also has characteristics that support its potential as an edible oil and as a raw material for other industrial applications.

Further development of protein-rich ingredients, functional foods and processed products could help move winged bean beyond household consumption into organized markets. Improving processing methods, product quality and consumer acceptance could therefore add economic value to the crop and encourage its wider cultivation.

Potential in India

In India, winged bean is mainly grown as a backyard crop in several northeastern and southern states, including Assam, Manipur, Mizoram, Kerala, Tamil Nadu and Karnataka. The crop has shown encouraging performance in trials, indicating potential for wider cultivation in other suitable regions of the country. Several varieties have also been identified for different purposes. AKWB-1 is a dual-purpose variety suitable for vegetables and pulses, while IWB-1 is a high-yielding,

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medium-duration variety. IWB-2 can be used for green pods, seeds and fodder, and Chhattisgarh Pankhiya Sem-2 performs well under backyard conditions (Adegboyega *et al.*, 2019). These varieties indicate the potential of winged bean for diversification of vegetable and pulse production in India.

Future Prospects

The future of winged bean lies in better varieties, improved cultivation practices and stronger value chains. Breeding efforts need to focus on high-yielding types with better nutritional quality, palatability and wider adaptability, while addressing problems such as photothermal sensitivity, inconsistent productivity and anti-nutritional factors. Modern tools such as genomics, marker-assisted breeding, genome-wide studies and AI-based nutritional screening could accelerate the development of improved winged bean varieties. At the same time, better processing technologies, value-added products, farmer awareness and market development will be important for bringing this neglected crop into mainstream agriculture.

Conclusion

Winged bean may have remained in the background for years, but its story is far from over. A crop that can offer nutritious food, support farming systems and provide opportunities for value addition deserves more attention than it has received so far. The real potential of winged bean lies not only in what the crop can provide, but in what we choose to do with it. Bringing this neglected crop back into cultivation, kitchens and markets could turn an overlooked resource into a meaningful part of tomorrow's food system. From a forgotten crop in the backyard to a nutritious crop on the table, winged bean has every reason to be rediscovered.

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Digital Phenotyping: The New Eyes of Plant Breeders

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What is Phenotyping?

Phenotyping is the measurement and analysis of plant traits, including agronomic, adaptive, physiological, yield-related and stress-response traits, shaped by the interaction between genotype and environment. Efficient phenotyping is fundamental to plant breeding because it reveals how the genetic potential of a plant is expressed under different environmental conditions, enabling breeders to identify superior plants and make informed selection decisions throughout the breeding cycle.

Why is Traditional Phenotyping Challenging?

Traditional phenotyping is often labour-intensive, time-consuming and costly, particularly when large breeding populations need to be evaluated across multiple environments and growth stages. Manual measurements can also be subject to observer variation, limiting consistency and reproducibility. These constraints create a major bottleneck in large-scale breeding programs. While modern breeding has generated vast amounts of genomic information, obtaining equally comprehensive, precise and environment-sensitive phenotypic data remains challenging. The resulting gap between high-throughput genotyping and phenotyping can limit accurate understanding of genotype-phenotype relationships, especially when multi-environment trials require repeated measurements of thousands of plants.

What is Digital Phenotyping?

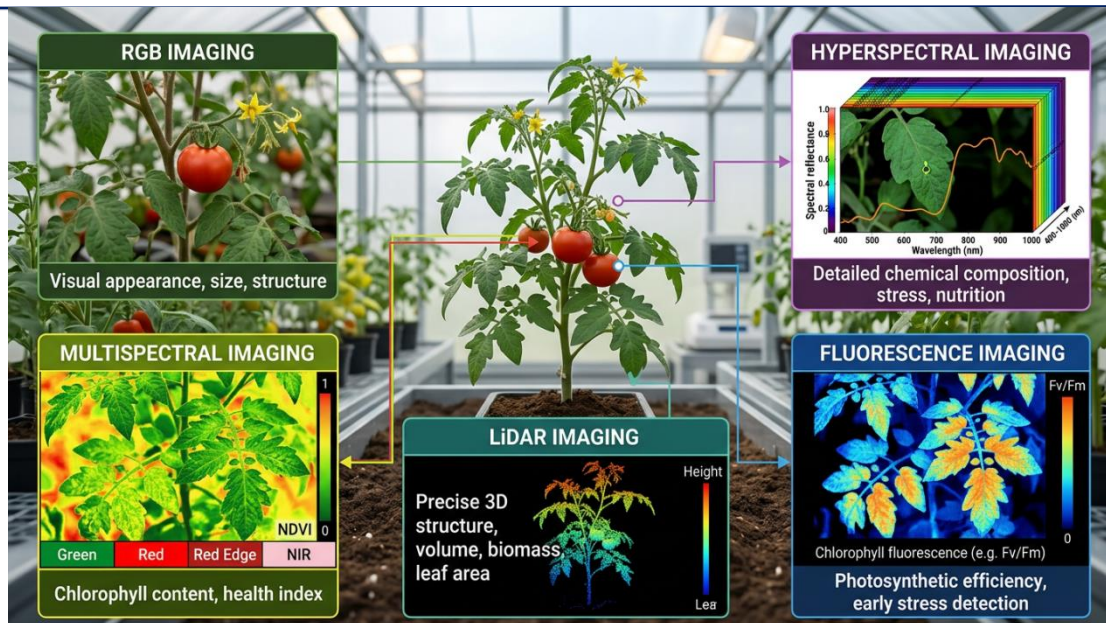
Digital phenotyping is the use of digital sensors, imaging technologies, automated platforms and computational approaches to measure and analyse plant traits objectively, repeatedly and at scale. It integrates technologies such as RGB cameras, thermal and hyperspectral imaging, chlorophyll fluorescence and LiDAR (Light Detection and Ranging), deployed on greenhouse systems, field carts, robotic platforms, UAVs (unmanned aerial vehicles) and handheld devices. Computer vision, machine learning (ML) and artificial intelligence (AI) then transform images and sensor data into quantitative plant traits, enabling rapid assessment of plant architecture, growth, biomass, physiological status, stress responses, disease symptoms and developmental traits across large breeding populations.

Tools and Technologies Used in Digital Phenotyping

Digital phenotyping integrates imaging and sensing technologies, automated platforms, robotics and computational tools to convert plant signals into measurable traits. Sensors capture information from plants, while ground-based, aerial and controlled-environment platforms enable rapid and repeated data collection. The resulting images and sensor data are processed using computer vision, machine learning (ML) and artificial intelligence (AI) to extract quantitative traits that can support breeding decisions.

1. Sensor types:

- a. **RGB imaging:** RGB (red, green and blue) cameras capture reflected light in the visible spectrum to produce two-dimensional images. Image analysis can be used to estimate traits such as plant height, canopy area, leaf area, plant architecture and shoot biomass.
- b. **Thermal imaging:** Thermal cameras detect infrared radiation emitted by plants and convert it into surface temperature information. Differences in canopy temperature can be used to assess plant water status and identify responses to drought and heat stress. Thermal measurements can also provide indirect information related to stomatal regulation.
- c. **Chlorophyll fluorescence:** Fluorescence sensors measure the weak light re-emitted by chlorophyll after light absorption. Fluorescence parameters provide information on the functioning of the photosynthetic apparatus and can help detect physiological stress before visible symptoms appear.
- d. **Multispectral and hyperspectral imaging:** These systems capture reflected radiation across multiple spectral bands, including visible and near-infrared regions, while hyperspectral sensors record information across many narrow and contiguous wavelengths. Spectral signatures can be used to estimate physiological, biochemical and stress-related traits and to distinguish differences that may not be visible to the human eye.
- e. **LiDAR and 3D imaging:** LiDAR (Light Detection and Ranging) systems emit laser pulses and measure the time taken for the reflected signals to return to the sensor. These measurements generate three-dimensional representations of plants, enabling estimation of traits such as plant height, canopy structure, volume and biomass.



2. Platforms and carriers:

- Ground-based platforms:** Carts, tractors, stationary rigs and mobile platforms can carry cameras and sensors through field plots to collect detailed measurements at the plot or plant level.
- Aerial platforms:** UAVs (unmanned aerial vehicles), commonly known as drones, can carry RGB, multispectral, thermal and other sensors to rapidly survey large breeding fields and screen numerous plots.
- Greenhouse and laboratory platforms:** Automated conveyor systems, robotic arms and fixed imaging systems enable repeated phenotyping under controlled environmental conditions, allowing plant responses to be monitored throughout growth and development.
- Portable and low-cost platforms:** Smartphones, handheld cameras and portable sensors offer flexible and relatively inexpensive options for early-stage screening and phenotyping in resource-limited breeding programmes.



3. Analysis software and computational tools: The value of digital phenotyping lies not only in data acquisition but also in converting large volumes of images and sensor data into meaningful plant traits. Computer vision, image processing, machine learning and AI-based methods can perform tasks such as image segmentation, object detection, trait extraction, classification and prediction.

- Image processing and analysis**
 - ImageJ / Fiji
 - OpenCV
 - MATLAB Image Processing Toolbox
- Plant segmentation and trait extraction**

- i. PlantCV
 - ii. Ilastik
 - iii. LemnaGrid
- c. Root phenotyping**
 - i. WinRHIZO
 - ii. RhizoVision Explorer
 - iii. RootNav
- d. Field and UAV image analysis**
 - i. Pix4D
 - ii. Agisoft Metashape
 - iii. OpenDroneMap
- e. 3D and LiDAR data analysis**
 - i. CloudCompare
 - ii. MeshLab
 - iii. Open3D
- f. High-throughput phenotyping platforms/software**
 - i. PlantCV
 - ii. LemnaGrid
 - iii. Field Scanalyzer
 - iv. PhenoVation
- g. AI and machine-learning frameworks**
 - i. TensorFlow
 - ii. PyTorch
 - iii. scikit-learn
 - iv. YOLO

Applications in Plant Breeding

- 1. High-throughput screening:** Rapid evaluation of large breeding populations for growth, biomass, architecture and developmental traits.
- 2. Stress tolerance:** Early detection of responses to drought, heat and other environmental stresses to identify tolerant genotypes.
- 3. Disease and pest resistance:** Automated detection and quantification of disease symptoms and pest damage using imaging and AI.
- 4. Biomass and yield estimation:** Digital measurement of plant height, canopy area, volume and other traits associated with biomass and yield.
- 5. Plant architecture and root phenotyping:** Precise assessment of above-ground and below-ground traits, including plant height, leaf area, tillering, canopy structure, root length, branching and architecture.
- 6. Physiological and biochemical traits:** Assessment of photosynthetic performance, water status, pigment composition and other physiological responses using thermal, fluorescence and spectral sensors.
- 7. Genotype × environment evaluation:** Repeated measurements across environments help reveal how genotypes respond to changing environmental conditions.
- 8. Genomic-assisted breeding:** High-quality phenotypic data can strengthen QTL mapping, genome-wide association studies and genomic prediction, supporting more accurate selection of superior genotypes.

Future Prospects

Digital phenotyping enables faster, precise and cost-effective evaluation of large breeding populations under diverse environmental conditions. The integration of low-cost sensors, smartphones, UAVs, AI and open-source software can support early identification of genotypes tolerant to drought, heat, salinity, diseases and other stresses. Combined with genomic information, digital phenotyping can improve selection efficiency and contribute to the development of high-yielding, climate-resilient and resource-efficient crop varieties suited to diverse agro-ecological conditions.

Hidden Hunger in an Era of Calorie Sufficiency

Article ID: 74419

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Summary

Hidden hunger represents a persistent and increasingly complex form of malnutrition in which micronutrient inadequacy can coexist with sufficient or excessive energy intake. In India, ongoing nutrition transition, urbanisation and changes in food environments have contributed to the coexistence of undernutrition, micronutrient deficiencies, overweight and diet-related non-communicable diseases. This paradox highlights the limitations of evaluating nutritional adequacy primarily through calorie intake and anthropometric indicators. Beyond energy sufficiency, nutritional health is influenced by dietary quality, nutrient density, dietary diversity, food matrix and micronutrient bioavailability. Diets dominated by energy-dense but nutrient-poor foods may provide adequate calories while failing to supply sufficient quantities and diversity of essential micronutrients. Moreover, reported nutrient intake does not necessarily reflect physiological availability, as absorption and utilisation are influenced by dietary composition, food processing and nutrient interactions. The coexistence of micronutrient inadequacy with overweight and metabolic dysfunction further underscores the need for a broader understanding of nutritional adequacy. Addressing hidden hunger therefore requires an integrated approach combining dietary diversification, nutrient-dense food choices, appropriate food processing, fortification and targeted supplementation for vulnerable groups. Future nutrition strategies and assessment frameworks should move beyond calorie adequacy towards a multidimensional concept incorporating quantity, quality, diversity and bioavailability. Such a shift is essential for addressing the evolving nutritional challenges of India and advancing from food sufficiency towards genuine nutritional adequacy.

Keywords: Hidden hunger; dietary diversity; nutrient density; bioavailability; nutrition transition; India; malnutrition.

Introduction

Historically, nutrition policies and public-health programmes primarily concentrated on preventing energy and protein deficiency. Nutritional adequacy was often assessed through indicators such as calorie availability, protein intake, body weight, growth faltering, wasting and underweight. Over time, however, nutrition science has demonstrated that adequate energy consumption does not necessarily ensure sufficient intake of vitamins and minerals. This has encouraged a gradual shift in nutrition policy from an exclusive focus on protein-energy malnutrition towards micronutrient adequacy and overall diet quality.

Hidden hunger refers to micronutrient malnutrition arising when the intake, absorption or utilisation of essential vitamins and minerals is insufficient to meet physiological requirements. Unlike severe energy deficiency, hidden hunger may occur without obvious clinical signs, wasting, stunting or low body weight. The consequences of hidden hunger may include impaired immune function, poor cognitive and physical development, reduced work capacity, increased susceptibility to infection and adverse maternal and child health outcomes. Consequently, an apparently well-nourished individual may still experience inadequate status of nutrients such as iron, vitamin A, iodine, zinc, folate, vitamin B12, calcium or vitamin D.

In the contemporary food environment, calorie sufficiency or excess may coexist with micronutrient inadequacy. Diets dominated by refined grains, added sugars, edible oils and ultra-processed foods can provide substantial energy while contributing limited amounts of vitamins, minerals, fibre and other protective food components. This paradox is particularly relevant to India, which is undergoing a nutrition transition characterised by changing dietary patterns, urbanisation, increased availability of processed foods and the persistence of traditional forms of undernutrition. Calorie intake, body weight and body mass index (BMI) although useful for evaluating energy balance and certain forms of malnutrition, cannot fully characterise nutritional health because they do not indicate the nutrient density, diversity or bioavailability of the diet, nor do they directly identify micronutrient deficiencies. Nutritional adequacy should consequently be evaluated beyond calories by considering nutrient density, dietary diversity, food processing, nutrient-nutrient interactions, bioavailability and overall dietary quality. Accordingly, this article examines hidden hunger in an era of calorie sufficiency and proposes that a comprehensive assessment of nutritional health must integrate dietary quality and micronutrient adequacy with conventional indicators of energy balance and anthropometric status.

The Changing Epidemiology of Malnutrition in India

India has transitioned from a predominantly calorie-deficiency-focused nutrition problem to a complex nutritional landscape characterised by the coexistence of undernutrition, micronutrient deficiencies, overweight, obesity and diet-related non-communicable diseases. This situation is described as the triple burden of malnutrition which comprises

undernutrition, micronutrient deficiencies and overnutrition. These forms may occur simultaneously within the same population, household or even individual.

Hidden hunger can occur across all population. Women of reproductive age, pregnant women, children, adolescents and older adults are particularly vulnerable because of their increased physiological requirements and greater susceptibility to nutrient inadequacy. Thus, micronutrient inadequacy may exist within conditions of energy sufficiency or excess, requiring nutritional adequacy to be defined not only by the amount of food or calories consumed but also by nutrient density, dietary diversity, bioavailability and diet quality.

From Calorie Adequacy to Nutrient Density and Dietary Diversity

Calorie adequacy does not necessarily ensure micronutrient adequacy. Diets dominated by refined cereals, added sugars, energy-dense snacks and highly processed foods may provide sufficient or excessive energy while supplying limited amounts of vitamins, minerals, fibre and other protective components. Therefore, Nutrient density which is the amount of essential nutrients supplied per unit of energy is a more useful concept for evaluating dietary quality.

Table: Advanced concepts in evaluating nutrient adequacy:

Advanced Concept	Relevance to hidden hunger
Food-matrix effect	The physical structure of a food can influence nutrient release, digestion, absorption and physiological utilisation even when two foods have similar nutrient composition.
Bioaccessibility versus bioavailability	A nutrient must first be released from the food matrix and then absorbed and utilised; therefore, nutrient content alone may overestimate nutritional benefit.
Nutrient displacement	Increased consumption of energy-dense foods reduce the intake of pulses, vegetables, fruits and other nutrient-dense foods.
Limitations of dietary diversity scores	Diversity scores are useful proxy indicators but may not reflect portion size, nutrient quantity, food fortification, seasonal variation or absorption inhibitors.
Processing-nutrition relationship	Processing may reduce, retain or improve nutrient availability depending on the method; therefore, processed foods should not be treated as nutritionally identical.

Dietary diversity improves the probability of micronutrient adequacy by incorporating pulses, whole grains and millets, vegetables, fruits, nuts, seeds and where appropriate, animal-source foods. However, diversity alone does not guarantee adequacy, since the quantity consumed, food quality, preparation practices and nutrient bioavailability are also important. India's dietary transition should therefore provide attention to changes in food composition, dietary diversity and the displacement of nutrient-dense foods by energy-dense processed products.

Beyond Intake: Bioavailability, Absorption and the Food Matrix

Micronutrient status is determined through a series of processes like intake → digestion → absorption → metabolism → utilisation rather than by dietary intake alone. Bioavailability refers to the proportion of an ingested nutrient that is released from the food matrix absorbed and made available for physiological functions. Phytate and polyphenols in cereals, millets, legumes, tea and coffee can bind minerals such as iron and zinc and reduce their absorption, while nutrient interactions may either inhibit or enhance utilisation. In contrast, vitamin C improves non-haem iron absorption by increasing iron solubility and facilitating its reduction to a more absorbable form.

Food processing and preparation can substantially modify nutrient bioavailability. Soaking, germination and fermentation activate endogenous or microbial phytase, reduce phytate and improve the bioaccessibility of minerals whereas cooking can improve digestibility but may also cause losses of heat-sensitive nutrients depending on the method used. These effects demonstrate the importance of the food matrix in which nutrients interact with fibre, proteins, antinutritional factors and other food components. Therefore, nutrient databases and reported dietary intake may not accurately represent the quantity of nutrients that becomes physiologically available.

Reframing Assessment and Intervention Strategies

Nutritional assessment should move beyond a predominantly calorie-centric approach towards an integrated framework that considers energy adequacy, nutrient density, dietary diversity, dietary patterns, micronutrient intake, anthropometry, biochemical biomarkers and nutrient bioavailability. A useful conceptual model is: Nutritional adequacy = quantity + quality + diversity + bioavailability. No single method is sufficient: dietary data may contain reporting errors, anthropometry may fail to identify hidden hunger and biomarkers may be influenced by infection, inflammation or recent intake. Therefore, a combination of dietary, anthropometric and biochemical indicators provides a more complete assessment.

Interventions should be complementary rather than competing. Dietary diversification should form the foundation supported by food fortification to address population-level deficiencies and targeted supplementation for high-risk groups. Nutrition education can improve food selection, preparation and feeding practices, while food-system interventions should increase the availability, affordability and accessibility of nutrient-dense foods. These strategies

should be adapted across the life course, including maternal and child nutrition, school and adolescent nutrition and the nutritional needs of older adults and other vulnerable populations.

Conclusion

Calorie sufficiency should no longer be regarded as synonymous with nutritional adequacy. The contemporary Indian nutrition landscape demonstrates that micronutrient inadequacy can persist alongside adequate or excessive energy intake, particularly when dietary patterns are characterised by low diversity, reduced nutrient density and limited consumption of nutrient-rich foods. Hidden hunger must therefore be understood within the broader context of dietary quality, food matrix and nutrient bioavailability rather than as an isolated deficiency of individual micronutrients. Addressing this challenge requires a shift from a predominantly calorie-centred approach towards a multidimensional framework encompassing quantity, quality, diversity and bioavailability. Dietary diversification should remain the foundation of this approach, complemented by fortification, targeted supplementation, nutrition education and supportive food environments where appropriate. Future nutrition research, assessment and policy in India should consequently move beyond asking whether populations are consuming enough calories to examining whether those calories are accompanied by diverse, nutrient-dense foods and biologically available nutrients. Such a transition from food sufficiency to nutritional adequacy is critical for addressing the increasingly complex forms of malnutrition emerging in India.

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A Promising Technology for Disease Management, Climate Resilience and Sustainable Vegetable Production

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Introduction

Cucurbitaceous vegetables occupy an important position in Indian horticulture. Watermelon, cucumber, muskmelon, bitter gourd, bottle gourd, pumpkin, ash gourd and other cucurbits are cultivated extensively under open-field as well as protected conditions. These crops provide income to farmers, contribute to nutritional security and have considerable demand in domestic markets. However, intensive cultivation of cucurbits is increasingly challenged by soil-borne diseases, nematodes, salinity, drought, water scarcity, temperature fluctuations and declining soil health.

One of the promising technologies capable of addressing several of these constraints is **vegetable grafting**. Grafting is a form of vegetative propagation in which two living plant parts are joined so that they grow as a single plant. In vegetable grafting, the upper portion is known as the **scion**, generally selected for desirable fruit quality, yield and market characteristics, while the lower portion is the **rootstock**, selected for desirable root characteristics such as vigour, disease resistance and tolerance to abiotic stresses.

In India, research institutions like **ICAR-Indian Institute of Vegetable Research (IIVR)**, Varanasi, Tamil Nadu Agricultural University, Coimbatore and IIHR, Bengaluru have contributed to the development and promotion of vegetable grafting technologies. Recent ICAR initiatives have included grafted vegetable production and entrepreneurship development, indicating the growing relevance of grafting technology in Indian vegetable production.

Why Do Cucurbit Crops Need Grafting?

Traditionally, farmers have attempted to manage these problems through crop rotation, soil solarization, chemical treatments, resistant varieties and improved sanitation. However, these approaches may not always provide adequate protection, particularly under intensive production systems.

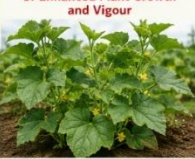
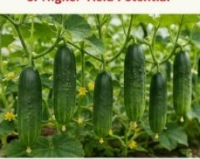
Grafting offers another biological and physiological approach.

When a susceptible but high-performing scion is grafted onto a suitable resistant or tolerant rootstock, the rootstock can provide a stronger root system and improved tolerance to particular soil and environmental stresses. The resulting plant can retain the desirable fruit characteristics of the scion while benefiting from the root characteristics of the rootstock.

However, grafting should not be considered a universal cure for every production problem. The effectiveness of grafting depends on the **rootstock**, **scion**, **pathogen**, **environmental conditions** and **compatibility** between the two partners.

Major Advantages of Cucurbit Grafting


MAJOR ADVANTAGES OF CUCURBIT GRAFTING


1. Management of Soil-borne Diseases  Grafting with resistant rootstock reduces incidence of soil-borne diseases like Fusarium wilt.	2. Improved Root Vigor and Strong Establishment  Grafted plants develop a stronger and more extensive root system, ensuring better anchorage and establishment.	3. Better Tolerance to Abiotic Stresses  Grafted plants show better tolerance to heat, drought, salinity and other environmental stresses.	4. Improved Water and Nutrient Uptake  A vigorous root system improves absorption of water and nutrients, leading to better plant growth.
5. Enhanced Plant Growth and Vigour  Grafted plants generally show faster growth, thicker stems, larger leaves and overall vigour.	6. Higher Yield Potential  Better root performance and improved plant health can result in higher yield and better quality fruits.	7. Extended Harvest Period  Grafted plants often remain productive for a longer period, extending the harvest duration.	8. Economic Benefits  Improved yield, quality and reduced disease losses contribute to higher profits and better economic returns.

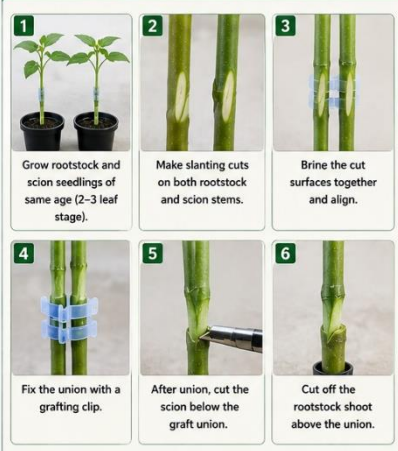

 Grafting combines the best of both plants – strong roots + superior fruits = better yield, better profit!
 

Important Grafting Techniques in Cucurbits

Cucurbit seedlings are herbaceous and tender, and therefore grafting requires precision and careful environmental management.

1. APPROACH GRAFTING

(Both rootstock and scion remain on their own roots until the union is successful)



1. Grow rootstock and scion seedlings of same age (2-3 leaf stage).

2. Make slanting cuts on both rootstock and scion stems.

3. Brine the cut surfaces together and align.

4. Fix the union with a grafting clip.

5. After union, cut the scion below the graft union.

6. Cut off the rootstock shoot above the union.

Successful grafted plant



Scion (desired variety)
Graft union
Rootstock (strong & resistant)

2. HOLE-INSERTION GRAFTING

(A hole is made in the rootstock and the scion is inserted into it)



1. Make a hole in the rootstock stem using a grafting tool.

2. Prepare the scion in a wedge shape.

3. Insert the scion wedge into the hole.

4. Ensure proper contact of cambial surfaces.

5. Secure the graft with a clip.

6. Keep in high humidity chamber for healing (5-7 days).

Successful grafted plant



Scion (desired variety)
Graft union
Rootstock (strong & resistant)

3. CLEFT GRAFTING

(A slit is made in the rootstock and the scion is inserted into the slit)



1. Cut the rootstock seedling at cotyledonary or 1-2 leaf stage.

2. Make a vertical slit in the centre of the rootstock.

3. Prepare the scion in a wedge shape.

4. Insert the scion wedge into the slit.

5. Ensure proper cambial contact and secure with a clip.

6. Keep in healing chamber for 5-7 days.

Successful grafted plant



Scion (desired variety)
Graft union
Rootstock (strong & resistant)

Key for success: Use healthy seedlings • Match stem diameter • Use clean & sharp tools • Ensure proper contact • Maintain high humidity • Provide good aftercare

Nursery Management of Grafted Cucurbits

Production of grafted seedlings is more technically demanding than ordinary seedling production.

The first step is to select healthy and high-quality seed of both rootstock and scion.

The sowing time of the rootstock and scion should be synchronized so that both seedlings reach the appropriate stage for grafting at nearly the same time.

The seedlings should be grown under optimum nursery conditions with proper Light, temperature, moisture, nutrition, sanitation

Tools used for grafting should be clean and sharp. Poor sanitation can introduce pathogens into the grafting wound.

After grafting, plants should be transferred carefully to a suitable healing environment.

Another important point is the removal of rootstock shoots emerging below the graft union. If rootstock shoots are allowed to develop, they can compete with the scion and alter the intended plant architecture. The graft union should also be planted above the soil surface during field establishment so that the scion does not develop its own roots from the buried portion and come into direct contact with soil-borne pathogens.

Cucurbitaceous Species/Rootstocks and their Potential Resistance or Tolerance to Biotic and Abiotic Stresses

Cucurbitaceous species / rootstock	Suitable scion / crop	Major abiotic stresses
<i>Lagenaria siceraria</i> (Bottle gourd)	Watermelon, cucumber, melon	Flooding/waterlogging, low soil temperature, some drought conditions
<i>Cucurbita moschata</i> (Moschata pumpkin)	Watermelon, cucumber, melon, bitter gourd	Low temperature, salinity and other root-zone stresses
<i>Cucurbita maxima</i> × <i>C. moschata</i> (Interspecific squash hybrid)	Cucumber, watermelon, melon	Salinity, heat, drought, acidity, heavy-metal toxicity
<i>Cucurbita ficifolia</i> (Fig-leaf gourd)	Cucumber and other cucurbits	Low temperature, salinity

<i>Citrullus lanatus</i> var. citroides (Citron watermelon)	Watermelon	Drought and other water-related stresses reported in some accessions
<i>Cucumis metuliferus</i> (African horned cucumber)	Melon, cucumber, watermelon	Stress tolerance reported in selected accessions
<i>Cucumis sativus</i> var. hardwickii	Cucumber, melon	Stress tolerance under investigation
<i>Luffa cylindrica</i> (Sponge gourd)	Cucumber, bitter gourd	Drought tolerance in cucumber; flooding tolerance in bitter gourd
<i>Cucumis ficifolius</i>	Cucumber, melon	Stress tolerance under evaluation
<i>Cucumis africanus</i>	Cucumber, melon	Abiotic stress tolerance under evaluation
<i>Cucumis anguria</i> (West Indian gherkin)	Cucumber, melon	Stress tolerance under evaluation
<i>Benincasa hispida</i> (Ash/wax gourd)	Watermelon	Waterlogging/flooding tolerance reported

The Major Stress-Rootstock Combinations of Cucurbit Grafting and Stress Tolerance

Rootstock	Recommended crop/scion	Major target problem
Bottle gourd (<i>Lagenaria siceraria</i>)	Watermelon	Fusarium wilt, nematodes, soil-borne diseases
<i>C. maxima</i> × <i>C. moschata</i> hybrid	Watermelon	Fusarium wilt, drought, salinity, heat and other stresses
<i>C. maxima</i> × <i>C. moschata</i> hybrid	Cucumber	Fusarium wilt, Pythium, salinity and heat
<i>Luffa cylindrica</i>	Cucumber	Drought stress
<i>Cucurbita ficifolia</i>	Cucumber	Low temperature and salinity

Challenges that Need Attention

Despite its potential, several challenges need to be addressed before grafting becomes a routine technology for every farmer.

Higher Seedling Cost: Grafted seedlings are more expensive than conventional seedlings because of the additional labour and infrastructure involved.

Requirement of Skilled Labour: Successful grafting requires trained workers. Incorrect cutting, poor alignment or improper handling can result in graft failure.

Rootstock-Scion Compatibility: Not every rootstock is suitable for every scion. Compatibility trials are essential before large-scale adoption.

Healing Infrastructure: A controlled healing environment is highly desirable for commercial production. Low-cost healing chambers can help make the technology more accessible.

Need for Region-Specific Research: Rootstock performance can vary with soil type, climate, pathogen population and scion cultivar. Therefore, locally validated rootstock-scion combinations are important.

The World Vegetable Center has emphasized the importance of low-cost and simplified grafting technologies, including low-cost healing chambers and grafting tools, to facilitate adoption in developing countries.

Future Prospects

The future of cucurbit grafting in India is promising.

Research institutions and agricultural universities can contribute by identifying:

1. High-performing rootstocks
2. Compatible rootstock-scion combinations
3. Disease-resistant rootstocks
4. Stress-tolerant rootstocks
5. Low-cost grafting techniques
6. Low-cost healing chambers
7. Mechanized grafting systems
8. Farmer-friendly nursery protocols

There is also scope for integrating grafting with **protected cultivation**, **precision irrigation**, **fertigation** and **climate-smart horticulture**.

Conclusion

Cucurbit vegetable grafting represents a significant technological opportunity for Indian horticulture. Its importance extends beyond simply joining two plants. It is a strategy for **combining desirable fruit characteristics with strong root-system characteristics**.

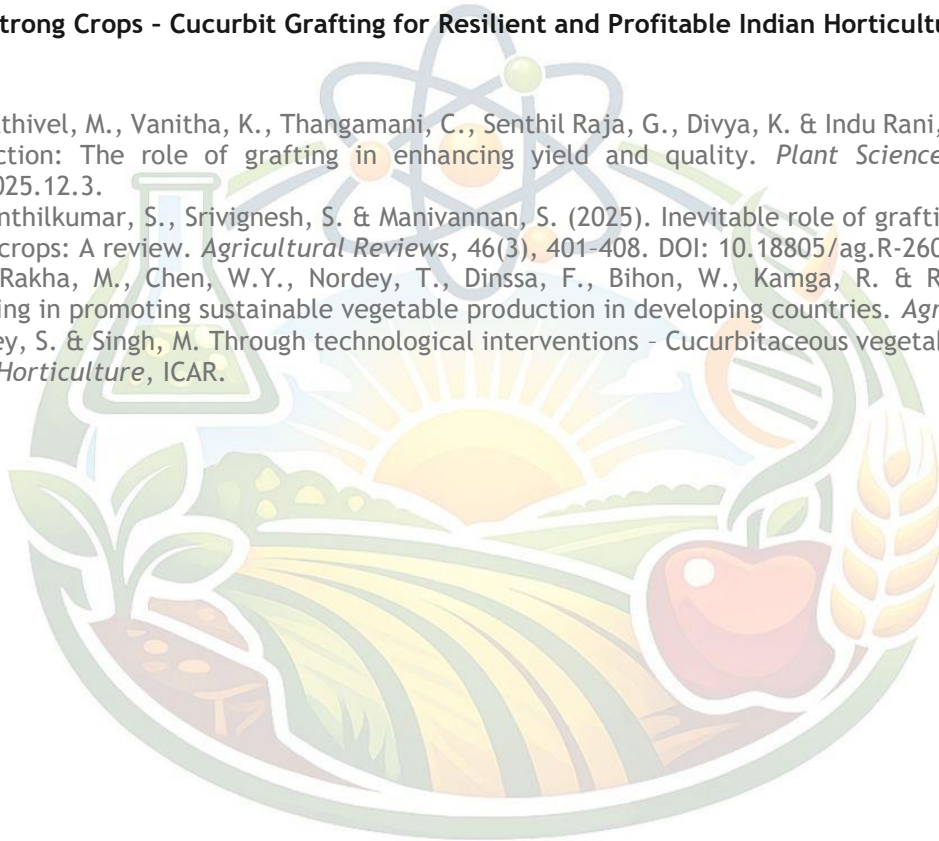
The technology can contribute to the management of soil-borne diseases, improve root vigour, enhance water and nutrient acquisition and provide tolerance to selected environmental stresses. For Indian farmers, particularly those involved in intensive vegetable production and protected cultivation, grafted seedlings could become an important component of future production systems.

However, successful adoption requires **quality rootstocks**, **compatible scions**, **skilled grafting**, **proper healing**, **good nursery management** and **economic evaluation under local conditions**.

“Strong Roots for Strong Crops - Cucurbit Grafting for Resilient and Profitable Indian Horticulture.”

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The Secret Life of a Superfood: Your Morning Matcha

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Matcha (*Camellia sinensis* L.) consumption became a popular global health phenomenon especially among the millennials and Gen Z population during the early 2020s. The term matcha is a Japanese language word, where *ma* stands for powder and *cha* is tea. What was once used in traditional Japanese rituals (*chanoyu*) as a symbol of peace and meditation has now transformed into modern-day superfood for culinary enthusiasts owing to their holistic benefits for the body. Matcha is an exceptionally rich source of polyphenols, especially catechins from a nutritional perspective. While most of us see this as a fine green powder, to an agriculturist, matcha production is an ultimate test of precision farming mostly because of the methods of cultivation practices directly shaping the phytochemical profile that ultimately determines their therapeutic effectiveness. Matcha (*Camellia sinensis* L.) is one of the most comprehensive examples of this principle.



It Starts with the Right DNA

Tea genotype, the genetic character or type of tea (cultivar) is one of the most important determinants for growing plants in matcha production, because it significantly impacts the quality of the product and influences taste, color, and aroma of the end product. The genotype defines unique possibilities of biochemical composition, especially the proportion of L-Theanine amino acids and catechins that give astringency. It decides whether the matcha produced will have strong umami taste, inherent natural sweetness or bitterness. Most popular cultivars include:

1. Yabukita is the dominant one as gives it stable, earthy balance of flavors, considered an industry standard. Graded as a good to premium quality matcha, highly stable for blending.
2. Okumidori are popular because of their capability to give the bright green color and fresh taste. The result is a stable balance of flavors. Good to premium quality matcha, stable for blending. The taste is fresher (fresh) and a little lighter. Gives bright green color.
3. Saemidori is known to be sweet naturally, full of a mellow umami flavor, with very little bitterness possible. This is the cultivar believed to have the mildest taste. Gold standard for use as Ceremonial Grade Matcha.

The Shading Secret: Where Agronomy and Physiology Come into Play

The most critical part of matcha farming is shaded cultivation. About three to four weeks before harvest, farmers cover the tea bushes with screens, blocking out up to 90% of the sunlight. This creates a massive physiological trigger within the plant which results into substantial improvement of matcha quality.

The high premium matcha quality, distinguished by the bright green color, the distinct umami aroma, and smooth texture, is influenced not only by the genetics of the tea plant but also by certain practices, such as the use of shading prior to harvesting to boost the content of chlorophyll and L-theanine and the way of harvesting. Unique growing practices, including shading, affect the taste and the nutrition composition of matcha. The unique way of shading significantly increases the amount of such bioactive components of matcha as amino acids, especially L-Theanine, which gives the umami taste, caffeine, and chlorophyll, which gives the deep green color; in addition, shading reduces the amount of such components as catechins, responsible for bitter taste and astringency. Thus, the unique combination of bioactive substances not only provides the health benefits of matcha but also determines its organoleptic properties, including the taste and aroma.

The Whole-Leaf Advantage

While traditional green tea involves brewing the tea leaves and disposing of them, matcha involves grinding the whole leaf into an extremely fine powder which is between 5 to 17 microns thin; finer than conventional powders and thus conventional in use for its many applications in different products: ice cream, cakes, bread, candies, instant noodles, beverages, supplements, even beauty products.

Unlike green tea, matcha is unique since the entire leaf is ingested for its nutritional value, such as the high content of antioxidants like epigallocatechin gallate (EGCG).

The Oxygen Radical Absorbance Capacity (ORAC) value of matcha is significantly higher than that of other superfoods, including blueberries and goji berries. Its high antioxidant properties qualify it as an agent that can be used to counter oxidative stress, which is a major cause of several pathological conditions ranging from premature aging to degenerative diseases.



Why Your Gut and Brain Love Plant Science

By mastering the plant's internal chemistry on the farm, agriculturists provide us with compounds that directly benefit our bodies:

- 1. A Gut Revolution:** Matcha green tea comes from finely ground green tea leaves. What sets Matcha green tea apart from regular green tea is its ability to produce positive impacts on the gut microbiota, since it is more nutrient dense in terms of tea catechins and insoluble dietary fiber. According to recent studies, consuming matcha on a daily basis for two weeks brings about a positive change in the gut microbiome; it boosts good bacteria, such as *Coprococcus*, which generates acids beneficial to the human body, while reducing harmful bacteria such as *Fusobacterium*.
- 2. Alert Calmness:** The combination of caffeine with the high amount of L-theanine produces relaxed focus. It enhances social cognition and concentration without the usual jitters that coffee usually produces. Catechin antioxidants found in green tea aid in reducing blood pressure and lowering the level of LDL cholesterol. Rutin, a type of bioflavonoid present in matcha, helps produce the same effects.
- 3. The Beauty Glow:** The high amount of polyphenols in matcha is effective in protecting the skin from the harmful effects of UV rays in the tropics and pollutants. It acts as an antioxidant by eliminating free radicals which are responsible for causing wrinkles and even reduces the chances of acne due to skin irritation.

The Future of the Field

Demand for matcha is growing significantly, particularly amongst Gen Z and millennials who prize their holistic benefits. For farmers in places such as Indonesia, it represents the chance to employ precision agriculture and smart farming practices to perfect the chemistry of the tea even more. Through the use of specific fertilizers and dynamic shading, agriculturists can make sure that every single cup of matcha stays the most functional food possible. Matcha is literally where genetics meets agronomy to produce something incredible.

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Silage and Haymaking for Sustainable Dairy Farming in Punjab

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Introduction

Punjab is one of India's leading dairy-producing states, with a large livestock population requiring a continuous supply of quality fodder. However, seasonal shortages of green fodder during summer (May-June) and winter (November-December) make fodder conservation essential. Silage and hay are the most effective methods for preserving surplus green fodder, ensuring year-round availability of nutritious feed, reducing losses, and improving livestock productivity. In recent years, silage production has increased rapidly in Punjab due to mechanization, custom hiring services, and the growth of commercial silage enterprises.



Fig.1 Silage and Hay Making

Silage Making

Silage is fermented green fodder preserved under anaerobic (air-tight) conditions. During fermentation, lactic acid bacteria convert soluble carbohydrates into lactic acid, lowering the pH to 3.8-4.5. This acidic environment prevents spoilage and preserves the nutritional value of the fodder for long-term storage.

Advantages of Silage

1. Provides nutritious fodder throughout the year.
2. Maintains high palatability and digestibility.
3. Minimizes fodder losses and wastage.
4. Ensures quality feed during droughts and lean fodder periods.
5. Improves milk production, animal health, and reproductive performance.
6. Enables efficient use of surplus green fodder during peak production.

Forage Crops Used for Silage and Haymaking

Silage: Maize, Sorghum (Jowar), Pearl millet (Bajra), Oats, Barley, Triticale, Rye (in limited areas)

Hay Making: Guinea grass, Cowpea, Oats, Lucerne Berseem (late cut) (Alfalfa) Other soft-stemmed legumes.

Table 1 Optimum time for harvesting:

Crop	Recommended Harvest Stage
Maize	Flowering to Milk to further early dough stage (90-100 days after sowing)
Sorghum	Flowering to milk stage
Pearl millet	Boot stage
Napier-Bajra hybrid	About 1 m plant height
Guinea grass	About 1 m plant height
Oats	Early milk stage

Determining Suitable Moisture Content

Before ensiling, check the fodder moisture by squeezing a handful of chopped fodder into a ball. If no water oozes out and the hands remain dry, the fodder is suitable for silage making.

Silo Trench Construction: Construct the silo trench on elevated land near the cattle shed to prevent water logging. A trench 1.5-2.0 m deep with cement-plastered floor and walls helps prevent water seepage and ensures proper preservation. The trench size should be based on the quantity of fodder and the number of animals. As a guideline, 1 m³ of silo space can store about 500-600 kg of chopped green fodder.

Procedure for Silage Making

1. Harvest the fodder crop at the recommended stage of maturity and chop the fodder into 5-8 cm pieces.
2. Fill the chopped fodder quickly into the silo and compact each layer thoroughly to remove air.
3. Continue filling, leaving about 1 m above ground level for settling and cover with a thin layer of dry fodder or wheat straw.
4. Seal the silo tightly with a polyethylene sheet and cover it with soil to maintain airtight conditions.
5. Allow the silage to ferment for 45-60 days before feeding it to livestock.

Good-quality silage should possess the following characteristics:

- a. Greenish brown to golden-brown colour.
- b. Pleasant fruity or mildly acidic aroma.
- c. Firm texture without mould growth.
- d. pH between 3.8 and 4.5.
- e. Free from fungal contamination, foul odour, and excessive heating.
- f. High lactic acid and low butyric acid content
- g. Minimal nutrient and nitrogen losses

Feeding Silage: Introduce silage gradually by feeding 5-10 kg per animal per day mixed with green fodder during the first week. Thereafter, 20-30 kg of silage per adult animal per day can be fed along with dry fodder and concentrate, depending on the animal's production level.

Hay Making

Hay is prepared by drying forage crops to 15-20% moisture, which prevents spoilage and allows safe long-term storage. It provides a valuable source of nutritious dry fodder during periods of green fodder scarcity.

Advantages of Hay

- a. Easy to transport, store, and handle.
- b. Reduces storage losses and fodder wastage.
- c. Provides nutritious dry roughage during green fodder scarcity.
- d. Promotes rumen health and is suitable for all classes of livestock.
- e. About 1 kg of good-quality hay is equivalent to 6 kg of fresh green fodder in feeding value.

Procedure for Hay Making: Harvest the crop before flowering and spread it in a thin layer on a clean surface. Dry in the sun for 2-3 days, turning it regularly for uniform drying. When the stems break easily on twisting (15-20% moisture), bale or stack the hay under a well-ventilated shed. Protect the stored hay from rain, ground moisture, and rodents.

Good-quality hay should have:

- a. Bright green colour and pleasant natural aroma.
- b. Soft, leafy texture with minimum leaf loss.
- c. Freedom from mould, dust, weeds, and other foreign materials.

Conclusion

Silage and hay making are simple and effective fodder conservation techniques that ensure a year-round supply of quality feed for livestock. Their adoption helps overcome seasonal fodder shortages, reduces wastage, improves animal health and milk production, and increases the profitability of dairy farming. Promoting these practices will strengthen fodder security and support sustainable dairy farming in Punjab.

Benefits of Fodder Conservation

Both silage and hay offer several advantages for dairy farmers:

1. Ensure year-round availability of nutritious fodder.
2. Reduce seasonal feed shortages.
3. Maintain milk yield during lean periods.
4. Improve livestock health and productivity.

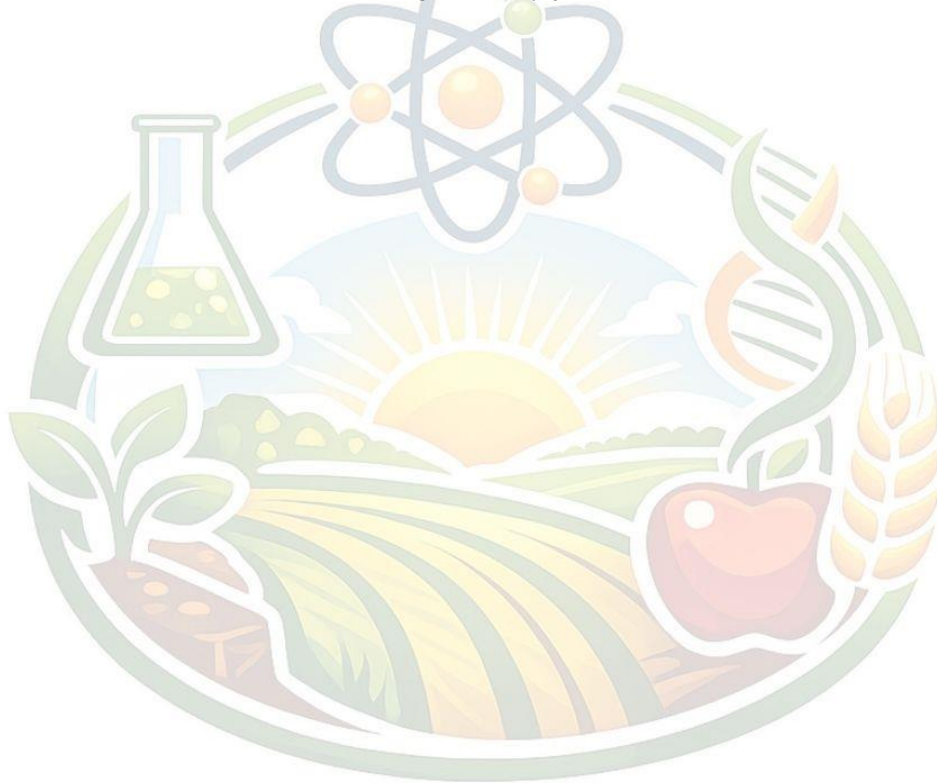
5. Minimize wastage of surplus green fodder.
6. Lower dependence on purchased feed.
7. Enhance farm profitability through efficient fodder utilization.

Proper preparation and storage of silage and hay play a crucial role in sustainable dairy farming by ensuring a continuous supply of high-quality feed throughout the year.

Current Status of Silage Production in Punjab

Punjab has witnessed remarkable growth in commercial silage and hay production during the last decade, particularly using maize as the primary forage crop. Both trench silage and plastic-wrapped bale silage are adopted by progressive dairy farmers and commercial dairy enterprises. The availability of modern forage harvesters, balers, silage wrappers, and custom hiring services has significantly enhanced the efficiency of silage production.

Research and extension organizations, particularly Punjab Agricultural University (PAU), Ludhiana, and various ICAR institutes, have played a pivotal role in promoting scientific fodder conservation through farmer training programmes, frontline demonstrations, and capacity-building initiatives. These efforts have substantially improved awareness regarding the economic and nutritional benefits of silage and hay production.



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Tiny Grains, Big Harvests: How Pollen Determines Cashew Productivity

Article ID: 74423

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Introduction

When farmers think about improving cashew yield, they usually focus on flowering intensity, nutrient management, irrigation, or pest control. However, one of the most important factors determining productivity is often overlooked because it is invisible to the naked eye—a tiny pollen grain. Every cashew nut harvested from an orchard begins its journey with a successful pollination event. Before a flower can develop into a nut, pollen must be transferred, germinate successfully, and complete fertilization. Any disruption in this process can reduce fruit set and ultimately lower yield. As climate change brings increasing temperatures and unpredictable weather patterns, understanding pollen biology has become more important than ever.

The Remarkable World of Cashew Flowers

Cashew trees produce attractive flowering panicles containing hundreds of flowers. However, not all flowers are capable of producing nuts. Two types of flowers occur on a cashew panicle: male flowers and hermaphrodite flowers (Fig. 1). Male flowers produce pollen, while hermaphrodite flowers possess both male and female reproductive organs and are capable of developing into fruits after fertilization. Interestingly, only a small proportion of flowers produced on a panicle are hermaphrodite flowers. In many cases, less than ten percent of the flowers are capable of producing nuts. Therefore, successful pollination and fertilization become critical for obtaining a good harvest. The transfer of pollen from male flowers to receptive stigmas is mainly carried out by insects such as bees, flies, ants, and wasps. Once pollen lands on a receptive stigma, it germinates and produces a pollen tube that carries the male genetic material to the ovule. Only after this process is completed can a cashew apple and nut begin to develop.



Fig. 1: Cashew flower morphology: A. cashew inflorescence bearing both male and hermaphrodite flowers; B. male flower and C. hermaphrodite flower (Source: Babli et al., 2023)

What is Pollen Morphology?

Pollen grains may appear simple under ordinary observation, but under high magnification, they reveal remarkable diversity in size, shape, and surface structure. The study of these characteristics is known as pollen morphology. Scientists often describe pollen grains as biological fingerprints because their size and shape differ among species and even among varieties within a species. These features can provide valuable information about reproductive efficiency, adaptation, and genetic diversity. To understand pollen characteristics in cashew, researchers at ICAR-Directorate of

Cashew Research, Puttur used scanning electron microscopy (SEM), a powerful technique capable of producing highly detailed images of pollen grains (Fig. 2). The investigation revealed significant differences among cashew varieties. Early, mid, and late-flowering varieties differed in pollen size and shape, indicating substantial genetic variability in reproductive traits.

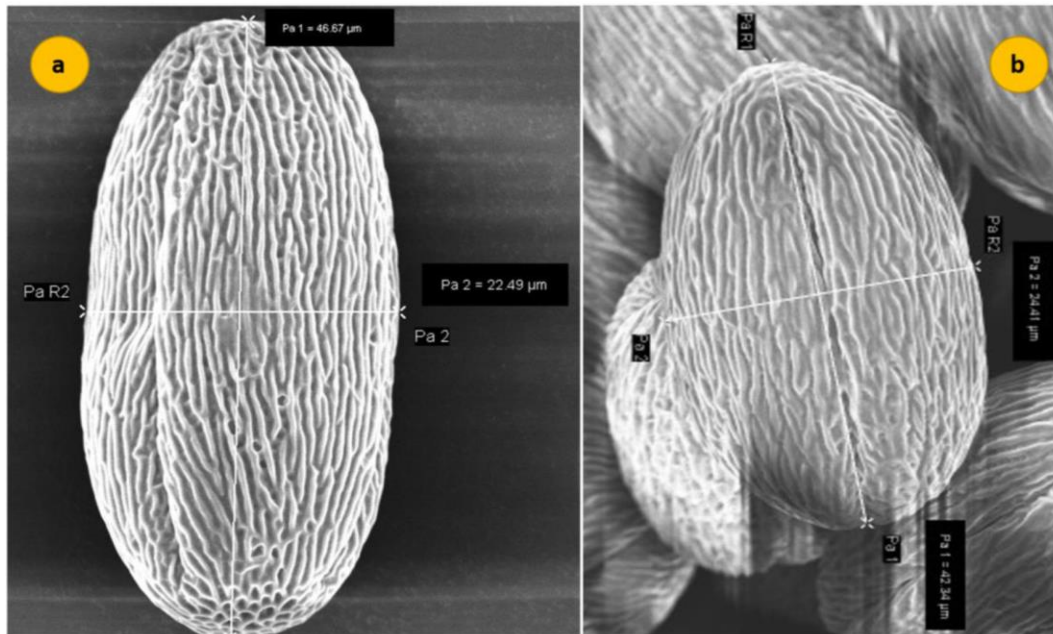


Fig. 2: Pollen shape of cashew varieties photographed under SEM microscope. a. perprolate and b. prolate (Source: Babli et al., 2023).

Why Does Pollen Size Matter?

At first glance, pollen size may seem unimportant. However, pollen grains function as miniature biological packages carrying genetic information and nutrient reserves required for germination. Larger pollen grains often contain greater amounts of stored carbohydrates and nutrients. These reserves provide energy for pollen germination and pollen tube growth after pollination. Research has shown that pollen size can influence reproductive success in many horticultural crops. In cashew, differences in pollen dimensions among varieties may contribute to differences in fertilization efficiency and fruit set. These findings suggest that pollen morphology is not merely a taxonomic characteristic but also an important indicator of reproductive performance.

Temperature: A Silent Threat to Reproduction

While flowers are clearly visible, the effects of temperature on pollen often go unnoticed. Yet pollen grains are among the most sensitive structures in a plant. The flowering period of cashew generally coincides with the dry season, when temperatures may fluctuate considerably. Moderate temperatures favour pollen germination and fertilization, but excessive heat can severely disrupt reproductive processes. Studies conducted in several horticultural crops have demonstrated that pollen development and germination are often more sensitive to heat stress than vegetative growth. Even when trees appear healthy, reproductive processes may already be affected by high temperatures. This is one reason why some years with abundant flowering still produce disappointing yields.

How Do Cashew Pollens Respond to Temperature?

To better understand temperature effects, researchers evaluated pollen germination of different cashew varieties under temperatures ranging from 5°C to 50°C (Fig. 3). The results revealed clear varietal differences. Early-flowering varieties such as VRI-3, Vengurla-4, and Ullal-3 showed maximum pollen germination around 25°C. Mid and late-flowering varieties such as Bhaskara and Madakkathara-2 performed best at approximately 30°C. Under favourable conditions, early-flowering varieties exhibited higher pollen germination percentages. However, when temperatures increased beyond 40°C, some mid- and late-flowering varieties maintained better pollen performance, indicating greater tolerance to heat stress. This finding has important implications for future cashew cultivation. As temperatures continue to rise, varieties capable of maintaining pollen function under heat stress may offer greater yield stability.

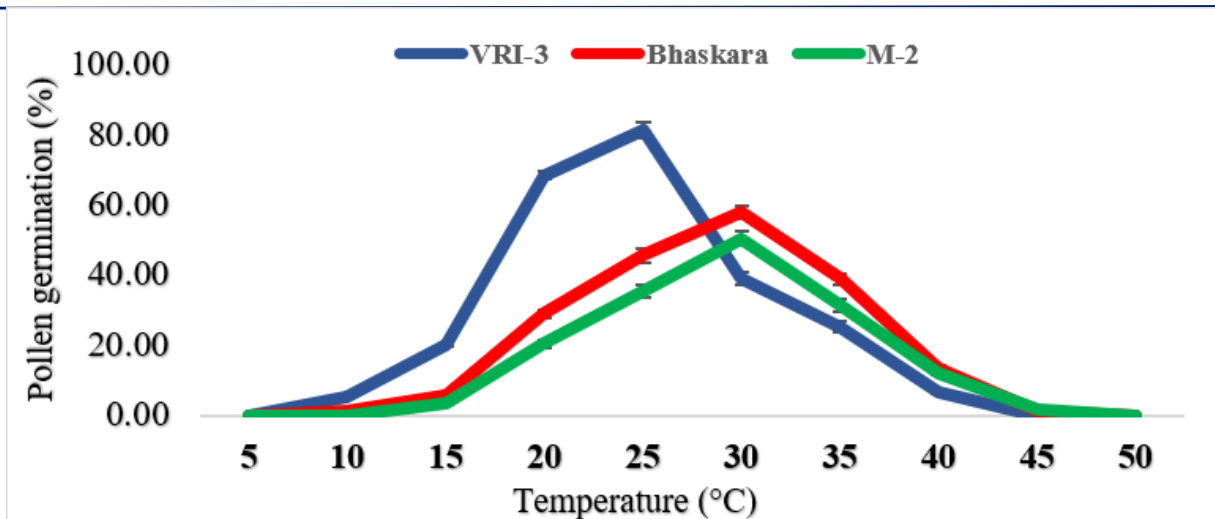


Fig. 3: *In vitro* pollen germination of cashew varieties in response to temperature throughout the experimental period. Varieties with variation in pollen germination (VRI-3: early; Bhaskara: mid and Madakkathara-2: late) are presented for clarity. Error bars indicate $\pm$ SD (Source: Babli et al., 2023).

◇ BOX 1. HOW HEAT AFFECTS CASHEW POLLEN

Heat stress during flowering can significantly reduce cashew productivity through several mechanisms:

- ✓ Reduces pollen viability.
- ✓ Decreases pollen germination.
- ✓ Interferes with fertilization.
- ✓ Interferes with fertilization.
- ✓ Increases flower and fruitlet drop.
- ✓ Ultimately reduces nut yield.

Key Message: A flower may appear healthy, but if its pollen fails to function properly, fertilization and fruit development cannot occur.

Sugars: Fuel for Pollen Performance

Successful pollen germination requires adequate energy reserves. Researchers observed that pollen grains of early flowering varieties contained higher concentrations of reducing sugars, especially glucose and fructose. These sugars were positively associated with better pollen germination under optimum temperatures. Carbohydrates provide energy for pollen tube growth and fertilization. Heat stress often disrupts carbohydrate metabolism, leading to reduced pollen viability. Therefore, sugar composition may serve as an additional indicator of pollen health and reproductive efficiency.

What Can Climate Change Mean for Cashew Reproduction?

Climate change is expected to increase both average temperatures and the frequency of extreme weather events. Such changes may influence flowering behaviour, pollinator activity, pollen viability, and fruit set. Scientists now recognize that reproductive processes are often more vulnerable to climate stress than vegetative growth. Consequently, understanding pollen behaviour provides valuable insights into how varieties may perform under future climatic conditions. The discovery that some cashew varieties maintain better pollen germination at elevated temperatures offers hope for developing climate-resilient cultivars capable of sustaining productivity under warming conditions.

From Pollen to Breeding Climate-Resilient Varieties

Traditionally, plant breeders evaluate varieties based on growth, yield, and nut quality. However, pollen traits are emerging as valuable tools for identifying stress-tolerant genotypes. Pollen-based screening can provide rapid

information about reproductive performance under high-temperature conditions. This approach allows researchers to identify promising varieties before conducting long-term field evaluations. Varieties capable of maintaining pollen viability and germination under heat stress may serve as valuable parents in breeding programmes aimed at improving climate resilience.

What Does This Mean for Farmers?

Although pollen grains are invisible to the naked eye, they play a crucial role in determining cashew productivity. Recent research on pollen morphology and temperature responses provides several important insights for farmers and researchers alike:

1. Good fruit set depends not only on the number of flowers produced but also on the quality and viability of pollen.
2. Temperature during flowering has a direct influence on pollen germination, fertilization, and ultimately nut production.
3. Cashew varieties differ in their ability to tolerate high temperatures, with some varieties maintaining better pollen performance under heat stress.
4. Climate-resilient varieties capable of sustaining pollen function under adverse weather conditions can help stabilize yields in the face of climate change.
5. Conservation of pollinators such as bees, flies, and other beneficial insects is essential for effective pollen transfer and successful fruit set.
6. Pollen-based screening offers a rapid and reliable tool for identifying heat-tolerant varieties and can accelerate the development of climate-resilient cashew cultivars.
7. Understanding pollen behaviour can help scientists and breeders develop improved varieties that are better adapted to future climatic conditions.

Key Message

A successful cashew harvest begins long before nuts develop on the tree. It starts with healthy pollen, favourable weather, active pollinators, and successful fertilization. Protecting these processes will be essential for sustaining cashew productivity under a changing climate.

Looking Ahead

As climate change continues to alter temperature patterns, understanding pollen behaviour will become increasingly important for sustaining cashew productivity. Recent studies have shown that cashew varieties differ significantly in pollen morphology and their ability to maintain pollen germination under heat stress. These differences provide valuable opportunities for identifying and developing climate-resilient cultivars.

Future breeding programmes should integrate pollen-based screening to select varieties with superior reproductive performance under challenging environmental conditions. By combining advances in pollen biology, plant breeding, and climate-smart orchard management, it is possible to develop resilient cashew production systems capable of sustaining yields under a changing climate. Ultimately, the future harvest of cashew begins with a healthy pollen grain. Protecting this critical stage of reproduction will be essential for ensuring productivity, profitability, and sustainability in the years ahead.

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Heliotropism Unlocked: How and Why Sunflowers Move

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Over the years, the sunflower (*Helianthus annuus*) has served as a symbolic representation of the sun due to the flower's golden petals and remarkable ability to move towards the source of light across the sky. Heliotropism, or solar tracking, is the scientific name for this unique phenomenon of plants moving in response to an external stimulus. Heliotropism is an intricate process in which the sunflowers bend towards the west in line with the movement of the sun all through the day while being guided by their circadian rhythm in re-orienting to the east in the evening. This bending occurs as a result of the differential growth pattern on either side of the stem where the east side grows faster in the daytime while the west side grows in the evening. Though one may be tempted to think that this is just a simple matter of a flower looking at the sun, science has proven otherwise.

The Daily Dance of the Golden Giants

Young sunflowers start their day facing east, waiting for the first rays of dawn. As the sun moves across the sky, the plants steadily track it, pivoting their heads toward the west until sunset. Then, in a remarkable display of anticipation, they reorient themselves overnight to face east once again, ready for the next morning.

This movement is not merely for show; it is vital for the plant's health. Scientists have noted a significant loss in photosynthetic productivity while disrupting this tracking by either staking the plants in place or rotating them so they face the wrong way which ultimately resulted in a 10% decrease in both dry biomass and leaf area. Solar tracking, it turns out, is a major driver of growth.

The Biology of a Bend

Whereas in animals there are muscles which help with locomotion, sunflowers lack this feature. Thus, differential growth is used instead. When it is daytime, the east part of the stem grows faster compared to the western one, pushing the flower head towards the west direction. In turn, at night time, when it is the opposite situation - the west part of the stem grows faster, swinging the flower head back to the east. Such growth is controlled with the help of a circadian clock - an internal 24-hour timer, which gives information about the time of sunrise. This means that even if sunflowers are placed into the conditions of constant light, their growth and movement will last for several days, showing that they act according to the internal rhythm of their body.

At the heart of this growth is auxin, a plant hormone that directs cells when to elongate. Phototropically driven auxin movement promotes growth of the shaded side over the illuminated side of the stem, causing curvature that keeps the shoot tracking the Sun west-ward. As the Sun passes the zenith, the shaded side becomes the east side, continuing to drive curvature westward. At night, intrinsic circadian signals cause auxin to reaccumulate on the west side, driving the direction of shoot growth back east.

Recent research has even delved into the mechanism of this growth: the phosphorylation of proton pumps (AHA proteins) in the stem. These pumps acidify the cell walls, making them flexible enough to stretch and expand, driving the plant's rhythmic movement. It has been found that the regulation of the heliotropic growth takes place through the autoinhibition of H⁺-ATPase (AHA) protein in plasma membrane or even at a lower level. Analysis of phosphoproteome of tracking stems has indicated that there is an elevated concentration of AHA protein phosphorylated on a particular site which is responsible for promoting ATPase activity on the eastern side of the stem during daytime and western part during night. This can be correlated with the growth pattern of the stems and suggests regulation of heliotropic growth by the phosphorylation of AHA protein.

Why Mature Sunflowers Stop Dancing

As a sunflower reaches maturity and its flowers begin to open, its daily tracking comes to an end. The stem stiffens, and the plant settles into a permanent eastward-facing position. This isn't accidental. By facing east, the flower heads warm up significantly faster in the morning sun.

This morning warmth provides a major reproductive advantage. Bees and other pollinators are more active when they are warm, and studies have shown that east-facing sunflowers attract five times more pollinating insects than those facing west.

Circadian oscillators enhance fitness by co-ordinating physiological processes with predictable changes in the environment. Such coordination generates the heliotropic movement of young sunflowers, enhancing plant growth, and

also leads to the eastward orientation of blooming sunflower disks, promoting a key component of reproductive performance and further enhancing seed production.

A New Scientific Mystery

For a long time, scientists assumed that heliotropism was simply a specialized version of phototropism which is the standard way plants grow toward a blue light source. However, groundbreaking new research using RNA sequencing has shown that the two processes are actually very different.

When sunflowers respond to a steady blue light in a lab, they trigger expression of thousands of classic phototropic genes within an hour of directional illumination.

But in the field, these genes are surprisingly quiet during the daytime tracking. Instead, researchers found that when sunflowers first start tracking the sun, they activate genes typically associated with shade avoidance, *PHYTOCHROME B* (*PHYB*) and *HOMEODOMAIN PROTEIN 2* (*HB2*) key components of the red/far-red light signaling pathway which are homologs of *Arabidopsis thaliana*. This suggests that sunflowers aren't just using blue light sensors; they are likely using red and far-red light receptors (phytochromes) to navigate their environment.

Furthermore, the nighttime reorientation might involve a process called auto-straightening or proprioception, portions of a stem bent during a tropic response subsequently straighten in a gravity-independent process. This complex interplay of multiple light signaling pathways and internal mechanical sensing makes the sunflower's behaviour far more sophisticated than previously imagined.

Conclusion

The sunflower is not merely an object for a gardener's attention - it is an expert at adjusting to new circumstances. Due to the work of its internal biological clock, hormonal cues, and various types of photoreceptors, it adjusts to all the changes that can take place. While studying more details about the routine of this flower, one realizes how interesting even the life of the most ordinary plants may be.

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The Garden of the Deep: How Seaweed Extracts are Revolutionizing the Future of Food

Article ID: 74425

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Agriculture being the anchor of human life on earth is facing an unprecedented crisis as a result of the world's rapidly booming population that is projected to reach 10 billion people by 2050 (UN DESA, 2017) and the simultaneous reduction of arable land brought on by urbanization, climate change, and soil degradation has significantly contributed to the reduction of agricultural productivity. For decades, the heavy reliance on synthetically manufactured fertilizer and pesticides was the conventional norm to boost yields. However, the price for this chemical revolution came at a cost of overall environmental pollution, human health hazards, and a decline in soil vitality. Despite these challenging environmental conditions, substantial increases in food production must be met while decreasing the environmental footprint of agriculture. Today, an alternative greener revolution has come forth of sustainable agriculture from the vast seas commonly known as seaweed extracts, a powerful plant biostimulant.

Beyond Fertilizers: What is a Biostimulant?

To unlock the true power of seaweeds we need to unravel the essence of seaweeds. Seaweed extracts do not simply play the role of fertilizers. While fertilizers are known to provide nutrients directly, biostimulants help to increase nutritional processes independent of the crop's nutrient content with the specific aim of enhancing nutrient use efficiency, resilience to abiotic stress and improve quality traits. On the basis of their pigmentation, seaweeds, or macroalgae are multicellular marine organisms that are further subdivided into three main categories: Phaeophyta (brown), Rhodophyta (red), and Chlorophyta (green). The dominant group are the Brown seaweeds with over 10,000 species scientifically studied out of which *Ascophyllum nodosum*, *Fucus*, and *Laminaria* are commercially used in the agriculture sector.

The Chemical Treasure Trove

Seaweed extracts are useful because of their intricate chemical composition. They are essentially a mixture of bioactive substances that terrestrial plants hardly ever make on their own. These include:

- 1. Unique Polysaccharides:** In most cases, brown seaweeds like *Ascophyllum nodosum*, *Fucus*, *Laminaria*, *Sargassum*, and *Turbinaria* spp. make commercial seaweed extract products, of which main bioactive compounds like laminarin, fucoidan, and alginates make up a significant portion of the extract which are typically absent in terrestrial plants. Laminarin acts as an energy reserve while fucoidan provide structural flexibility and protection. Alginates, the soil conditioners on the other hand gives rigid support and strength to the seaweed cell wall and helps in improving water retention and aeration, which in turn fosters deeper root systems.
- 2. Heavy metal adsorbents:** Red seaweed, *Kappaphycus* sp is an efficient and low-cost biosorbent used for removing toxic heavy metals like lead, copper, cadmium, chromium, and nickel from wastewater.
- 3. Phytohormones:** Seaweeds are rich in natural growth regulators, including auxins, cytokinins, and gibberellins. These biostimulants help in reducing seed dormancy and enhance root systems, flowering, fruit quality, and taste, and the overall quality of produce which further improve crop productivity.
- 4. Betaines and Amino Acids:** These act as osmoprotectants, helping plant cells maintain their water balance during periods of high salt or drought.
- 5. Minerals and Vitamins:** Seaweed extract provides a spectrum of macro- and micronutrients, including magnesium, iron, and zinc, alongside vitamins that bolster the plant's metabolic health.

Shielding Crops from Abiotic Stress

With the rise of climate change due to urbanization, industrialization and various anthropogenic activities agricultural fertile land is at the brink of extinction. Additionally, biotic stresses like fungal, bacterial, and viral pathogen attacks on crop plants affect the world's agricultural production. Over 50% of average yield losses have been accounted from abiotic stresses inflicted on crops. Seaweeds are macroscopic, multicellular organisms rich in lipids, proteins, carbohydrates, enzymes, and bioactive compounds and have the capacity to tolerate adverse situations such as high temperatures, salinity, and light.

Under drought conditions, studies have shown that application of *Ascophyllum nodosum* extracts helps to reduce leaf wilting and speed up recovery in crops like soybean, wheat, and tomato. The molecular mechanism of seaweed extracts

involves upregulation of genes via abscisic acid (ABA) signaling pathway thereby helping in stomatal closure to prevent water loss.

Additionally, salinity is another issue of global concern affecting over 800 million hectares of land. Seaweed extracts (*A. nodosum*) help plants maintain an ionic balance, specifically by regulating the Na^+/K^+ ratio. In studies of wheat and *Arabidopsis*, SE treatment upregulated Na^+ transporters that move harmful salt into vacuoles, keeping the rest of the cell safe.

A Natural Defense against Pathogens

Apart from stress caused by the environment, seaweed extracts can be considered as a powerful strategy in IPM program. They rarely act by directly destroying the pathogen; rather, they stimulate the activity of the plant's own immune system. This effect is known as Induced Systemic Resistance (ISR) and Systemic Acquired Resistance (SAR).

Phyco-elicitors (algal-derived chemicals that induce defense) such as carrageenans from red seaweed have proven their ability to slow down virus replication and restrict fungal growth. Thus, SE application in foliar sprays has helped to control powdery mildew in strawberries and grapes and has decreased the intensity of Early Blight (*Alternaria solani*) in tomatoes.

Even the unseen dangers lying in the soil, including root-knot nematodes, can be handled using the SE. Seaweed extracts of *Ecklonia maxima* and *Spatoglossum variabile* species were found to decrease the number of nematode galls by up to 96% due to betaines and phenolic substances contained in them.

Revolutionizing Soil Health and the Microbiome

The positive traits of seaweeds are not limited to their underwater features. The extracts of seaweeds serve as prebiotic for the soil, providing nutrients for beneficial microorganisms. In the rhizosphere (vicinity of roots), the SE can increase the number of beneficial fungi and bacteria, which will help plants absorb the nutrients easier.

Furthermore, alginates, which are extracted from brown seaweeds, form complexes with metal ions found in the soil, making it more stable. Thus, the soil that cannot sustain life is transformed into fertile soil that is able to retain water and prevent erosion.

This soil conditioning was well-known even in Roman times, but science begins to prove it only now.

The Protein Transition and Nutritional Value

One of the most exciting recent findings is the role of seaweed extracts in the protein transition. To produce 1 kg of animal protein, we currently need 3-6 kg of plant protein. By the year 2050, the demand for plant-based fodder will be astronomical.

Seaweed extracts offer a solution by significantly increasing the protein content of staple crops. Studies have shown that SE application can double the crude protein content in cowpea (*Vigna sinensis*) and significantly boost it in wheat, rice, and onions. Furthermore, crops treated with SE often have higher levels of antioxidants, flavonoids, and Vitamin C, making the final food product more nutritious for the consumer.

From Ocean to Field: The Extraction Challenge

The magic of seaweed is only as good as the method used to extract it. The challenge is maintaining the biochemical integrity of sensitive hormones and proteins. Traditionally, alkaline hydrolysis was used, but it can degrade certain hormones.

Today, researchers are moving toward Green Extraction technologies:

- 1. Microwave-Assisted Extraction (MAE):** Uses microwaves to rapidly extract sugars and phenolics while keeping their structure intact.
- 2. Ultrasound-Assisted Extraction (UAE):** Uses sound waves to create cavitation in cells, shaking loose bioactive compounds without using harsh chemicals.
- 3. Enzyme-Assisted Extraction (EAE):** Uses specific enzymes to break down the tough algal cell walls, a process that is eco-friendly and results in high-quality extracts.

Conclusion: Toward A Sustainable Future

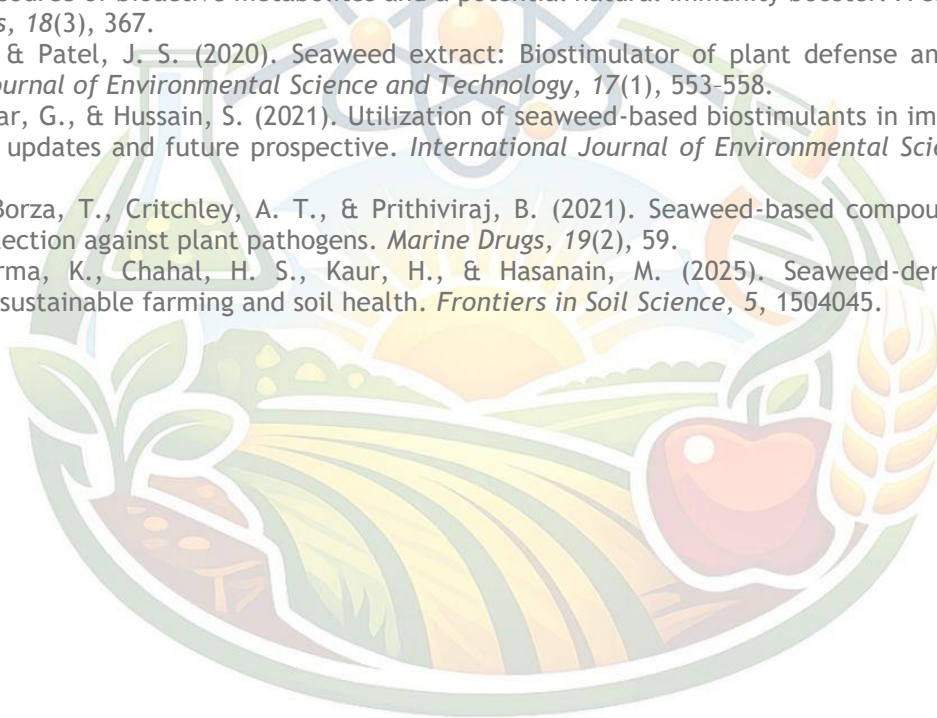
The move from a niche crop for specialty horticulture to a common agricultural practice for large-scale farming lies ahead of SEs. Linking SE usage with regular mineral fertilizers will allow for increasing the efficiency of fertilization, decreasing the quantity of fertilizers applied while increasing crop yield at the same time.

Seaweed is a renewable source of bio-resource which doesn't conflict with agricultural land as a means of providing food resources. With further development of the algae bio-refinery concept, one day we will obtain bio-fertilizers, biofuel, and even health care supplements out of one harvesting of seaweed per ton.

In our struggle with hunger and environmental destruction, the emerald depths of our seas could prove to be the answer. It turns out that the seaweed extracts are not only a plant biostimulator but a biostimulator for the sustainable future. And as the science community will continue to unlock the molecular secrets of these oceanic wonders, one thing becomes evident: The garden of the deep is ready to feed the world.

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Emerging Significance of Microgreens in Human Nutrition and Sustainable Agriculture

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Introduction

Microgreens have emerged as a globally significant food source, distinguished by their high nutrient density, rapid growth cycle, and minimal environmental footprint. Although their integration into mainstream markets is relatively recent, they represent a novel intersection between contemporary nutritional requirements and sustainable agricultural practices. They are young, tender seedlings harvested shortly after the cotyledon leaves have developed, typically within 7 to 21 days after germination. Microgreens are physically small but have rich nutritional composition, vivid coloration, and concentrated flavor profiles. In the context of escalating global challenges such as food insecurity, climate change, resource depletion, and the increasing prevalence of chronic diseases, microgreens offer a promising solution for addressing both health and sustainability concerns. Consequently, they are becoming an important focus of scientific research and a critical component in the advancement of resilient and sustainable food systems.

Understanding Microgreens

Microgreens are basically a stage between sprouts and baby greens in their stage of development. They are produced from a wide range of plant species, including leafy vegetables, herbs, cereals, and legumes. Commonly known microgreens are broccoli, radish, mustard, fenugreek, beet, spinach, sunflower, basil, and wheatgrass. The cultivation process is simple: seeds are sown in soil or a soilless medium, lightly watered, exposed to appropriate light, and harvested within a few days. Because of this controlled and rapid growth cycle, microgreens are not significantly exposed to pests, harsh climatic conditions, or soil contamination. This results in cleaner, safer produce without the need for pesticides or synthetic inputs.

The small size of microgreens often leads people to assume they are less nutritious than mature vegetables; however, research contradicts this. Microgreens contain higher concentrations of vitamins, minerals, antioxidants, and phytochemicals compared to their fully grown counterparts. Their nutritional density makes them a highly efficient source of essential nutrients, especially in diets where vegetable intake is inadequate.

Nutritional Composition of Microgreens

The exceptional nutritional quality of microgreens is one of the primary reasons behind their increasing popularity. Since they are harvested at an early stage, their tissues are metabolically active and packed with nutrients required for the plant's early development. This results in a higher density of vitamins, minerals, and phytonutrients when compared on a gram-for-gram basis with mature vegetables.

Microgreens are abundant in vitamins such as C, E, K, and beta-carotene, and are distinguished by their potent antioxidant capacity, which is critical in mitigating oxidative stress and supporting cellular integrity. In addition, they provide essential micronutrients including folate, iron, potassium, magnesium, calcium, and zinc. Their elevated levels of polyphenols, flavonoids, and carotenoids further contribute to anti-inflammatory and anticancer properties.

Among the diverse varieties, broccoli microgreens have gained notable scientific attention due to their exceptionally high sulforaphane content, a bioactive compound linked to detoxification, reduced inflammation, and enhanced cardiovascular health. Radish and mustard microgreens are rich in glucosinolates, compounds associated with metabolic regulation and immune support. Conversely, beet and amaranth microgreens are characterized by their substantial pigment content, particularly betalains and anthocyanins.

The nutrient density of microgreens makes them valuable in regions where access to fresh vegetables is limited or where micronutrient deficiencies are common. Their ability to deliver concentrated nutrition in small quantities makes them a powerful tool for improving overall dietary quality.

Health Benefits of Microgreens

The broad spectrum of nutrients and phytochemicals present in microgreens underpins their extensive health-promoting potential. Owing to their high antioxidant content, microgreens mitigate the damaging effects of free radicals, thereby enhancing immune function, reducing inflammatory responses, and supporting cellular repair processes. Antioxidants further contribute to delaying the onset of aging and slowing the progression of degenerative disorders.

Microgreens also play a significant role in cardiovascular health by lowering cholesterol, improving lipid metabolism, and supporting vascular integrity. Elevated levels of potassium and magnesium aid in blood pressure regulation, while dietary fiber promotes digestive efficiency and assists in glycemic control.

Certain varieties, including broccoli and kale microgreens, are particularly rich in phytochemicals that activate detoxification pathways, facilitating the removal of harmful metabolites and environmental toxins. Moreover, the substantial concentrations of vitamins C and E commonly found in microgreens strengthen immune defenses and contribute to skin health.

Because microgreens are typically consumed raw, they retain a high level of bioavailable nutrients that might otherwise be diminished through cooking processes. Their ease of incorporation into daily meals further enhances their practicality, positioning them as an accessible and effective option for individuals seeking to improve dietary quality and overall health.

Microgreens in Sustainable Agriculture

Sustainability represents one of the most compelling advantages of microgreens. Compared to conventional crops, their cultivation demands substantially fewer inputs, positioning them as a model for environmentally responsible agriculture. Since they have a short growth cycle, microgreens consume markedly less water, soil, and energy than mature vegetables. Furthermore, they can be produced in compact, controlled environments, thereby minimizing land use and enabling cultivation across both urban and rural settings.

The absence of pesticide requirements and the feasibility of indoor production significantly reduce risks of environmental contamination. Controlled cultivation systems also mitigate reliance on variable climatic conditions, ensuring a consistent and year-round supply. By supporting localized food networks, microgreen production decreases carbon emissions associated with long-distance transportation of fresh produce.

Microgreens are particularly compatible with hydroponic, aeroponic, and vertical farming technologies, which maximize spatial efficiency and resource utilization. Vertical farming facilitates the stacking of multiple trays, allowing dense production even in constrained areas such as apartments, rooftops, or community facilities. Consequently, microgreens emerge as a vital component of sustainable urban agriculture and climate-resilient food systems.

Microgreens as a Tool for Food Security

Growing interest in microgreens aligns with the urgent need to address global food security. As population growth accelerates, agricultural land diminishes and climatic conditions become increasingly unpredictable, reliance on conventional farming methods alone may prove insufficient to meet future nutritional demands. Microgreens present a complementary and highly efficient alternative.

Due to their rapid growth cycle, microgreens can yield fresh produce within days rather than the extended timelines required for mature crops. Their ease of cultivation makes them suitable for households, schools, and community organizations, thereby fostering localized sources of nutrient-rich food. This is particularly advantageous in urban environments where access to fresh vegetables is limited. Moreover, microgreens hold potential in emergency nutrition initiatives, humanitarian relief efforts, and remote regions where food supply chains are unreliable.

In addition to their nutritional benefits, microgreens are economically accessible, requiring minimal resources, equipment, and space. This affordability enables adoption by low-income families and small-scale farmers seeking to enhance food security and generate income. Their relatively high market value further creates entrepreneurial opportunities, particularly for women and youth, positioning microgreens as both a nutritional and socio-economic asset.

Microgreens in the Future of Functional Foods

With the growing demand for functional foods, microgreens are increasingly recognized as valuable components in nutrient-enriched products. They are now incorporated into smoothies, powders, juices, snack items, and ready-to-eat meals. Their distinctive flavors and visual appeal further enhance their use in culinary contexts, particularly within gourmet and health-oriented cuisines.

Microgreens also correspond with prevailing global trends such as plant-based eating, clean-label formulations, and minimally processed nutrition. Their versatility and concentrated nutrient profile indicate that they are poised to play a significant role in advancing health-focused food innovation in the future.

Conclusion

Microgreens represent a unique combination of nutrition, sustainability, and modern agricultural practices. Characterized by exceptional nutrient density, rapid growth cycles, minimal input requirements, and year-round availability, they represent an optimal food source for addressing the dietary needs of an expanding global population. Their ecological benefits, coupled with ease of cultivation and economic viability, underscore their relevance within both domestic and commercial food systems.

As functional foods are gaining importance in modern dietary patterns, microgreens distinguish themselves as a nutritionally superior and environmentally sustainable choice. Whether cultivated in household settings or incorporated into large-scale farming operations, microgreens hold significant potential to reshape the future of nutrition and advance sustainable food production.

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Digital Twin in Food Processing: Virtual Models for Real World Efficiency

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Abstract

Digital twin technology is transforming food process engineering by creating dynamic virtual replicas of physical assets that update continuously with real time sensor data. This article outlines core twin components, including sensor networks, data infrastructure, and hybrid physics machine learning models, and operator dashboards and their applications in food processing, fermentation, drying, packaging, cold storage, and energy management. Benefits include accelerated troubleshooting, reduced experimental costs, improved product uniformity, predictive maintenance, lower energy use, and reduced postharvest losses. Barriers include data integration challenges, model validation needs, workforce training gaps, and uncertain economic returns. As sensors become affordable and modeling matures, twins are transitioning from demonstrations to routine engineering tools.

Keywords: digital twin, food processing, cold storage, process optimization, hybrid modeling, predictive maintenance, Industry 4.0.

Introduction

The food industry faces expanding demand, stricter safety regulations, tighter margins, and sustainability expectations that conventional methods cannot efficiently address. Digital twins offer a solution by creating virtual counterparts that mirror physical assets through continuous sensor data integration. Unlike offline simulations, digital twins operate synchronously with physical processes. This enables estimation of hard to measure variables such as internal temperatures, moisture gradients, microbial inactivation, and shelf life evolution. Engineers test scenarios virtually before implementation.

Digital twin technology originated in aerospace and manufacturing. Adoption in food processing lagged due to biological complexity, safety requirements, and fragmented data systems. Recent advances in IoT sensors, cloud computing, and machine learning now make twins viable. Industry reports from 2026 show accelerating deployment despite cost and expertise barriers. Digital twins can represent single units like dryers or pasteurizers, complete production lines, cold storage facilities, or entire plants. They combine mechanistic models for heat transfer, fluid dynamics, and reaction kinetics with data driven approaches and live operational data. This integration enables capabilities beyond physical sensors alone, such as estimating internal temperature distributions or predicting remaining shelf life during cold storage.

This article provides a practical overview of digital twin components and applications across thermal processing, fermentation, drying, packaging, cold storage, and energy management. It also covers key advantages and challenges for food process engineers (Abdurrahman and Ferrari, 2025).

Concept and Core Components

A digital twin is a real time, dynamic virtual replica that stays synchronized with its physical counterpart via continuous data flow. Effective food processing twins integrate five layers:

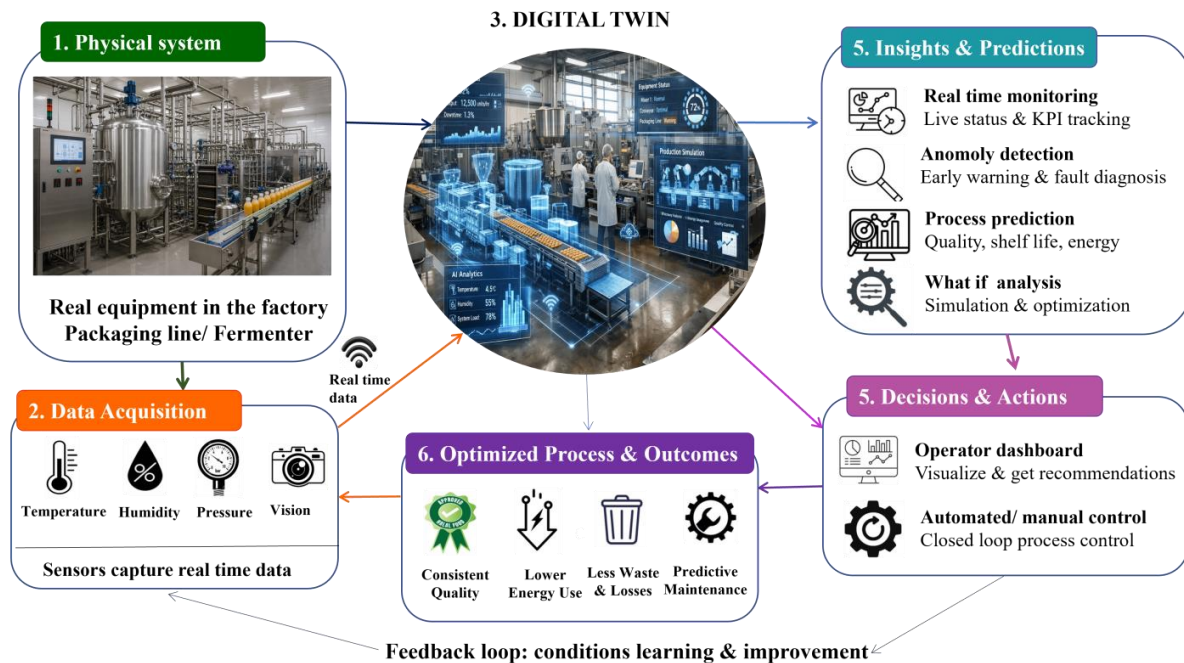
Physical Layer: Sensors (temperature, pressure, humidity, flow, vision), actuators (valves, pumps, heaters, compressors), and control hardware (PLCs, SCADA, DCS).

Data Infrastructure: Real time acquisition, time series databases, and preprocessing for noise reduction, outlier removal, and temporal alignment.

Modeling Layer: Physics based models (CFD, heat transfer, kinetic models) coupled with machine learning trained on historical and streaming data.

Analytics Layer: State estimation (e.g., kalman filters), anomaly detection, predictive modeling (equipment life, shelf life, quality), and optimization (MPC, reinforcement learning).

Decision Support: Dashboards, alerts, recommendations, and optional closed loop control integration (Purlis, 2024).



Applications

Thermal Processing: Estimate internal temperatures, moisture profiles, and microbial inactivation during drying, cooking, and pasteurization to optimize energy while meeting quality targets (Defraeye and Onwude, 2020).

Fermentation: Infer biomass, substrates, and metabolites from limited sensors. Predict kinetics under seasonal raw material variability. Recommend adjustments to temperature, pH, or feeding to ensure batch consistency (Goffi *et al.*, 2025).

Drying: Predict intra particle moisture distributions to prevent over or under drying. Simulate airflow and heat recovery. Control powder flowability, solubility, and bulk density.

Packaging: Monitor seal integrity, fill volumes, and label positioning. Simulate format changes to reduce changeover waste. Forecast failures for scheduled maintenance (Huang *et al.*, 2024).

Cold Storage: Identify hot/cold spots. Predict remaining shelf life for inventory prioritization. Cut energy use 10-20% via optimized set points and load shifting. Evaluate “what-if” scenarios virtually (Zhang *et al.*, 2026).

Energy and Sustainability: Benchmark energy use. Estimate carbon intensity. Assess heat recovery, variable frequency drives, and renewable integration. Support solar-hybrid cold storage for remote sites.

Advantages and Limitations

Digital twins enable faster hypothesis testing, lower experimentation costs, improved consistency, predictive maintenance, reduced energy consumption, and decreased postharvest losses through shelf life prediction. Adoption barriers include limited sensor coverage, data silos, the need for hybrid modeling expertise, workforce training gaps, high upfront investment with uncertain ROI, regulatory compliance (HACCP, GMP), and cold storage specific modeling challenges (complex airflow, respiration, heterogeneous loads) (Purlis, 2024).

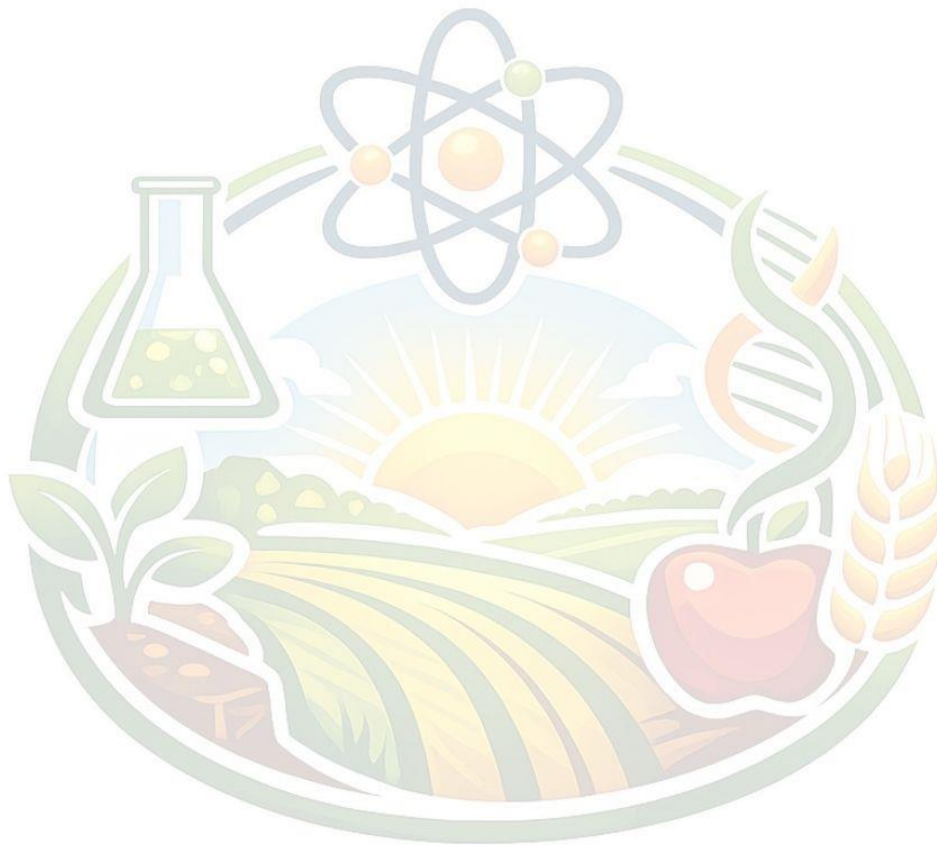
Conclusion

Digital twins are evolving from novel concepts to essential tools for food process engineers, providing virtual environments for testing, optimization, and prediction to design safer, more efficient, and sustainable processes. In cold storage, they offer powerful capabilities for temperature control, shelf life prediction, and energy optimization that can significantly reduce losses. As sensor costs decline, modeling techniques advance, and platforms mature, twins are moving toward standard practice. Priorities include building hybrid modeling capacity, fostering engineer data scientist collaboration, and launching focused pilot projects (single dryers, pasteurizers, fermenters, or cold stores) that demonstrate measurable gains in quality, energy, equipment availability, or shelf life.

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Heating Foods with Radio Waves: A New Era in Food Processing

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Abstract

Conventional thermal processing methods that rely on heat conduction and convection have long been the foundation of food preservation. However, limitations including prolonged processing times, uneven heat distribution, and negative impacts on sensory and nutritional properties of foods have driven interest in alternatives. Radio frequency (RF) heating, a dielectric technology that generates heat from within food materials through electromagnetic energy, has emerged as a promising solution. Operating at permitted frequencies of 13.56, 27.12, and 40.68 MHz, RF heating offers rapid, volumetric, and deep-penetration heating suitable for a wide range of food products. This article presents an overview of the scientific principles, advantages, and diverse food processing applications of RF technology, including pasteurization, disinfestation, drying, and grain and produce processing, while highlighting its role in improving food safety and quality.

Keywords: Radio frequency heating; food processing; dielectric properties; pasteurization; disinfestation; food safety.

Introduction

Thermal treatment is a very common method in food processing industries to eliminate microorganisms and inhibit the activity of harmful enzymes in order to ensure the safety of food products and extend product shelf life (Altemimi et al., 2019). Thermal treatment involves the transfer of heat through conduction and convection, which can prolong the time required for heating depending on the food matrix (Altemimi et al., 2019). These restrictions can lead to significant physicochemical changes within thermally treated food products, resulting in alterations in sensory and textural properties as well as a decrease in nutritional value (Altemimi et al., 2019).

In recognition of these drawbacks, researchers have increasingly sought alternative technologies. Radio frequency (RF) heating, operating in the frequency range between 10 and 50 MHz for industrial applications, was first described as a heat source in the middle of the twentieth century, when it was used to melt frozen foods and to process and preserve meat products (Altemimi et al., 2019). The electromagnetic heating process is relatively quick and takes place through the direct transmission of electromagnetic energy to the product, generating heat within the food without the need for external heat transference (Altemimi et al., 2019).

Safety concerns regarding postharvest agricultural products, environmental pollution caused by chemical fumigations, and increased international regulations to limit the use of fumigants have made it extremely urgent to develop novel and environmentally friendly physical alternatives for the postharvest control of insect pests and pathogens (Wang & Li, 2023). RF treatment has been identified as a leading candidate among such alternatives, providing fast and volumetric heating that is well-suited to a variety of food processing and preservation applications (Wang & Li, 2023). This article reviews the scientific principles, advantages, and key applications of RF heating technology in food processing.

Scientific Principles of Radio Frequency Heating

RF heating is classified as a novel thermal processing method in food engineering and is also referred to as dielectric loss heating or dielectric heating (Altemimi et al., 2019). The range of frequencies permitted by the Federal Communications Commission for Industrial, Scientific, and Medical applications are 13.56, 27.12, and 40.68 MHz (Bermudez-Aguirre & Niemira, 2023). RF is a novel thermal technology based on the volumetric heating of the product, using the dielectric and thermal properties of the food to generate heat from inside the product (Bermudez-Aguirre & Niemira, 2023).

The underlying mechanism of RF heating involves two dominant processes: dipole rotation and ionic conduction (Altemimi et al., 2019). When foods containing polar molecules such as water are placed in an alternating electric field, the polar molecules continuously rotate to align with the changing field, and friction among molecules converts electromagnetic energy into heat, raising the temperature of the treated material (Altemimi et al., 2019). At the same time, the oscillating motion of dissociative ions in the food in response to the alternating electric field generates additional heat through friction, a mechanism known as ionic conduction (Altemimi et al., 2019). Temperature and frequency play an important role in both mechanisms, as increases in either lead to greater molecular movement and heat generation (Altemimi et al., 2019).

RF heating differs importantly from microwave heating in terms of penetration depth. The penetration depth of RF at 27.12 MHz has been reported at approximately 20 cm in milk or yogurt products, while microwaves at 2.35 kHz offer only about 1 cm of penetration in the same substrates (Altemimi et al., 2019). Longer wavelengths used in RF heating do not result in the patterns of cold and hot spots that are commonly associated with microwave heating (Altemimi et

al., 2019). The dielectric properties of each food material are unique and are a function of several factors, including temperature and moisture content (Bermudez-Aguirre & Niemira, 2023).

Advantages and Limitations

RF heating presents multiple characteristics compared with conventional heat transfer and heat diffusion methods (Altemimi et al., 2019). Because RF power can penetrate deeper into foods than conventional microwaves, heat is generated inside the food and distributed evenly (Altemimi et al., 2019). Construction of a large-scale RF heating system is practical, and this eco-friendly technology offers higher energy use efficiency than traditional systems (Altemimi et al., 2019). The processing time is reduced compared to traditional heating, thermal damage to the food is minimized, and the products' final quality can be considerably better than conventional thermal processes (Bermudez-Aguirre & Niemira, 2023). RF energy can penetrate through non-metallic packaging, enabling non-contact heating of packaged food products (Tang et al., 2024).

RF heating also presents limitations. The main drawback of the technology is the lack of uniform heating, mainly when the product is surrounded by packaging material with different dielectric properties from the food (Bermudez-Aguirre & Niemira, 2023). Several factors affect RF heating uniformity, including physical, dielectric, thermal, and chemical properties of the food, the distance between the treated product and the electrodes, and the engineering design of RF heating devices (Altemimi et al., 2019). RF heating equipment is also more expensive compared with equipment used in traditional heating systems (Altemimi et al., 2019). To address the uniformity problem, methods such as rotation, agitation, mixing of product containers between electrodes, pulse mode operation, and computer simulation modeling have all been investigated for various food products including wheat flour, soybeans, meat, and dry foods (Altemimi et al., 2019).

Applications in Food Processing

1. Pasteurization and Microbial Inactivation: RF has been successfully applied in the inactivation of significant pathogens such as *Salmonella* spp., *Listeria monocytogenes*, and *Escherichia coli* in both low- and high-moisture foods (Bermudez-Aguirre & Niemira, 2023). RF heating has also been demonstrated effective in the pasteurization of yogurt and the destruction of microorganisms in liquid and solid foods, and RF-treated meat has shown improved quality and coagulation with acceptable taste and appearance (Altemimi et al., 2019). Pilot-scale RF heating systems for the pasteurization of beef sausage and ready-to-eat meat products have confirmed the feasibility of scaling the technology for industrial applications (Wang & Li, 2023). For food grains, RF technology has been regarded as a promising alternative to traditional heating methods for improving safety due to its fast, volumetric, and deep-penetration heating characteristics (Ling et al., 2020). Post-harvest losses caused by insects, fungi, food-borne pathogens, and undesirable enzymes remain a major concern for the grain industry, and RF treatment addresses these challenges while avoiding the chemical residues associated with conventional fumigation (Ling et al., 2020).

2. Disinfestation of Agricultural Products: Disinfestation of crops using RF is possible because of selective heating, as insects are inactivated first due to the different dielectric properties between the pests and the food material (Bermudez-Aguirre & Niemira, 2023). The large difference in dielectric loss factors between target pests and host foods means that RF energy can selectively heat and kill the organisms without damaging the agricultural product (Tang et al., 2024). RF disinfestation has been studied for grains, nuts, and dried fruits, where RF treatment successfully inactivates insects and molds without causing significant damage to product quality (Ling et al., 2020). RF heating provides rapid, volumetric, and deep-penetration heating characteristics that make it a promising alternative treatment for replacing conventional thermal processing in the fresh produce sector (Tang et al., 2024).

3. Drying Applications: There has been increased interest in the RF drying method due to the homogeneity of heating, greater penetration depth, and more stable control of the product temperature (Altemimi et al., 2019). RF drying provides greater penetration depth and better drying uniformity than microwave drying, making it particularly suitable for treating large-volume food samples (Tang et al., 2024). In the case of large-scale paddy rice drying, RF heating combined with hot air has been shown to affect milling and cooking qualities of milled rice (Wang & Li, 2023). For grain products, RF drying has also been applied to inactivate undesirable enzymes; hot air-assisted RF heating for the stabilization of rice bran reduced enzyme activity while preserving phenolic content, antioxidant activity, and microstructure (Ling et al., 2020).

4. Blanching, Thawing, and Other Applications: RF heating has been used to blanch vegetables to increase ascorbic acid content, achieving the highest vitamin C levels compared with conventional blanching methods (Altemimi et al., 2019). RF heating has also been reviewed for its role in blanching as a means of inactivating enzymes that would otherwise cause quality deterioration in fruit and vegetable products during subsequent processing or storage (Tang et al., 2024). The use of RF thawing technology has resulted in better quality of treated food, and RF tempering has been studied for frozen fish products including tilapia fillets and salmon, positively influencing temperature distribution and physiochemical properties (Wang & Li, 2023). RF heating has been tested for other food processing applications such as roasting, baking, and cooking, further demonstrating the breadth of its applicability across the food industry (Bermudez-Aguirre & Niemira, 2023).

RF Heating for Specific Food Categories

1. Food Grains and Their Products: Food grains constitute a vital part of the daily diet of populations worldwide and are generally considered safe products with high storage stability due to their low moisture contents (Ling et al., 2020). However, post-harvest losses caused by insects, fungi, food-borne pathogens, and undesirable enzymes remain a major concern for the grain industry (Ling et al., 2020). A comprehensive review of RF heating for food grains has covered applications including disinfestation, pasteurization, enzyme inactivation, drying, and roasting for processing food grains and their products (Ling et al., 2020). Research has also examined the effects of RF treatment on the microstructure, digestibility, and physicochemical properties of rice grains (Wang & Li, 2023).

2. Fruits and Vegetables: Thermal processing is commonly employed to ensure the quality and extend the shelf-life of fruits and vegetables, and RF heating has been used as a promising alternative treatment to replace conventional thermal processing methods, with advantages of rapid, volumetric, and deep penetration heating characteristics (Tang et al., 2024). Research covering RF heating uniformity and applications in processing fruit and vegetable products has addressed a range of operations including disinfestation, blanching, drying, and pasteurization (Tang et al., 2024). The dielectric properties of fruits and vegetables are central to determining the effectiveness of RF treatment, as these properties govern the extent to which electromagnetic energy is absorbed and converted to heat within the product (Tang et al., 2024). The variation in dielectric properties across different fruits and vegetables, as well as the influence of temperature and moisture content on these properties, therefore represents a key area of ongoing research that underpins the practical optimization of RF processing protocols (Tang et al., 2024).

Conclusion

Radio frequency heating represents a significant advancement in food processing technology. By generating heat volumetrically from within food materials through electromagnetic energy, RF technology overcomes many limitations of conventional conduction and convection-based thermal methods, offering faster processing times, deeper heat penetration, and better preservation of nutritional and sensory properties. Its applications span pasteurization, disinfestation, drying, blanching, thawing, and roasting across diverse food categories from grains and nuts to fruits, vegetables, and meat products. While challenges such as heating non-uniformity and high equipment costs remain to be fully resolved, ongoing advances in computer simulation modeling and process engineering continue to narrow these gaps. RF heating is well positioned to play an increasingly central role in the future of safe, efficient, and quality-focused food processing.

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Seed Storage Reserves

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About 70% of all food for human consumption comes directly from seeds (Mostly those of cereals and legumes). In addition to the normal chemical constituents found in all plant tissue, seeds contain extra amounts of substances stored as a source of food reserves to support early seedling growth Bewley *et al.* (2013); Copeland & McDonald, (2001). These are carbohydrates, fats and oils and proteins, others like phytin, and undesirable or even toxic (e.g., alkaloids, lectins, proteinase inhibitors phytin, raffinose oligosaccharides)

The chemical composition of seeds is determined ultimately by genetic factors some modifications of compositions may result from agronomic practices (e.g.: nitrogen fertilizer application, planting dates) or may be imposed by environmental conditions prevalent during seed development and maturation. The major food reserves may be deposited within the embryo usually the cotyledons. In Brazil nut, they occur within radical/hypocotyls or within-extra-embryonic tissue the endosperm/rarely perisperm-coffee, yucca.

Different reserves maybe located within different storage tissues; in fenugreek seeds, endosperm is exclusive source of carbohydrate but cotyledons contain protein and fats. The reserves maybe distributed unevenly within any one storage tissue ex. In maize grain, there are proteins rich regions (horny endosperm) and starch rich regions (floury endosperm) within endosperm. Chemical differences also exist within species in relation to distribution of particular reserve. E.g. In rapeseed, the oil in the cotyledons and hypocotyl contains different proportions' of erucic and palmitic acid.

Carbohydrate Storage in Seeds

The major storage substances in most cultivated cereals & grasses-rich in CHO'S & low in fats and proteins, peas and beans- moderately high in CHO'S. Seeds of many trees as chestnut, buckeye, have a relatively high carbohydrate content.

Starch and hemicelluloses are major forms of CHO storage in seeds other carbohydrates that occur in non storage forms are pectin's and mucilage's.

1. Starch: Seeds are composed largely of metabolically inactive food reserves that are stored until needed during germination. Starch is stored in two related forms, amylose and amylopectin, which are two polymers of D- glucose, one linear and other branched. Starch is the principal, most widespread storage carbohydrate of seeds.

Amylose is composed of 200 to 1000 glucose units linked by α -1 $\rightarrow$ 4 glucosidic bonds ranging from 10,000 - 1,00,000. It stains blue with iodine & is 100% digestible by B- amylase.

Amylopectin-is a larger molecule consisting of 20-25 glucose units per branch, linked by both α -1 $\rightarrow$ 4 and α -1 $\rightarrow$ 6 glucosidic bonds with molecular weight ranging from 50,000 to 1,000,000 stained purplish red when exposed to iodine 50% digestible by the enzyme B- amylase. Both amylase and amylopectin are hydrolyzed by the enzyme α and B- amylase during normal metabolism and germination.

α -amylase attack both amylose & amylo pectin randomly cleaving α 1,4 and α 1,6 linkages. On amylolysis large amounts of dextrin molecules to maltose and finally glucose the enzyme the enzyme is formed de novo in the aleurone layer of barley & scutellum of corn. B-Amylase hydrolyzes both amylose and amylopectin from the non reducing end by breaking the α -1,4 linking and forming maltose Taiz *et al.* (2015), Buchanan *et al.* (2015).

In seeds most starch is laid down in discrete sub cellular bodies called starch grains that range from 2-100 μ in size. Within the endosperm many starch grains appear to form around a central point, the hilum around which shells of the polysaccharide are deposited. The shape of the starch grain appears to depend on the amylose content - less angular and rounded grains having high amylase levels. Most starch grains are composed of about 50-75% amylopectin and 20-25% amylase.

2. Hemicelluloses: is usually found in cell walls of plants in certain seeds found as reserve food materials. These are found in the thickened tertiary layers of cell walls of the endosperm or cotyledons instead of the interior region of the endosperm. They are composed principally of mannans, they are characteristic of the palm species.

3. Other seed carbohydrates:

a. Mucilages: are complex carbohydrates consisting principally of polyuronides and galactouronides that chemically resemble the pectin compounds & hemicelluloses. They are similar to the gums found in the bark and stems of many plants.

b. Pectin compounds: occur in seeds in other plant parts mainly as components of the cell wall and the middle lamella. Three principal pectin compounds are pectic acid, pectin and protopectin. They are used as setting agents in Jams & jellies.

Lipid Storage in Seeds

Lipids are plant/ animal substances that are insoluble in water, but soluble in ether. They are esters of either fatty acids or glycerol or their various hydrolytic products. They are known as glycerides specifically triglycerides, because each glycerol molecule is combined with three fatty acids molecules. Oils remain liquid at room temperature.

Fatty acids constitute natural fats. Free fatty acids are seldom found in plant parts other than in germinating or deteriorating seeds as a result of fat hydrolysis. Fatty acids are saturated/ unsaturated depending on the type of carbon linkage in the molecule. The unsaturated fatty acids contain one or more double bond links. The unsaturated fatty acids are most common in seeds with oleic acids (one double bond) and linoleic acids (two double bonds) accounting for 60% of the weight of all lipids present in most oilseed crops Bewley et al. (2013); Copeland & McDonald (2001). Saturated fatty acids (even no 'C' atoms 4-24) are also present. Palmitic acids (n=14) most common saturated fatty acid in oilseeds. Trihydroxy alcohol and glycerol form esters with different fatty acids

Lipids are classified as a) simple b) compound or c) derived.

Simple lipids- esters of fatty acids and glycerol. Ex. Fats & fatty oil

Compound lipids- esters of fatty acids containing additional chemical groups. Ex: phospholipids

Derived lipids-derived from simple & compound lipids. Ex: cholesterol.

Majority of seed lipids are simple lipids which include fats, fatty oils & waxes. Waxes are simple lipids that are fatty acid esters of some alcohol other than glycerol. They are usually found as coverings for the leaves, fruits & seeds of many plants. Hydrolysis of lipids- when oilseeds with a high lipid content germinate, there is a rapid disappearance of lipid with a concomitant rise in sucrose content. Lipase activity rises sharply and participates in stepwise hydrolysis of triglycerides to diglycerides monoglycerides and finally free glycerol and free fatty acids. These are further oxidized by both alpha and beta-oxidation during the course of germination.

Most lipids are stored in oil storage bodies called sphaerosomes, size range in 0.2 to 6.0µ in diameter. Many of the enzymes essential for fatty acid biosynthesis or for triglycerides hydrolysis are present in sphaerosomes.

Protein Storage in Seeds

Proteins are nitrogen containing molecules of huge size and exceedingly complex structure, greater part of which yield amino acids upon hydrolysis of peptide bond. Proteins are important as all physiological reactions of living cells revolve around their physical and chemical properties and those of related compounds and are the principal components of all protoplasm Osborne (1924).

They are a valuable food storage component in seeds of most plant species e., soybean. Soybean plants known to have high protein seed are legumes having nitrogen fixing capacity. Many high protein species are nonlegumes. Seed storage proteins are less complex than protoplasmic proteins. Majority of seed proteins are metabolically inactive & serve merely as food reserves for use by the growing embryo during germination.

Proteins are stored in the seed in units known as protein bodies that are 1-20µ in diameter bound by a lipoprotein unit membrane. These are deposited in the albuminous aleurone layers of cereal seeds and that, during seed germination, play an important role both as food reserves and as hydrolytic enzymes to aid in starch breakdown.

Osborne (1924) on the basis of solubility, classified seed protein into

1. Seed albumins- are soluble in water at neutral/ slightly acid pH and are coagulated by heat, ex: Leucosins-cereal grains, ricin rice, legumelin of pulse seeds.
2. Seed globulins- are soluble in saline conditions but not in water and are difficult to coagulate with heat ex: found dominantly in dicot seeds as legumes. Legumin, vignin, glycinin, vicilin, arabin.
3. seed glutelins- are soluble in aqueous or saline solutions or ethyl alcohol, can be extracted with storage acid or alkaline solutions found in most cereal seeds ex. Gluten of wheat, oryzenin rice.
4. seed prolamines- soluble in 70-90% ethyl alcohol but not in water. They are found only in cereal seeds ex. Gliadin of wheat, zein maize. Upon hydrolysis they yield prolamines, glutamic acid & ammonia.

Other Chemical Compounds Found in Seeds

Tannins: also occur in seed coat structure, they are found in testa of cocoa and bean seed.

Used generally in tanning process- for removing hair from animal skins.

Alkaloids- Socrates died from drinking a cup of hemlock containing alkaloid poison conium. Better known alkaloids that occur in plants or their seeds are morphine from poppy fruits, strychnine from seeds of *Strychnos nuxvomica*, atropine

from deadly night shade, colchicine from meadow saffron, caffeine from coffee, tea, nicotine from tobacco leaves, theobromine from cocoa.

c) Glucosides- are found mostly in vegetative organs of plants, some do appear in seeds.

Ex. Salicin in bark & leaves of willows, amygdaline in seeds of almonds', peaches plums, sinigrin in black mustards, quercitron in bark of oak, saponin- tung seed - highly poisonous to both man& animals.

d) phytin- insoluble mixed potassium, magnesium and calcium salt of myoinositol hexa phosphoric acid. A major form of phosphorous storage in seeds, in cereal grains, phytin is associated with protein bodies in the aleurone layer & more or less absent from the protein bodies of the cotyledons. During germination of seeds, phosphatases that hydrolyze phytin increase several folds. The phytase activity is highest in the scutellum & aleurone layers because of the presence of these nutrients, a seeds subsequent metabolism is dependent on the hydrolysis of phytin.

e) Hormones- certain organic compounds, that when present in minute quantities exert important regulatory effects on metabolism. Phyto hormones- in seeds are

Gibberellins: are normal constituents of green plants as well as seeds, play a major physiological role in both seed development and seed germination, also exert an influence on floral induction& initiation.

Cytokinins: 1st discovered in coconut milk appear necessary for cell growth & differentiation. It is the basis for their influence in promoting seed germination. They inhibit senescence of leaves and regulate the flow of chemicals through plant system.

Inhibitors: that influence germination is coumarins, ABA, Maleic hydrazide. Dormancy in seeds, buds tubers/plants is regulated by a balance of interaction between endogenous inhibitors and growth promoters.

Vitamins: Thiamine- necessary for developing embryo and endosperm of seeds in some species & also for normal root development. It is produced in the vegetative plant parts or by the cotyledons & translocated into areas needed. Biotin & ascorbic acid - involved in respiration of seeds. Ascorbic acid- responsible for regulating the oxidation- reduction potential during germination.

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Plant Defence Mechanisms: Signaling Pathways and Gene Regulation

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Abstract

Plants are continuously exposed to pathogens, herbivorous insects and environmental stresses, yet they lack the antibody-based adaptive immune system found in animals. Instead, plants possess a sophisticated innate defence system that enables them to perceive threats, transmit molecular signals and activate appropriate responses. Defence begins with recognition of microbial or damage-associated signals by pattern-recognition receptors, followed by rapid calcium influx, reactive oxygen species production, mitogen-activated protein kinase activation and protein phosphorylation. Pathogen effectors can activate intracellular immune receptors and stronger effector-triggered immunity. These signalling events converge on transcriptional networks involving WRKY, MYB, NAC, AP2/ERF and bZIP transcription factors. Salicylic acid, jasmonic acid and ethylene act as major hormonal regulators and interact extensively to determine defence specificity. Defence gene expression is further controlled at post-transcriptional, translational and epigenetic levels. Understanding these mechanisms provides important opportunities for disease-resistance breeding, genome editing and sustainable crop protection.

Introduction

Plants are constantly exposed to bacteria, fungi, oomycetes, viruses, nematodes and herbivores. Because they are sessile, their survival depends on rapid recognition of threats and activation of effective defence mechanisms. Unlike animals, plants lack circulating immune cells and classical adaptive immunity. Instead, plant immunity is distributed throughout tissues and involves cellular surveillance, signaling networks, structural barriers and antimicrobial compounds. Two interconnected layers of recognition are particularly important: perception of conserved microbial molecules at the cell surface and intracellular detection of pathogen-derived effectors or their effects on host components (Jones & Dangl, 2006). Plant defence is a dynamic network rather than a single pathway. Receptor activation rapidly induces calcium influx, reactive oxygen species (ROS), protein kinase cascades, membrane-potential changes and hormonal signaling. These events subsequently modify transcription and the expression of numerous defence-associated genes. The response involves coordinated communication among the plasma membrane, cytoplasm, nucleus, chloroplasts, mitochondria and other cellular compartments. Defence responses also depend on pathogen lifestyle. Biotrophic pathogens are commonly associated with salicylic acid (SA)-mediated resistance, whereas necrotrophic pathogens and herbivores frequently activate jasmonic acid (JA) and ethylene pathways. However, these responses are not completely separate. Extensive hormonal crosstalk allows plants to adjust defence according to the nature, intensity and duration of stress.

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Pathogen Perception and Activation of Immunity

The first stage of plant defence is recognition of potential danger. Plants perceive pathogen- or microbe-associated molecular patterns (PAMPs/MAMPs), including bacterial flagellin and elongation factor Tu, fungal chitin and other microbial molecules. They also recognize damage-associated molecular patterns released from injured host tissues. Recognition is primarily mediated by pattern-recognition receptors (PRRs), including receptor-like kinases and receptor-like proteins located at the plasma membrane. Ligand recognition activates receptor complexes and initiates pattern-triggered immunity (PTI). Within seconds to minutes, changes in ion fluxes, calcium concentration, ROS production and protein phosphorylation occur, establishing the first layer of defence (Boller & Felix, 2009). Pathogens have evolved effector molecules that suppress or manipulate PTI. Plants consequently possess intracellular immune receptors capable of recognizing pathogen effectors or their effects on host proteins. This activates effector-triggered immunity (ETI), which can produce stronger defence responses, including extensive transcriptional reprogramming and hypersensitive cell death. PTI and ETI overlap considerably and should therefore be viewed as interconnected components of plant immunity (Dodds & Rathjen, 2010).

Early Intracellular Signalling

A rapid increase in cytosolic calcium is one of the earliest responses following pathogen recognition. Calcium functions as a second messenger, with the magnitude and duration of calcium signatures providing information about the stimulus. Calcium-dependent protein kinases and calmodulin-associated proteins subsequently regulate downstream defence mechanisms. ROS production is closely associated with calcium signalling. Plasma-membrane NADPH oxidases generate superoxide, which can form hydrogen peroxide. ROS function as antimicrobial molecules and signalling components and contribute to gene regulation, cell-wall modification and programmed cell death. Mitogen-activated protein kinase (MAPK) cascades provide another major signalling route. These cascades involve sequential activation of MAPKKKs, MAPKKs and MAPKs. Activated MAPKs phosphorylate transcription factors and other proteins, linking pathogen perception with changes in gene expression. MAPK pathways also integrate responses to wounding and abiotic stresses. Defence signalling additionally involves ubiquitination and proteasome-mediated degradation. Controlled protein turnover allows rapid removal of signalling inhibitors and transcriptional repressors, providing both speed and reversibility.

ROS, Nitric Oxide and Redox Signalling

ROS are central components of plant immunity and commonly appear as an early oxidative burst. Hydrogen peroxide can participate in local and intercellular signalling, while ROS also promote cell-wall reinforcement and defence-gene activation. Nitric oxide (NO) interacts with ROS and contributes to redox regulation. Changes in protein oxidation can modify enzyme activity, localization and stability. Redox regulation is especially important in SA-mediated defence because the cellular redox state influences important immune regulators. Excessive ROS, however, can damage lipids, proteins, nucleic acids and photosynthetic machinery. Plants therefore maintain antioxidant systems involving superoxide dismutase, catalase, peroxidases and the ascorbate-glutathione cycle, together with non-enzymatic antioxidants such as ascorbate, glutathione, tocopherols and phenolic compounds.

Phytohormonal Regulation

Phytohormones provide a major regulatory layer connecting pathogen perception with defence-gene expression. SA, JA and ethylene are particularly important, while abscisic acid, auxin, cytokinins, gibberellins and brassinosteroids also influence immunity. SA is strongly associated with resistance to many biotrophic and hemibiotrophic pathogens. Infection stimulates SA accumulation and activates defence genes through regulatory components including NONEXPRESSOR OF PATHOGENESIS-RELATED GENES1 (NPR1). NPR1 interacts with TGA transcription factors and contributes to activation of pathogenesis-related genes. SA signalling is also important in systemic acquired resistance (SAR), which increases the defensive capacity of tissues distant from the original infection. JA is particularly important in defence against herbivores and necrotrophic pathogens. The active jasmonate JA-Ile is perceived by the COI1-JAZ receptor system. JA-Ile perception promotes degradation of JAZ repressors, releasing MYC transcription factors and activating JA-responsive genes. Ethylene frequently works together with JA in resistance to necrotrophic pathogens. SA and JA often show antagonistic interactions, although their relationship is context dependent and can also be cooperative. Hormonal crosstalk therefore allows plants to tailor their responses to different pathogens and stresses.

Transcription Factors and Defence Gene Regulation

Defence signalling ultimately converges on transcription factors and chromatin regulators. Major transcription-factor families involved in immunity include WRKY, AP2/ERF, NAC, MYB and bZIP proteins. WRKY transcription factors are among the best-characterized regulators of plant immunity. They bind W-box elements in gene promoters and can act as either positive or negative regulators of defence. Their activity is regulated through phosphorylation, protein-protein interactions and hormonal signalling. AP2/ERF transcription factors are important components of JA- and ethylene-responsive defence and regulate genes encoding antimicrobial proteins and enzymes involved in secondary metabolism. NAC proteins participate in defence and development, while MYB transcription factors contribute to phenylpropanoid metabolism, cell-wall reinforcement and defensive secondary metabolites. bZIP proteins are important in SA signalling and interact with NPR1-associated regulatory complexes. These transcription factors operate as interconnected networks rather than independently. Their combinatorial action enables plants to produce context-specific immune responses (Tsuda & Somssich, 2015).

Defence-Related Genes and Cellular Responses

Defence signalling activates genes encoding antimicrobial proteins, cell-wall-modifying enzymes, detoxification proteins and stress-protective components. Pathogenesis-related proteins such as chitinases and glucanases can degrade fungal cell-wall components. Other defence proteins include protease inhibitors, antimicrobial peptides and oxidative enzymes. Structural defence is also important. Pathogen attack can stimulate callose deposition, lignification, suberization and modification of cell-wall polysaccharides. These changes restrict pathogen penetration and movement. Plants also activate secondary metabolism. Phenylpropanoid pathways generate lignin, flavonoids, phytoalexins and other phenolic compounds, while terpenoid and alkaloid pathways generate additional antimicrobial metabolites. Because these processes require substantial metabolic resources, their activation must be tightly regulated.

Post-Transcriptional and Post-Translational Regulation

Plant immunity is regulated beyond transcription. Alternative splicing can generate different transcript isoforms, while changes in mRNA stability can rapidly alter protein production. MicroRNAs and small interfering RNAs regulate defence-associated genes through transcript cleavage or translational repression. Small RNAs can influence transcription factors, hormone pathways and resistance mechanisms and are also important in plant-virus interactions. At the protein level, phosphorylation, ubiquitination, sumoylation and acetylation regulate signalling proteins. Ubiquitination can control protein stability, while phosphorylation can modify enzyme and transcription-factor activity. These mechanisms provide multiple regulatory checkpoints and allow rapid adjustment of immune responses.

Epigenetic Regulation

Epigenetic mechanisms provide another layer of immune regulation. DNA methylation, histone modification and chromatin remodelling influence the accessibility of defence-related genes. Histone acetylation generally promotes transcriptionally permissive chromatin, while different histone methylation marks can either activate or repress gene expression. Epigenetic regulation is particularly relevant to defence priming. Plants previously exposed to pathogens or inducing stimuli can respond more rapidly and strongly to subsequent attack. Such molecular memory may involve chromatin modifications, altered transcriptional states and small-RNA pathways.

Systemic Signalling and Defence Priming

Plant immunity extends beyond the site of infection. Signals produced in infected tissues can move to distant organs and establish systemic resistance. SA, mobile metabolites, peptides, hormones, electrical signals and ROS can contribute to long-distance communication. Defence priming allows plants to maintain enhanced responsiveness without continuously expressing high levels of defence genes. A primed plant can therefore activate stronger and faster defence following subsequent attack while reducing the metabolic costs associated with constitutive defence.

Defence-Growth Trade-Off

Plant immunity requires considerable carbon, nitrogen, energy and reducing power. Continuous defence activation can therefore reduce growth, reproduction and yield. Plants have consequently evolved mechanisms that limit the intensity and duration of immune responses. Hormonal crosstalk is central to this balance. Auxin, gibberellins, brassinosteroids and cytokinins regulate growth while also influencing immunity. Modern crop improvement therefore aims not simply to produce stronger constitutive resistance but to develop resistance that is rapid, inducible and precisely regulated.

Pathogen Manipulation of Plant Signalling

Pathogens have evolved sophisticated mechanisms to interfere with plant immunity. Their effectors can suppress receptor activity, disrupt MAPK cascades, alter calcium signalling, interfere with hormone biosynthesis and manipulate transcription factors. Some effectors target ubiquitination, vesicle trafficking, chloroplast functions and nuclear processes. Pathogens may also exploit hormonal antagonism to suppress effective resistance. The continuous interaction between plant defence and pathogen suppression represents an evolutionary arms race, driving diversification of plant immune receptors and pathogen effectors.

Applications in Crop Improvement

Knowledge of plant defence signalling has important applications in crop improvement. Conventional breeding can exploit naturally occurring resistance genes and favourable alleles, while marker-assisted and genomic selection can accelerate the development of resistant cultivars. Genome editing provides additional opportunities to modify susceptibility genes, promoter regions, transcription-factor binding sites and immune receptor genes. Precise editing may allow defence to be activated primarily during pathogen attack, thereby reducing growth penalties associated with constitutive immunity. Defence-inducing compounds and beneficial microorganisms can also stimulate immune pathways and defence priming. Integration of molecular breeding, genome editing, biological control, beneficial microbes and precision agriculture may reduce dependence on conventional pesticides and support sustainable crop protection.

Future Perspectives

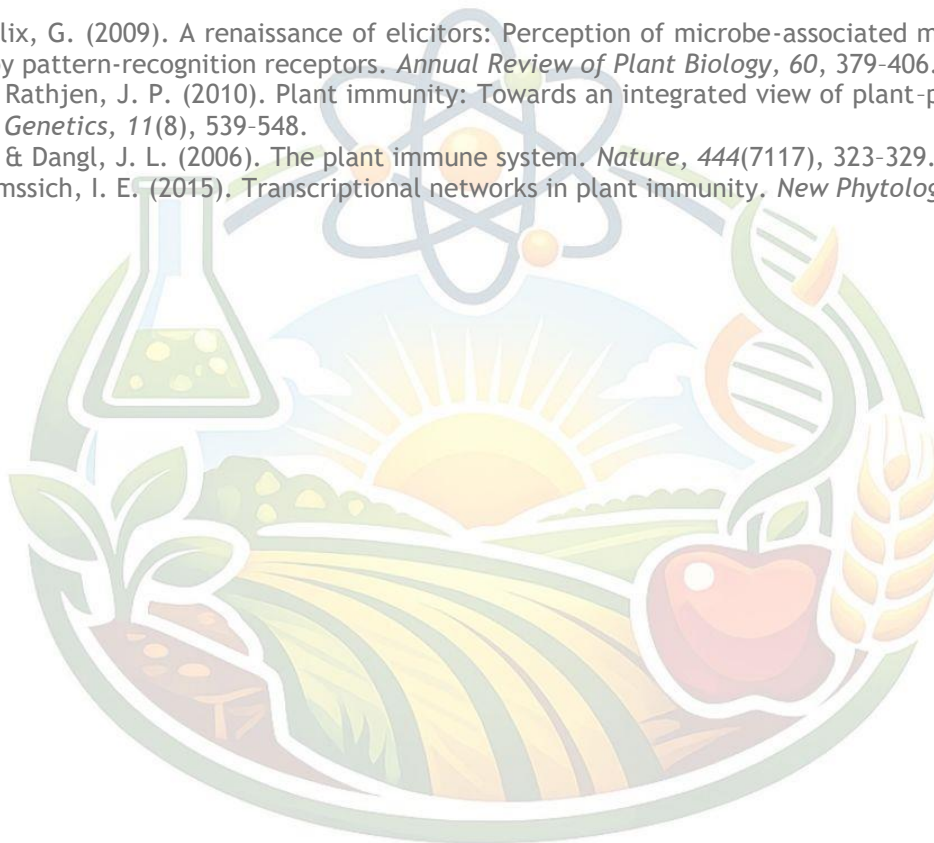
Despite major advances, the complexity of plant defence remains a significant research challenge. Plants frequently experience pathogens simultaneously with drought, heat, nutrient deficiency and other stresses. Understanding how plants integrate and prioritize these signals is therefore essential. Transcriptomics, proteomics, metabolomics, single-cell biology, spatial transcriptomics and chromatin profiling are providing increasingly detailed information about defence responses. Artificial intelligence and machine-learning approaches may further assist in identifying regulatory networks and predicting disease-resistance phenotypes. Future research should focus on developing crops capable of maintaining productivity under simultaneous biotic and abiotic stresses. Climate change is expected to alter pathogen distribution, insect populations and disease severity, making integrated understanding of immunity and environmental stress increasingly important.

Conclusion

Plant defence is a highly coordinated process involving pathogen perception, receptor activation, calcium signalling, ROS and nitric oxide production, MAPK cascades, phytohormone signalling, transcriptional regulation, protein modification, RNA regulation and epigenetic control. PTI provides an early layer of protection, while intracellular immune receptors can activate stronger ETI responses. These pathways converge on transcription factors and regulatory complexes that determine the activation and suppression of defence genes. SA, JA and ethylene are central hormonal regulators, but their activities are strongly influenced by other hormones and environmental signals. Plants must also balance effective defence with growth because immunity consumes substantial metabolic resources. A deeper understanding of defence signalling and gene regulation will therefore support the development of disease-resistant, climate-resilient and high-yielding crops. Future progress will depend on integrating molecular genetics, genomics, epigenomics, metabolomics, computational biology and precision genome editing to develop plants capable of mounting rapid, precise and energetically efficient immune responses.

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Plant Virology Current Trends and Future Perspectives

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Abstract

Plant viruses are highly diverse and rapidly evolving infectious agents that significantly affect crop productivity, global food security, biodiversity, and agricultural ecosystem stability. Over the past two decades, rapid advances in molecular biology, genomics, high-throughput sequencing, bioinformatics, structural biology, gene editing, and artificial intelligence have transformed plant virology from a descriptive discipline into a highly integrative and predictive science. Traditional diagnostic approaches such as symptom observation, biological indexing, serology, and targeted PCR remain important, but they are now increasingly complemented by metagenomics, small RNA sequencing, long-read sequencing, and computational virome analysis. These modern tools have revealed an extraordinary diversity of known and previously unknown viruses, viroids, satellites, and virus-associated nucleic acids in both cultivated and wild plants. At the same time, deeper understanding of plant immune systems—including RNA silencing, resistance genes, antiviral signalling pathways, autophagy, and hormone-mediated defence—has opened new avenues for developing durable resistance strategies. However, global challenges such as climate change, increased international trade, shifting vector populations, monoculture farming, and ecological disturbances are accelerating virus emergence and spread. As a result, plant virology is increasingly becoming a predictive, data-driven, and multidisciplinary field.

Keywords: plant viruses, virology, metagenomics, high-throughput sequencing, RNA silencing, CRISPR, diagnostics, climate change, epidemiology, artificial intelligence.

Introduction

Plant virology has evolved from a classical discipline focused mainly on symptom description and transmission studies into a highly advanced field integrating molecular genetics, genomics, structural biology, ecology, epidemiology, bioinformatics, and computational sciences. Plant viruses are obligate intracellular pathogens that depend entirely on host cellular machinery for replication, movement, and survival. Their compact genomes, high mutation rates (especially in RNA viruses), recombination ability, and close association with insect vectors allow them to adapt rapidly to changing environments. Plant viruses are responsible for major economic losses in agriculture, horticulture, ornamentals, and plantation crops. They cause symptoms such as mosaic patterns, chlorosis, leaf curling, necrosis, stunting, fruit deformation, and yield reduction. Beyond yield loss, viral infections also reduce market value, restrict trade, and increase production costs due to the need for disease management and certification systems.

Importantly, plant viruses are no longer viewed only as pathogens. They are now recognized as components of a broader plant-associated ecosystem or phytobiome. Many viruses exist in asymptomatic hosts, wild plants, weeds, and even insect vectors. Some remain latent under certain conditions, while others become highly pathogenic depending on environmental stress, host genotype, or mixed infections. Modern plant virology therefore focuses on a dynamic virus-host-vector-environment system rather than a simple pathogen-host relationship. Disease development depends on multiple interacting factors including temperature, humidity, plant nutrition, vector abundance, cropping systems, and ecological conditions (Lefeuvre et al., 2019). The introduction of high-throughput sequencing has revolutionized virus discovery by enabling detection without prior knowledge of the pathogen. However, identifying a viral sequence does not automatically confirm disease causation, making biological validation essential.

Diversity and Biology of Plant Viruses

Plant viruses exhibit remarkable diversity in genome type, structure, replication strategy, and transmission mode. Their genomes may consist of single-stranded RNA, double-stranded RNA, single-stranded DNA, or double-stranded DNA. RNA viruses dominate plant virus populations, although DNA viruses such as geminiviruses are also highly important. Positive-sense RNA viruses can directly function as messenger RNA, while negative-sense and double-stranded RNA viruses require

additional transcription steps. DNA viruses often interact with host nuclear processes. Viroids, which are small circular non-coding RNAs, represent a unique class of infectious agents that rely entirely on host machinery. Because viral genomes are compact, viral proteins are multifunctional. A single protein may be involved in replication, movement, suppression of host defence, and transmission. Viruses also manipulate host cellular structures such as membranes, chloroplasts, mitochondria, and the cytoskeleton.

The infection cycle includes entry, replication, protein synthesis, assembly, cell-to-cell movement, systemic spread, and transmission. Unlike animal viruses, plant viruses cannot move freely between cells due to rigid cell walls. Instead, they use movement proteins to modify plasmodesmata and facilitate intercellular transport. Systemic infection occurs mainly through the phloem, allowing viruses to spread throughout the plant. This systemic movement is critical for disease development and transmission efficiency.

Evolution and Emergence of Plant Viruses

Virus evolution is driven by mutation, recombination, reassortment, selection, and gene exchange. RNA viruses evolve rapidly due to error-prone replication. However, evolution is balanced by purifying selection that maintains essential functions. Recombination plays a major role in generating new viral variants with altered host range or virulence. In agricultural systems with genetically uniform crops, advantageous viral strains can spread rapidly. Landscape-level factors also influence virus evolution. Agricultural ecosystems include crops, weeds, wild plants, insect vectors, and environmental reservoirs that facilitate virus survival and genetic exchange. Molecular epidemiology helps trace virus movement and identify sources of outbreaks. Plant viruses are therefore not static pathogens but dynamic components of ecological and evolutionary systems (Lefevre et al., 2019).

Plant-Virus Interactions and Pathogenesis

Plant-virus interactions determine whether infection leads to resistance, tolerance, or disease. Viruses manipulate host metabolism, gene expression, hormone signalling, and cellular structures to create a favourable environment for replication. They often induce membrane rearrangements to form replication complexes. These structures protect viral components and enhance replication efficiency. Viruses also interfere with plant hormones such as salicylic acid, jasmonic acid, and ethylene, which regulate defence responses. Additionally, viruses manipulate protein degradation pathways such as the ubiquitin-proteasome system and autophagy. These interactions are complex and involve extensive host-virus protein networks.

RNA Silencing and Plant Immunity

RNA silencing is a key antiviral defence mechanism in plants. Viral double-stranded RNA is processed into small interfering RNAs, which guide degradation of viral RNA. This system provides sequence-specific immunity. However, viruses counteract this defence using suppressor proteins that inhibit RNA silencing pathways. This creates an evolutionary arms race between host defence and viral counter-defence (Pumplin & Voinnet, 2013). RNA silencing also influences symptom development and gene regulation. Understanding this system has enabled development of RNA-based resistance strategies and genetic engineering approaches for crop protection.

High-Throughput Sequencing in Virus Discovery

High-throughput sequencing (HTS) has revolutionized plant virology by enabling unbiased detection of all nucleic acids in a sample. It allows identification of known, unknown, and highly divergent viruses without prior assumptions. HTS has revealed mixed infections, novel viruses, viroids, and satellite RNAs in many crops. It is especially useful in vegetatively propagated crops where latent infections are common. However, HTS also presents challenges. Detection of viral sequences does not confirm pathogenicity. Biological validation is required to establish disease causation (Villamor et al., 2019).

Metagenomics and the Plant Virome

Metagenomics studies the entire viral community within a plant, known as the virome. Plants often contain multiple viruses simultaneously, including latent and non-pathogenic forms. A major challenge is distinguishing harmful viruses from harmless or unknown ones. Sequence detection alone is insufficient to confirm disease causation. Experimental validation, transmission studies, and epidemiological evidence are necessary. Metagenomics also generates large datasets requiring advanced bioinformatics tools for analysis, classification, and interpretation.

Artificial Intelligence and Computational Virology

Artificial intelligence (AI) is increasingly used in plant virology for virus classification, disease detection, and epidemiological prediction. Machine learning models can analyze genomic data, images, and environmental variables to identify disease patterns. AI-based image recognition systems can detect viral symptoms from field images. However, these systems require large, diverse datasets and careful validation to avoid errors under real-world conditions. Integration of AI with molecular diagnostics and field data will enhance predictive plant health management.

Genome Editing and CRISPR Technology

CRISPR-based genome editing offers powerful tools for developing virus-resistant crops. It can be used to modify host susceptibility genes or directly target viral genomes. Host-directed editing is particularly promising because it reduces the risk of viral escape. However, viruses evolve rapidly, so multiplex strategies targeting multiple genes may be required. Regulatory and biosafety concerns also influence the adoption of genome-edited crops.

RNA-Based Antiviral Technologies

RNA-based approaches such as spray-induced gene silencing use double-stranded RNA to trigger antiviral responses. These methods offer sequence-specific protection without genetic modification of the plant. Challenges include RNA stability, delivery efficiency, and environmental degradation. Nanotechnology-based delivery systems may improve effectiveness in the future.

Virus-Vector Interactions

Insect vectors such as aphids, whiteflies, and leafhoppers play a major role in virus transmission. Virus-vector interactions influence disease spread and epidemiology.

Viruses can alter plant traits to attract vectors, enhancing transmission. Environmental factors such as temperature and rainfall also affect vector populations and disease dynamics. Understanding these interactions is essential for integrated disease management.

Climate Change and Virus Epidemiology

Climate change significantly affects plant virus distribution and severity. Temperature, rainfall, and atmospheric CO₂ influence both host plants and insect vectors. Higher temperatures may increase vector reproduction and expand their geographical range. Water stress can also increase plant susceptibility to infection. Climate change therefore alters the entire disease triangle involving host, virus, and environment (Trębicki, 2020).

Disease Management Strategies

Effective management of plant viral diseases relies on prevention rather than cure. Key strategies include use of resistant varieties, clean planting material, vector control, crop rotation, and sanitation. Integrated disease management combines biological, cultural, and molecular approaches. Clean-plant certification systems are especially important for vegetatively propagated crops.

Future Perspectives

Future plant virology will be highly integrated and predictive. Technologies such as genomics, AI, CRISPR, and remote sensing will work together to improve disease forecasting and management. Development of global virome databases will help identify emerging threats early. Precision agriculture will enable targeted disease control based on real-time data. Climate-resilient crop protection strategies will become essential in the coming decades.

Conclusion

Plant virology is rapidly evolving into a multidisciplinary and predictive science. Advances in sequencing, bioinformatics, genome editing, and artificial intelligence are transforming how plant viruses are detected, studied, and managed. However, challenges remain in linking viral detection to disease causation, managing viral diversity, and translating laboratory findings into field applications. Future progress will depend on integrating molecular biology, ecology, epidemiology, and computational sciences. Ultimately, sustainable management of plant viral diseases will require coordinated global efforts combining surveillance, prediction, resistance breeding, and advanced biotechnology to ensure food security in a changing climate.

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Soil-Borne Diseases: Management and Control Strategies

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Abstract

Soil-borne diseases pose a persistent and major constraint to global agricultural productivity. Their causal agents—including fungi, oomycetes, bacteria, nematodes, and certain viruses—survive and multiply within the soil, rhizosphere, crop residues, and irrigation water. Unlike foliar diseases, these infections begin below ground, making early detection difficult as visible symptoms often appear only after significant damage to roots and vascular tissues has occurred. Key diseases include damping-off, root rots, *Fusarium* and *Verticillium* wilts, and bacterial wilt. The persistence of these pathogens is facilitated by resilient survival structures such as chlamydospores, sclerotia, and oospores, making eradication impractical. Consequently, effective management focuses on reducing pathogen inoculum, preventing introduction, enhancing soil health, and fostering beneficial microbial communities. Modern strategies emphasize an integrated disease management (IDM) approach that combines cultural practices, resistant cultivars, biological control, and targeted chemical interventions. A successful strategy requires a paradigm shift from pathogen eradication to the ecological management of the soil-plant-microbe system, where soil biological health is central to crop protection.

Introduction

Soil is a dynamic biological ecosystem, not merely a physical anchor for plants. It hosts vast populations of microorganisms that interact with roots, organic matter, and each other. Within this complex environment, numerous pathogenic organisms can survive for extended periods, making soil-borne diseases among the most challenging to manage. The term "soil-borne disease" refers to diseases where the primary source of inoculum is soil-associated and infection occurs through roots, crowns, or other tissues in contact with the soil. These diseases are particularly destructive in intensive agricultural systems characterized by monocropping, poor residue management, and depleted soil organic matter. This environment progressively increases pathogen populations. Conversely, practices like crop rotation and organic matter management can foster a biologically suppressive soil. A significant challenge is the formation of highly resistant survival structures by pathogens like *Fusarium* (chlamydospores), *Sclerotium* (sclerotia), and *Plasmodiophora brassicae* (resting spores), which can remain viable for years.

The epidemiology of soil-borne diseases is heavily influenced by initial inoculum density, soil temperature, moisture, pH, and microbial community composition. Therefore, management requires a holistic approach. The objective is not complete pathogen elimination but reducing its population and infection potential below an economic threshold. This aligns with the modern concept of soil health, which emphasizes the collective consideration of soil's physical, chemical, and biological characteristics for sustainable disease suppression (Janvier et al., 2007).

Nature and Characteristics of Soil-Borne Pathogens

The soil provides a unique environment where pathogens must survive adverse conditions and locate host tissues. They achieve this through dormant propagules, infected residues, alternative hosts, and contaminated water or machinery. Fungi and oomycetes are among the most important soil-borne pathogens, including genera like *Fusarium*, *Rhizoctonia*, *Pythium*, *Phytophthora*, and *Verticillium*. They cause a range of diseases from seed decay to vascular wilts.

Oomycetes like *Pythium* and *Phytophthora* are favoured by excessive soil moisture, as their motile zoospores can swim through water-filled soil pores to reach roots. Thus, irrigation management is crucial. Soil-borne bacteria, such as *Ralstonia solanacearum* (causal agent of bacterial wilt), are difficult to manage due to their ability to survive in soil, water, and alternative hosts. Plant-parasitic nematodes (e.g., *Meloidogyne*, *Heterodera*) cause direct root damage and can interact synergistically with fungal pathogens, creating disease complexes that are more severe than either pathogen alone.

Major Soil-Borne Diseases and their Symptoms

Soil-borne diseases affect crops at all developmental stages. Seed decay and damping-off are critical during germination, caused by pathogens like *Pythium* and *Rhizoctonia*. Root rots, characterized by root necrosis, lead to above-ground symptoms like chlorosis and wilting, which can be easily confused with drought or nutrient stress. Collar and crown rots affect tissues at the soil line, disrupting transport. Vascular wilts, such as *Fusarium* and *Verticillium* wilts, are particularly destructive as pathogens colonize the xylem, causing unilateral yellowing and progressive wilting. Other significant diseases include clubroot of crucifers, caused by the long-lived resting spores of *Plasmodiophora brassicae*, and white rot of alliums, whose pathogen (*Stromatinia cepivora*) produces persistent sclerotia. These examples highlight why simple rotation is often insufficient for eradication.

Disease Cycle and Epidemiological Considerations

The disease cycle begins with pathogen survival between crops. When a susceptible host is planted, root exudates stimulate dormant propagules to germinate, leading to root contact and infection. Soil temperature is a major driver of pathogen activity, while soil moisture is equally critical, with excess water favouring oomycetes. Soil texture and structure influence aeration and root development, impacting both pathogen and host. Organic matter quality and quantity are fundamental, as decomposition can generate antimicrobial compounds, stimulate antagonists, and alter soil chemistry (Bailey & Lazarovits, 2003).

Principles of Integrated Management

RNA silencing is a key antiviral defence mechanism in plants. Viral double-stranded RNA is processed into small interfering RNAs, which guide degradation of viral RNA. This system provides sequence-specific immunity. However, viruses counteract this defence using suppressor proteins that inhibit RNA silencing pathways. This creates an evolutionary arms race between host defence and viral counter-defence (Pumplin & Voinnet, 2013). RNA silencing also influences symptom development and gene regulation. Understanding this system has enabled development of RNA-based resistance strategies and genetic engineering approaches for crop protection.

Prevention and Sanitation

Prevention is more economical than reclaiming infested soil. Using disease-free seeds and planting material is paramount. Sanitation of farm machinery and tools is essential to prevent moving contaminated soil between fields. Removing and destroying diseased plants prevents further pathogen reproduction. Weed management is also vital, as weeds can serve as alternative pathogen reservoirs.

Crop Rotation and Cropping-System Management

Crop rotation is an environmentally compatible strategy that is most effective against pathogens with a narrow host range. Introducing non-host crops starves the pathogen, reducing its population. However, its effectiveness is limited against pathogens with broad host ranges or long-lived survival structures. In these cases, rotation must be combined with other methods. Diversification through intercropping can also modify the soil environment and interfere with pathogen establishment.

Resistant Cultivars and Genetic Management

Host resistance is a highly desirable control method as it requires no repeated chemical applications. It is particularly valuable for vascular wilts and nematode diseases. However, resistance can be race-specific and may erode as pathogen populations evolve. Grafting onto resistant rootstocks is an increasingly important strategy in vegetable production, allowing susceptible scions to be grown in infested soils. This is especially useful in intensive greenhouse systems where rotation is difficult.

Physical and Cultural Control Methods

Several physical and cultural methods offer effective non-chemical control.

- 1. Soil Solarization:** This involves covering moist soil with transparent polyethylene during high solar radiation periods. The resulting temperature increase reduces populations of susceptible pathogens and weed seeds. Its efficacy is limited by weather and penetration depth but can be combined with organic amendments for enhanced effect.
- 2. Steam Sterilization:** This is effective for greenhouses and nurseries but can create a "biological vacuum" by killing beneficial organisms, facilitating pathogen recolonization.
- 3. Anaerobic Soil Disinfestation (ASD):** Also known as biological soil disinfestation, this method involves incorporating decomposable organic matter, irrigating, and covering the soil to restrict oxygen. The resulting anaerobic conditions produce toxic compounds like acetic and butyric acids that suppress pathogens (Momma, 2008). Its effectiveness depends on carbon source, temperature, and pathogen sensitivity.

4. Organic Amendments: Applying compost, manure, and crop residues improves soil health and can suppress disease through several mechanisms, including stimulating antagonists and generating antimicrobial compounds. The quality of compost is critical; immature compost can be phytotoxic.

5. Biofumigation: This practice uses plants, typically from the Brassicaceae family, that release antimicrobial compounds (isothiocyanates) upon decomposition. It is not as potent as chemical fumigation but is a valuable component of an IDM program.

Biological Control and Suppressive Soils

Biological control uses beneficial microorganisms to suppress pathogens. Key agents include *Trichoderma*, *Bacillus*, *Pseudomonas*, and mycorrhizal fungi. They act through competition, antibiosis, parasitism, and by inducing plant defence responses. The rhizosphere is the critical battleground for these interactions (Raaijmakers et al., 2009). The main limitation is performance variability under field conditions. Future directions involve using microbial consortia rather than single strains.

The concept of disease-suppressive soils is central to modern management. These are soils where disease is naturally suppressed despite the presence of the pathogen and a susceptible host. Suppressiveness arises from the activity of the total microbial community (general suppression) or specific microorganisms (specific suppression). Managing for soil health is, therefore, managing for disease suppression (Janvier et al., 2007). Rhizosphere management, through the application of beneficial microbes or altering root exudates via plant genetics, is a key strategy for engineering these suppressive environments.

Chemical, Nutrient, and Water Management

1. Chemical Management: Chemical control remains important when disease pressure is high. However, it is challenging due to soil adsorption and degradation, and broad-spectrum fumigants can harm beneficial organisms. Therefore, chemical use should be targeted and integrated with other tactics to prevent resistance development.

2. Nutrient Management: Plant nutrition significantly influences disease susceptibility. Balanced nitrogen is crucial, as excess can increase susceptibility to some diseases. Potassium, calcium, and silicon contribute to cell wall strength and stress tolerance. Nutrient management should be based on soil and plant analysis.

3. Irrigation and Drainage: Water management is fundamental. Excess irrigation promotes waterlogging and favours pathogens like *Pythium*. Drip irrigation is preferable to flood irrigation, and improving drainage through raised beds can be highly effective in reducing disease risk.

Integrated Management of Complexes and Modern Diagnostics

Soil-borne diseases often occur as complexes (e.g., nematodes predisposing plants to *Fusarium* wilt). Management must target the entire complex rather than a single organism. Accurate diagnosis is the foundation of any management program. Molecular techniques like PCR and quantitative PCR allow for rapid, precise pathogen detection and quantification, enabling site-specific management decisions. Metagenomics is further expanding our understanding of the entire soil microbial community.

Precision Agriculture and Future Directions

Precision agriculture offers new opportunities to manage spatially variable soil-borne diseases. Remote sensing via drones and satellites can detect disease hotspots, and variable-rate technology can apply treatments only where needed. The future of soil-borne disease management lies in integrating microbiology, plant breeding, and digital agriculture. Emerging approaches include:

1. Microbiome Engineering: Deliberately assembling beneficial microbial consortia.

2. Omics Technologies: Using metagenomics and metabolomics to understand complex soil interactions.

3. Artificial Intelligence: Developing predictive models for disease risk based on integrated data.

Climate change will further modify disease epidemiology, with warmer temperatures expanding pathogen ranges and extreme weather events stressing plants and altering soil environments. This makes the adoption of resilient, soil-health-focused management systems even more critical.

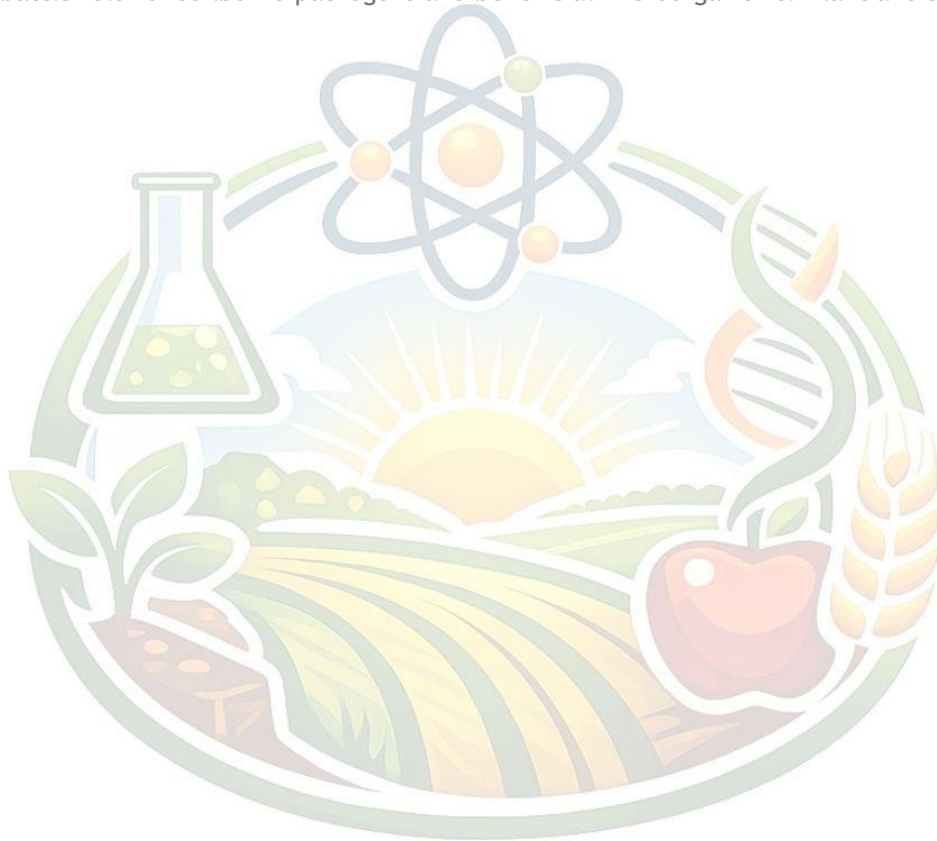
Constraints and Conclusion

Despite progress, challenges remain. The complexity of soil ecosystems means treatment outcomes can vary, and highly resistant pathogen structures often require repeated, integrated efforts. Biological products can also face issues of consistency and shelf-life. In conclusion, soil-borne diseases are a persistent and complex challenge. Their management requires a shift from a pathogen-eradication mindset to an ecological approach that prioritizes soil health. The most effective strategy is an Integrated Disease Management framework that combines prevention, sanitation, resistant cultivars, crop rotation, and cultural, biological, and chemical methods. This approach acknowledges that the pathogen

is just one component of a larger ecosystem. By reducing inoculum, improving soil health, strengthening host resistance, and promoting beneficial biological interactions, we can build resilient agroecosystems capable of naturally restricting disease. The future of sustainable agriculture depends on this transition towards ecological disease suppression.

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Climate Change & Weed Dynamics

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Introduction

Climate represents the cumulative long-term weather statistics of a region, governed by meteorological variables such as temperature, precipitation, wind, and sunshine hours. Within agricultural ecosystems, parameters like temperature, light, and soil moisture dictate crop growth, productivity, and the spatial distribution and adaptation of weeds. Beyond abiotic factors like soil fertility, crop success depends on maintaining optimal climatic ranges during critical, sensitive developmental stages. However, anthropogenic climate change alters these baseline environmental parameters, affecting both cultivated crops and their competitive counterparts weeds.

Weeds are defined ecologically as opportunistic plants with advanced survival mechanisms, including prolific seed production, seed dormancy, specialised seed dispersal, diverse vegetative propagation structures (e.g., rhizomes, tubers, bulbs, and suckers), inherent hardiness, self-regeneration, and aggressive capacity for succession. Sharing the same trophic level as crops, weeds compete directly for essential, finite resources, including soil nutrients, moisture, solar radiation, and physical space. Biotic yield loss in agriculture is predominantly driven by weed competition. For instance, unweeded direct-seeded rice field studies demonstrate yield losses up to 75.60% in the first year due to accumulated weed seed banks. Uncontrolled growth of *Schoenoplectus juncooides* in wet-seeded rice reduces net farm income by 81% relative to cost-effective management, while weedy rice (*Oryza sativa* f. *spontanea*) co-occurring at a density of 7.3 plants per m² causes a 40.23% yield loss in cultivated lowland rice. Understanding the comparative physiology and adaptive dynamics between crops and weeds under rising atmospheric CO₂, fluctuating temperatures, altered precipitation regimes, and shifting herbicide efficacy is essential for securing future food production.

Impact of Climate Change on Weeds

Climate change alters weed growth vigor, competitive dynamics, geographic distributions, and life cycle phenologies. Modified ecophysiological requirements enable invasive weeds to expand their geographic ranges through introduction and migration. Furthermore, many weed species adjust their developmental timelines to complete life cycles rapidly prior to stress onset, maximizing seed bank replenishment. In rice ecosystems, weedy rice morphotypes increasingly mirror cultivated varieties in physical appearance while retaining superior competitive traits.

Response to Photosynthetic Pathways (C₃ vs. C₄)

1. C₃ Pathway Mechanics: In C₃ plants (e.g., rice, wheat, oats, vegetables, and weeds like *Phalaris minor*, *Avena fatua*, *Eichhornia crassipes*, *Striga asiatica*, *Cirsium arvense*, and *Schoenoplectus juncooides*), atmospheric CO₂ enters stomata and is fixed by Ribulose 1,5-bisphosphate (RuBP) via RuBisCO to produce 3-Phosphoglyceric Acid (PGA). Under high temperatures and dry conditions, RuBisCO's affinity for O₂ increases. Stomatal closure concentrates internal O₂ relative to CO₂, triggering photorespiration and reducing photosynthetic efficiency.

2. C₄ Pathway Mechanics: In C₄ plants (e.g., maize, sugarcane, sorghum, millets, and weeds like *Cynodon dactylon*, *Echinochloa* spp., *Eleusine indica*, *Cyperus rotundus*, *Cyperus iria*, and *Amaranthus* spp.), initial CO₂ fixation is catalyzed by Phosphoenolpyruvate (PEP) carboxylase in mesophyll cells to form Oxaloacetic Acid (OAA). Decarboxylation inside bundle sheath cells concentrates CO₂ around RuBisCO, suppressing photorespiration. Consequently, C₄ plants maintain high photosynthetic efficiency under elevated temperatures.

Response to Elevated Carbon Dioxide

1. C₃ Crops vs. C₃ Weeds: Rising CO₂ favors C₃ plants by increasing the internal CO₂/O₂ ratio at RuBisCO, reducing photorespiration. Fast-growing wild C₃ species exhibit greater biomass gain (54%) than slow-growing species (23%) when CO₂ increases from 300 to 720 ppm. In comparative trials, cultivated rice (C₃) plateaued in reproductive output beyond 500 ppm CO₂, whereas red rice (C₃ weed) displayed a linear increase in biomass and seed yield from 300 to 500 ppm. Red rice yielded two-fold more seed at 300 ppm and four- to five-fold more at 400-500 ppm than cultivated rice due to greater genetic diversity and physiological plasticity. Enriched CO₂ environments also increase red rice height, tiller production, and anthocyanin pigmentation.

2. C₄ Crops vs. C₄ Weeds: Although C₄ plants possess internal CO₂ concentrating mechanisms and are less sensitive to atmospheric CO₂ rises, experimental evaluation (385 vs. 680 ppm CO₂) revealed that C₄ weeds increased photosynthetic rates by 19% compared to 10% in C₄ crops. *Amaranthus retroflexus* showed a 30% increase in photosynthesis, whereas maize increased by only 5%. In rice, the C₄ weed *Echinochloa crus-galli* at 8 plants/m² suppressed rice grain yields by 58% by lowering rice RuBisCO activity, leaf photosynthetic capacity, and energy conversion efficiency.

3. Cross-Path Interactions (C₃ Crops with C₄ Weeds & C₄ Crops with C₃ Weeds): Elevated CO₂ causes partial stomatal closure, improving Water Use Efficiency (WUE) across plants. If WUE increases by 70-100%, C₃ weeds threaten to invade drier habitats typically occupied by C₄ species. When the C₄ crop sorghum was grown with the C₃ weed *Xanthium strumarium* under elevated CO₂, the C₃ weed produced superior leaf area and biomass, severely reducing crop yield. In mixed associations, growing soybean (C₃) with *Chenopodium album* (C₃ weed) exacerbated soybean seed yield losses from 28% to 39% under elevated CO₂. Conversely, competition from *Amaranthus retroflexus* (C₄ weed) on soybean decreased under elevated CO₂ (yield loss reduced from 45% to 30%), though it was not eliminated. In sorghum (C₄), elevated CO₂ combined with C₃ weed competition reduced crop yield by 16%, while C₄ weed competition under elevated CO₂ reduced sorghum yield by 23%.

4. Alterations in Weed Biology: Rising CO₂ expands weed vegetative architecture. *Cirsium arvense* (C₃) showed a 70% growth increase under elevated CO₂. C₄ species like *Amaranthus viridis* profit during early developmental phases because juvenile leaves utilize C₃ pathways prior to full Kranz anatomy differentiation. Taller growth in wind-dispersed weeds (*Cirsium arvense*, *Sonchus arvensis*, *Carduus nutans*) aids seed dispersal. In *Ambrosia artemisiifolia*, increasing CO₂ from 280 to 600 ppm elevated pollen production by 320% due to larger floral spikes. Elevated CO₂ accelerates maturation in *Avena fatua* by 13 days, leading to early seed shattering and seed bank enrichment. *Parthenium hysterophorus* under elevated CO₂ produces taller plants with greater leaf area, floral density, and dry biomass.

Response of Weeds to Rising Temperature

1. Temperature governs weed germination, phenology, and geographic boundaries. Higher temperatures alter competitive balances by synchronizing weed and crop emergence. For instance, under normal temperatures, *Setaria viridis* (C₄ weed) emerges after maize (C₄ crop); elevated temperatures trigger synchronous emergence, increasing early-stage competition.

2. A 4° C temperature rise advanced *Chenopodium album* and *Setaria viridis* emergence by 26 and 35 days, and flowering by 50 and 31.5 days, respectively. High temperatures alter photosynthate partitioning: *Cassia obtusifolia* and *Sida spinosa* allocated more biomass to roots at 36° C (day/night), yielding root-to-shoot ratios of 1.6 and 1.3, compared to 0.8 in soybean. Higher root mass allows perennial weeds like *Cyperus rotundus* to retain viable underground tubers and regenerate rapidly following stress, whereas crops lack equivalent recovery potential.

Response of Weeds to Changes in Rainfall

1. Extreme weather events (droughts and floods) select for weeds with broad physiological plasticity. In flooded rice ecosystems, amphibious weed species like *Marsilea quadrifolia* and *Leptochloa chinensis* adapt to both submerged and low-moisture conditions, causing major weed shifts and outcompeting native *Echinochloa* species.

2. Excessive rainfall favors parasitic weeds such as *Rhamphicarpa fistulosa* in cereal crops. Under drought conditions, C₃ weeds like *Anoda cristata* and *Abutilon theophrasti* compete aggressively with cotton, causing severe yield declines, while *Striga hermonthica* infestations intensify during prolonged dry spells.

Interactive Effects of CO₂ and Temperature

1. Elevated CO₂ can ameliorate heat-induced stress in weeds such as *Agropyron repens*. At elevated temperatures (23°C/19°C) and 480 ppm CO₂, *Avena fatua* produced 44% more seeds than at 397 ppm CO₂. Under high light, temperature, and evaporative demand, C₄ weeds (*Amaranthus retroflexus*, *Sorghum halepense*) outcompete C₃ crops like soybean and cotton due to superior WUE and lower CO₂ compensation points.

2. In drought stress trials, *Phalaris minor* retained a competitive advantage over wheat under elevated CO₂. Similarly, *Amaranthus retroflexus* maintained height and biomass accumulation under water stress and elevated CO₂ (600-800 ppm), whereas tomato required non-stressed conditions to benefit from higher CO₂. *Cynodon dactylon* (C₄) exhibited maximum growth at +4° C above ambient temperature, utilizing high temperatures and limited moisture efficiently.

Weed Management in Changing Climate

Climatic modifications complicate standard mechanical, chemical, and integrated weed management strategies. Accelerated underground rhizome and tuber growth under elevated CO₂ renders tillage less effective, as mechanical disturbance fragments and spreads viable vegetative propagules. Morphological diversification in weedy rice (e.g., taller culms, higher tiller counts [11-20 per plant vs. 9-10 in cultivated varieties], earlier flowering, and grain awns) increases its persistence in field crops.

Climate/ Shift	Environmental	Plant/Weed Physiological Reaction	Impact on Management & Efficacy
Elevated CO ₂		1. Increased leaf cuticular thickness & pubescence. 2. Reduced stomatal conductance/closure. 3. Stimulated root/tuber biomass relative to shoots	1. Reduced foliar herbicide uptake. 2. Less effective mechanical tillage. 3. Dilution of systemic herbicides in larger plants
Elevated Temperature		1. Accelerated phenological development & early maturation. 2. Higher photosynthate translocation to underground roots. 3. Synchronized emergence with crops	1. Shortened herbicide-sensitive seedling window. 2. Rapid regeneration from underground structures. 3. Increased risk of crop injury from applied herbicides
Drought / Water Stress		1. Stomatal closure & reduced transpiration rate. 2. Increased leaf starch deposition. 3. Prolonged seed viability in soil seed banks	1. Restricted foliage absorption & translocation of post-emergence herbicides. 2. Reduced efficacy of systemic herbicides like glyphosate
Variable / Heavy Rainfall		1. Rapid seed/offset dissemination via water run-off. 2. Emergence of amphibious weed species	1. Reduced rain-free window after herbicide spray. 2. Foliar herbicide wash-off

Herbicide Efficacy and Environmental Interactions

1. Environmental factors alter herbicide performance by modifying plant morphology and physiology, or by changing herbicide availability at target sites. Relative humidity (RH) influences cuticle hydration and spray droplet drying times; for instance, glufosinate-ammonium efficacy depends directly on RH levels.

2. In direct-seeded rice systems, specialized chemical regimes are required to manage shifting weed spectra. Application of ethoxysulfuron (15 g ha⁻¹ at 15 DAS) followed by hand weeding at 35-40 DAS effectively manages *Schoenoplectus juncooides*. Stale seedbeds combined with glyphosate + oxyfluorfen, followed by cyhalofop-butyl + carfentrazone-ethyl, control *Cyperus iria* and *Monochoria vaginalis*. Pre-packaged mixtures like penoxsulam + cyhalofop-butyl or bensulfuron-methyl + pretilachlor achieve high weed control efficiency across grasses, sedges, and broadleaf weeds.

Mechanisms of Herbicide Resistance

1. **Target-Site Resistance (TSR):** Point mutations in target-site gene sequences modify protein structures, preventing herbicide binding.

2. **Non-Target-Site Resistance (NTSR):** Includes accelerated metabolic degradation of toxic molecules, reduced translocation caused by drought or heat, reduced foliar penetration due to modified cuticular structures, and vacuolar sequestration.

3. **Gene Amplification:** Extreme target-site amplification has emerged in species like *Amaranthus palmeri*, where the 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS) gene copy number increased up to 160-fold, conferring high glyphosate resistance.

Causes for Reduction in Glyphosate Efficiency

1. Glyphosate is a broad-spectrum, non-selective, post-emergence systemic herbicide. Its field efficacy is declining under climate change due to multiple plant adaptations:

a. **Shortened Sensitive Windows:** Accelerated growth rates shorten the vulnerable seedling stage (e.g., *Chenopodium album* reaches maturity 5 days faster), reducing the effective window for application.

b. **Reduced Uptake:** Drought-induced stomatal closure, reduced stomatal density, lower stomatal conductance, thicker leaf cuticles, and elevated starch accumulation restrict glyphosate penetration and foliar absorption.

c. **Dilution in Underground Biomass:** Enhanced allocation to subterranean roots, tubers, and rhizomes dilutes systemic herbicide active ingredients below lethal concentrations, permitting rapid regrowth. Stale seedbeds combined with pre-plant and post-emergence glyphosate applications reduce *Cyperus rotundus* tuber viability to 20-23.3% and limit regeneration to 6-8 sprouts/m².

d. **Unpredictable Weather:** Intense rainfall events shortly after application wash foliage-applied chemicals off, shortening required rain-free windows.

e. Increased Crop Injury: In transgenic glyphosate-resistant (Roundup Ready) crops, elevated temperatures increase herbicide translocation to meristematic tissues; soybean translocated significantly more ^{14}C -glyphosate at 35°C than at 15°C raising crop injury risks.

Future Weed Threats

Specific invasive weed species possess high physiological plasticity and stress tolerance, posing serious threats to future agricultural systems:

1. *Sphagneticola trilobata*: Highly invasive in open environments due to rapid vegetative growth, herbicide tolerance, and extreme heat-stress resilience. It maintains photosynthetic activity under high temperatures by efficiently partitioning excess light energy within the photosystem II (PSII) complex, preserving carbon assimilation capacity.

2. *Datura stramonium*: High temperatures stimulate vegetative and reproductive growth in this species, expanding its competitive impact in warm, semi-arid crop fields.

3. *Lantana camara*: A perennial shrub adapted to diverse environments. It survives extended drought periods, while avian seed dispersal expands its range. Climate-induced range shifts in biological control agents reduce the efficacy of classic biocontrol programs.

4. *Parthenium hysterophorus*: An invasive weed featuring a C_3 - C_4 intermediate photosynthetic pathway. Under elevated CO_2 (550 ppm), cooler temperatures ($30^{\circ}\text{C}/15^{\circ}\text{C}$), and high moisture, it exhibits increased biomass and seed yield. In warmer regimes, it develops taller structures, shorter life cycles, higher seed output, and extended seed longevity.

5. *Eichhornia crassipes*: A fast-growing aquatic broadleaf weed that reproduces via vegetative offsets. Increased storm intensity and frequent flooding facilitate the rapid transport and establishment of offsets in new aquatic and lowland field environments.

6. *Prosopis juliflora*: An invasive woody species covering approximately 6.0 million hectares (1.8% of India's land area). It allocates substantial assimilates to deep root systems, enabling rapid regeneration after top removal. It tolerates climatic extremes, including high summer temperatures and monsoon inundation.

Conclusion

Climate change alters crop-weed competitive dynamics, generally favoring weeds due to their superior genetic diversity, physiological plasticity, and adaptive stress tolerance. Perennial weeds utilizing C_4 and C_3 - C_4 intermediate photosynthetic pathways, supported by deep underground storage organs, present growing management challenges. Altered leaf morphology, reduced stomatal conductance, cuticular thickening, and metabolic resistance mechanisms collectively diminish chemical herbicide efficacy and narrow application windows.

Because major global food crops like rice utilize the C_3 pathway, their photosynthetic efficiency and yields remain vulnerable to rising temperatures and climate extremes relative to competing C_4 weeds. To safeguard future food security, agricultural research must prioritize developing crop varieties with enhanced thermal tolerance or integrated C_4 photosynthetic traits. Concurrently, sustainable weed management will depend on bioprospecting utilizing weed species for beneficial bio-based products and alternative economic uses to offset infestation pressure in climatically altered agricultural landscapes.

Horticultural Crops and Carbon Capture: A Green Pathway to Climate Change Mitigation

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Introduction

Climate change and increasing atmospheric carbon dioxide concentrations pose major challenges to sustainable agricultural production. Horticultural crops, besides contributing to food and nutritional security, have considerable potential to act as natural carbon sinks by assimilating atmospheric CO₂ and storing carbon in plant biomass and soil (Meena *et al.*, 2024; Ilakiya *et al.*, 2024)). Perennial fruit and plantation crops are particularly important because their long-term biomass accumulation can support sustained carbon storage. Integrating carbon-conscious management into horticultural production can therefore provide a dual benefit of productive agriculture and climate change mitigation, making horticulture an important component of a low-carbon and climate-resilient agricultural future.

Carbon Capture and Sequestration

Carbon capture in plants begins with photosynthesis, through which atmospheric carbon dioxide is converted into organic carbon. A portion of this carbon is retained in plant tissues such as leaves, stems, roots and fruits, while carbon entering the soil through roots and plant residues can contribute to soil organic carbon. When carbon is stored for longer periods in plant biomass or soil rather than rapidly returning to the atmosphere, the process is referred to as carbon sequestration. In horticultural systems, carbon sequestration therefore involves both biomass carbon storage and soil carbon accumulation (Shah *et al.*, 2024). The extent of sequestration depends on crop type, biomass production, soil properties and management practices. Sustainable management that increases organic carbon inputs and reduces carbon losses can further enhance this potential.

Horticultural Crops as Carbon Sinks

The carbon-storage potential of horticulture varies considerably among crop groups and production systems. Perennial fruit and plantation crops are particularly valuable because their long-term presence, woody growth and repeated biomass production provide opportunities for sustained carbon storage (Malhotra, 2017). Orchards can also return substantial organic material to the production system through leaf fall, root turnover and pruning residues.

Vegetable crops, although generally short-duration, contribute through rapid biomass production and the return of roots and crop residues to the soil. Diversified horticultural systems that combine perennial crops with annual vegetables, cover crops or agroforestry components can further increase biomass inputs and improve carbon retention. Thus, the carbon-sink value of horticulture lies not in a single crop, but in the type, duration, diversity and management of the production system.

Carbon Storage in Plant Biomass

Plant biomass is an important carbon reservoir in horticultural systems, with carbon stored in leaves, stems, branches, trunks and roots. The amount of carbon accumulated depends on crop species, plant age, growth habit and biomass production. Perennial fruit and plantation crops can retain considerable carbon in their woody structures over longer periods, while their roots contribute to below-ground carbon storage. In addition, fallen leaves, root turnover and pruning residues return carbon to the soil and contribute to the formation of soil organic matter. Therefore, retaining plant biomass within the production system and recycling horticultural residues can enhance carbon retention while also supporting nutrient cycling and soil health (Gokul *et al.*, 2026).

Soil Carbon in Horticultural Systems

Soil acts as an important reservoir of carbon in horticultural systems, with soil organic carbon (SOC) playing a key role in soil fertility, structure, water retention and biological activity. Carbon enters the soil through root growth and turnover, leaf fall, crop residues and other organic inputs, contributing to the soil carbon pool (Li and Tasnady, 2023). Perennial horticultural systems can support greater soil carbon accumulation because of their continuous root activity and regular addition of organic residues. Orchard soils, for example, receive carbon inputs through fallen leaves, root biomass and pruning residues, which can contribute to the build-up of soil organic matter over time.

Maintaining and improving soil carbon therefore has importance beyond climate mitigation. Practices such as residue retention, organic amendments, cover crops, mulching and diversified cropping systems can increase carbon inputs while improving soil quality and resource-use efficiency. Building healthy carbon-rich soils can consequently strengthen the productivity and resilience of horticultural systems under changing climatic conditions.

Carbon-Smart Horticultural Practices

Carbon-smart horticulture involves production practices that improve resource-use efficiency while increasing carbon retention within the production system. Mulching, cover cropping, residue retention, crop diversification and reduced soil disturbance can increase organic carbon inputs, conserve soil moisture and support better soil conditions. The use of compost, farmyard manure, green manure and other organic amendments can further contribute to soil carbon build-up while improving nutrient availability and soil biological activity. Their effectiveness, however, depends on the type of amendment, application rate, soil conditions and duration of management (Gokul *et al.*, 2026). Integrating these practices into horticultural production can create systems that are productive as well as environmentally sustainable. Such approaches not only support carbon sequestration but also improve soil health, water-use efficiency, nutrient cycling and crop resilience, making them valuable components of climate-smart horticulture.

Role of Perennial Crops and Orchards

Perennial horticultural crops occupy an important position in carbon-oriented agriculture because they remain established for several years and maintain continuous above-ground and below-ground biomass. Fruit and plantation crops such as mango, citrus, coconut and other tree-based systems accumulate carbon in their trunks, branches and root systems, while their long production cycles allow these carbon pools to persist for extended periods. Orchard soils also receive regular organic carbon inputs through root turnover, leaf litter and pruning residues. Continuous root activity and comparatively limited soil disturbance can support the development of soil organic carbon over time. The extent of carbon accumulation, however, varies with crop species, orchard age, soil characteristics and management practices. Integrating perennial crops with agroforestry, diversified planting and sustainable soil management can further enhance these benefits. Therefore, well-managed orchards can serve as multifunctional production systems that combine food and income generation with biomass accumulation, soil improvement and long-term carbon storage.

Biochar and Organic Carbon Management

Biochar has emerged as a promising tool for enhancing carbon storage in horticultural soils. It is a carbon-rich material produced through the pyrolysis of agricultural and other organic biomass under limited oxygen conditions. Because of its relatively stable carbon structure, biochar can remain in soil for longer periods while also improving soil physical and chemical properties. In horticultural systems, the incorporation of biochar can improve soil moisture retention, nutrient availability, microbial activity and soil structure, while contributing to carbon sequestration. Its use also provides an opportunity to convert crop residues and other organic wastes into a useful soil amendment, supporting a circular approach to resource management (Zulfiqar *et al.*, 2022).

The effectiveness of biochar depends on its feedstock, production conditions, application rate, soil characteristics and crop system. Therefore, appropriate selection and site-specific application are essential to obtain both carbon-storage and agronomic benefits.

Carbon Credits and Farmer Opportunities

Carbon credits are emerging as a potential economic incentive for farmers who adopt practices that reduce greenhouse gas emissions or increase carbon sequestration. In India, agricultural systems have considerable potential for carbon capture, and carbon-credit mechanisms could provide an additional source of income while encouraging the adoption of climate-friendly practices. For horticultural farmers, practices such as agroforestry, perennial crop cultivation, organic matter management and improved soil-carbon management may create opportunities for participation in carbon markets. However, carbon credits require reliable measurement, reporting and verification (MRV) of the carbon benefits, which can be challenging for individual smallholders. Collective participation through Farmer Producer Organizations (FPOs), cooperatives and other farmer groups can help overcome these challenges by reducing transaction costs and facilitating access to technical expertise and carbon markets (Sharma, 2026). With appropriate policies, transparent carbon accounting and institutional support, carbon farming could provide horticultural farmers with an additional economic incentive while contributing to climate-change mitigation.

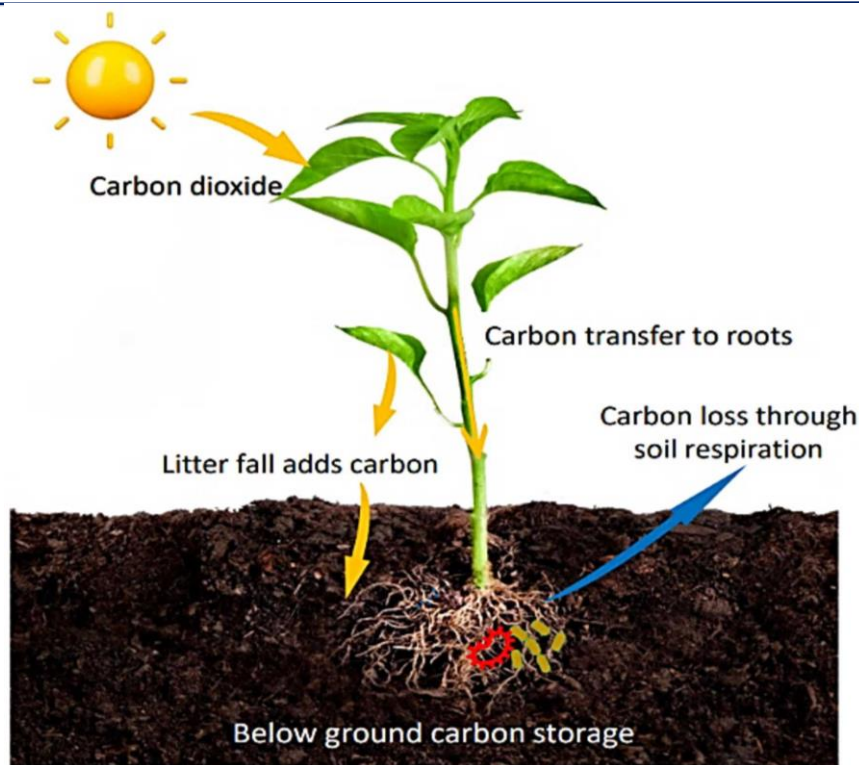


Fig. 1. Carbon Dynamics in Plant-Soil Systems

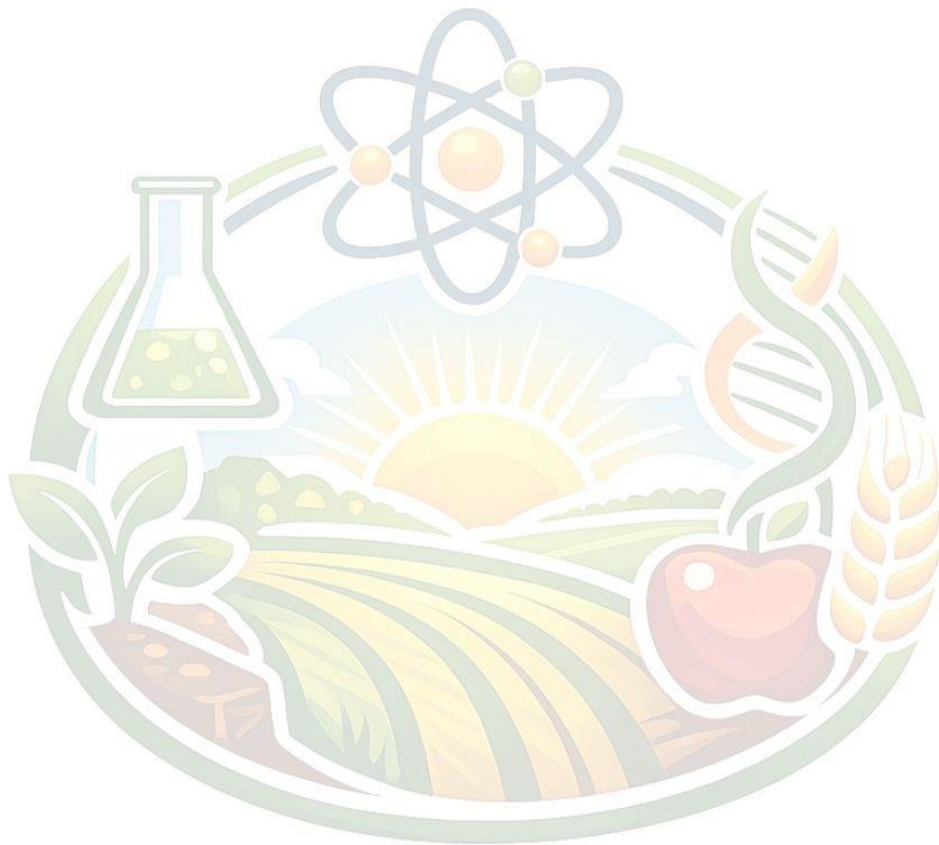
Conclusion

Horticultural crops offer a promising nature-based approach to climate change mitigation by linking carbon storage with food production, soil health and sustainable land management. Perennial crops and orchards are particularly valuable for long-term biomass and soil carbon accumulation, while practices such as residue recycling, organic amendments, mulching and biochar can further strengthen carbon retention. The future potential of carbon-smart horticulture will depend on the adoption of suitable management practices, reliable carbon measurement and supportive policies. Integrating carbon sequestration into horticultural production can therefore transform orchards, plantations and diversified cropping systems into productive landscapes that contribute simultaneously to farmer livelihoods, environmental sustainability and climate resilience. Ultimately, horticulture should be viewed not only as a source of food and income, but also as an important component of biological carbon management. Strengthening this role through science-based practices and farmer-oriented carbon opportunities can help move horticulture towards a more sustainable and climate-resilient future.

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Flatheaded Borer Infestation in Arjun (*Terminalia arjuna*): A Review of Incidence, Biology and Management

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Introduction

Terminalia arjuna (Combretaceae), commonly known as Arjun, is a large deciduous tree widely distributed along riverbanks and in mixed forests across the Indian subcontinent. Beyond its ecological role, the species holds major economic significance: its foliage is the primary host plant for the tropical tasar silkworm, *Antheraea mylitta*, making Arjun plantations central to tasar sericulture-based rural livelihoods, and its bark is extensively used in Ayurvedic and modern phytopharmaceutical preparations for cardioprotective and antimicrobial applications.

The monoculture nature of tasar-based Arjun plantations, combined with continuous defoliation for silkworm rearing, places sustained physiological stress on host trees. This stress, along with wounding, bark injury and weakened tree vigor, predisposes Arjun trees to attack by a complex of wood-boring insects, among which flat-headed (metallic wood-boring) beetles of the family Buprestidae are consistently reported as the most damaging borer group. This review synthesizes available literature on the taxonomy, biology, infestation pattern, economic impact and management strategies for flat-headed borers of Arjun.

Causal Organisms and Taxonomy

Flat-headed borers belong to the beetle family Buprestidae (Coleoptera), so named because the larvae possess a characteristically broadened, flattened thoracic segment immediately behind the head. On Arjun, the borer complex reported across Indian tasar-growing tracts includes several buprestid species acting either singly or together:

1. *Psiloptera fastuosa* reported as a major wood-boring pest of tasar host *Terminalia arjuna* plantations, causing extensive damage during the beetle's mating and oviposition season.
2. *Sphenoptera cupriventris* (Kerr) -the principal flat-headed stem borer recorded on *T. arjuna* in Chhattisgarh tasar plantations, frequently occurring alongside the bark-eating caterpillar *Indarbela quadrinotata*.
3. *Sphenoptera konbierensis* -reported to severely infest both *T. arjuna* and the related species *T. tomentosa*.

These flat-headed borers commonly occur alongside other stem- and bark-infesting pests of Arjun, including the cerambycid borer *Aeolesthes holosericea* and the cossid bark-eating caterpillar *Indarbela quadrinotata*, and infested trees may also show co-occurring termite damage, complicating field diagnosis of the primary damaging agent.

Biology and Damage Symptoms

Adult buprestid beetles oviposit in clusters within bark crevices, wounds, and cankered areas of the trunk and branches of Arjun. After hatching, the neonate larvae bore beneath the bark and feed on the phloem, cambium and outer vascular tissue, excavating characteristic winding, spiral tunnels that are often visible externally as ridge-like cankers or swellings on the trunk. As larvae mature through successive instars, they penetrate more deeply into the sapwood before pupating within the stem. Adults subsequently emerge by chewing distinct, D-shaped exit holes roughly 2-3 cm in width through the bark.

Field diagnosis of flat-headed borer infestation in Arjun relies on several visible symptoms: sawdust-like frass packed within galleries beneath loosened bark; spiral or winding cankers and ridges on the trunk surface; D-shaped emergence holes on the bark; general decline in tree vigor including sparse foliage and dieback of branches; and, in advanced infestations, girdling of the stem that can lead to branch or whole-tree mortality. Because larvae feed within the vascular tissue, infested trees suffer reduced sap flow and nutrient translocation, directly lowering leaf biomass available for silkworm rearing and depressing overall plantation productivity.

Incidence and Economic Impact

Field surveys across tasar-growing tracts of Chhattisgarh and other Indian states report substantial and economically significant levels of flat-headed borer infestation in Arjun plantations. Reported infestation levels vary by region, plantation type (block-planted versus natural stands) and management history, but are consistently high enough to threaten both tree survival and tasar cocoon productivity. A summary of documented infestation levels is presented below.

Location	Plantation type	Flat-headed borer infestation (%)	Source
Kargi Kota, Chhattisgarh	Tasar (<i>T. arjuna</i>) block plantation	51.84% (<i>Sphenoptera cupriventris</i>)	Tirkey <i>et al.</i> (2019)
Bilaspur, Chhattisgarh	Tasar (<i>T. arjuna</i>) block plantation	27.19% (<i>S. cupriventris</i>)	Tirkey <i>et al.</i> (2019)
Multiple field sites	Terminalia plantations (general)	22-40% (<i>Psiloptera fastuosa</i> and allied flat-headed borers)	Joshi (2012); Dhar <i>et al.</i> (1989), cited in Mandal & Das (2024)

Infestation by *S. cupriventris* has been reported to be significantly higher in block (monoculture) plantations than in natural, mixed-species plantations, which is consistent with the general observation that monocultures under continuous defoliation stress are more susceptible to borer buildup than diversified stands.

Management Strategies

1. Cultural and Silvicultural Control:

- Maintaining tree vigor through proper site selection, spacing, irrigation and balanced fertilization to reduce stress-related susceptibility to borer attack.
- Avoiding mechanical injury to bark during silkworm rearing operations and pruning, since wounds and bark crevices are preferred oviposition sites.
- Prompt removal and destruction of severely infested and dying trees to reduce carry-over populations of borers to the next season.
- Favoring mixed or natural plantation systems over dense monocultures where feasible, given the comparatively lower infestation recorded in natural plantations.

2. Mechanical and Physical Control:

- Manual removal of grubs from galleries using a sharp probe or wire, followed by plugging or sealing of bore holes.
- Swabbing or painting of trunks with mud or bark-protective coatings during the peak beetle emergence and oviposition period to deter egg-laying.

3. Chemical Control: Insecticidal management trials on the Arjun borer complex have demonstrated meaningful reductions in infestation using contact and systemic insecticides. Field evaluations report that chlorpyrifos 20% EC provided the highest degree of protection against bark- and stem-boring pests of *T. arjuna*, followed by dichlorvos 76% EC, while the botanical formulation azadirachtin (a neem-derived insect growth regulator) also achieved appreciable reduction in infestation, offering a comparatively eco-friendly alternative for tasar plantations where chemical residues can affect silkworm rearing. Trunk injection or soil application of systemic insecticides such as imidacloprid has similarly shown high protective efficacy against co-occurring wood-boring and termite pests of Arjun.

4. Integrated Pest Management (IPM): Given the biology of flat-headed borers-concealed larval feeding beneath bark that limits the effectiveness of contact sprays once larvae have bored in-an integrated approach combining vigor-enhancing cultural practices, timely mechanical destruction of eggs and early instars, targeted application of recommended insecticides during the adult emergence and oviposition window, and regular monitoring for early symptoms (bark cankers, frass, emergence holes) offers the most sustainable strategy for protecting Arjun plantations, particularly those integrated with tasar sericulture where insecticide choice must also safeguard silkworm health.

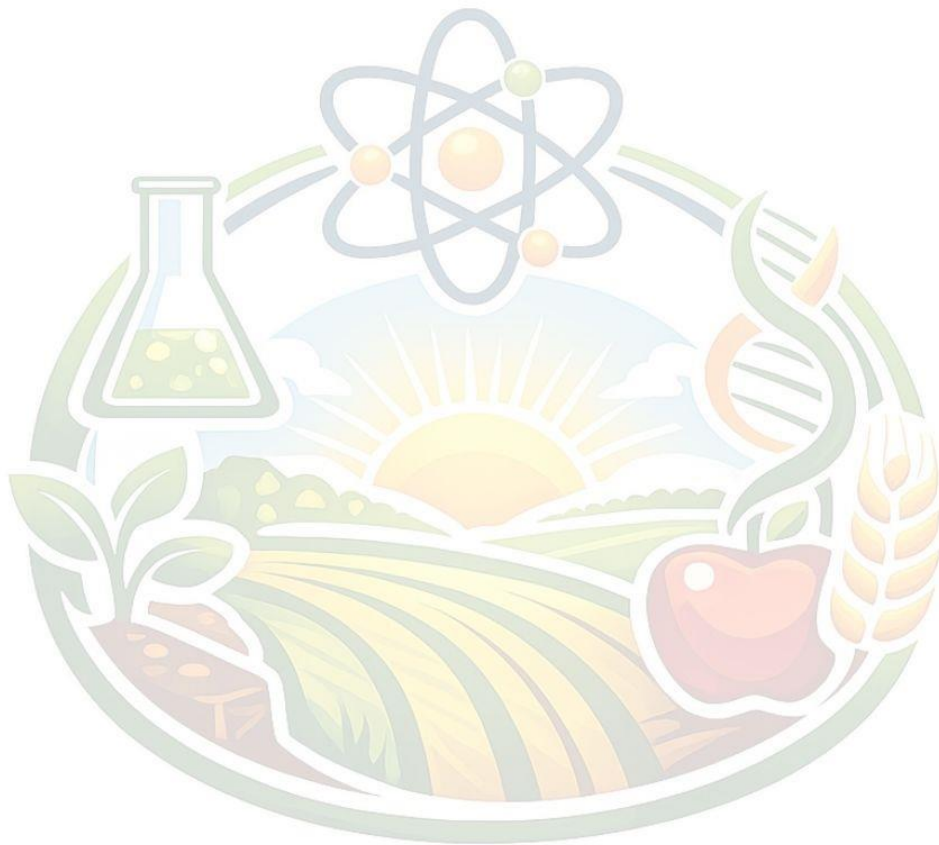
Conclusion

Flat-headed borers, principally *Sphenoptera cupriventris* and *Psiloptera fastuosa*, represent one of the most economically damaging pest complexes affecting Terminalia arjuna plantations in India, with documented infestation levels ranging from roughly 22% to over 50% depending on location and plantation management. Because Arjun underpins both tasar sericulture livelihoods and bark-based pharmaceutical value chains, sustained monitoring, vigor-based cultural management, and judicious integration of mechanical and chemical control measures are essential to limit yield and productivity losses caused by this borer complex. Further region-specific research is warranted to quantify the precise economic loss to tasar cocoon production and to refine IPM packages suited to different agro-climatic zones.

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Green Fuel or Green Illusion? Reassessing E85 and E100 Ethanol Fuels in India: Agricultural Trade-offs, Environmental Impacts, and the Byrnihat Case

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Abstract

India's rapid transition towards ethanol blending has positioned E85 and E100 as potential alternatives to conventional fossil fuels. However, the environmental benefits of high-ethanol fuels are not inherently guaranteed and depend strongly on feedstock selection, agricultural practices, land and water requirements, and production pathways. This article critically examines the agricultural and environmental trade-offs associated with expanding ethanol production in India, including food-fuel competition, soil and water pressures, greenhouse-gas emissions, air-quality benefits, and agricultural-residue utilization. A sustainable ethanol transition therefore requires diversified feedstocks, lifecycle-based assessment, effective regulation, and evidence-based pollution management.

Keywords: Agricultural impacts; E100; E85; Ethanol blending; Environmental impacts.

India's Ethanol Journey: From E5 to E100

India's Ethanol Blended Petrol programme, launched in the year 2003, has grown from a policy experiment into a central pillar of the energy strategy. The Ethanol Blending reached 20.0% (E20) in ESY 2025-26, with five years ahead of the originally targeted deadline 2030. The country is now gradually preparing to scale towards higher blends like E25, E27, and E30 in a phased manner. (PIB, 2026). India's revised National Policy on Biofuels framework explicitly incorporates higher ethanol blends, such as E85 and E100, to facilitate the adoption of flex-fuel vehicles (FFVs), a shift that would require roughly double India's current ethanol production capacity. Maize has overtaken sugarcane as the leading feedstock in recent years. However, this is not a fixed result, but an ongoing strategic effort to diversify the feedstock pool. The progression of India's ethanol blending percentages of Ethanol Supply Year (2020-2026) is shown in Table 1.

Table 1. Progression of India's Ethanol Blending Percentages (ESY 2020-2026):

Ethanol Supply Year	Blending Percentage / Status
ESY 2020-21	~8.1%
ESY 2021-22	10.0%
ESY 2022-23	12.1%
ESY 2023-24	14.60%
ESY 2024-25	19.20%
ESY 2025-26 (Nov-June 2026)	20%

Source: PIB (2026)

Lifecycle assessments show that ethanol's carbon footprint depends entirely on its source. For instance, sugarcane-based ethanol can actually achieve net-negative emissions, whereas cereal crops like maize and rice show less impressive outcomes (Azad et al., 2024). This feedstock dependency is the real cause of the E85/E100 debate. The environmental benefits are never guaranteed, but are completely shaped by what is grown, and how it is farmed. Table 2 shows the comparison between pure ethanol with the Petrol and Diesel.

Table 2. The comparison between pure ethanol with the Petrol and Diesel:

Parameter	Petrol	Diesel	Pure Ethanol (E100)
Energy content (calorific value)	~34.2 MJ/L	~38.6 MJ/L	~21.1 MJ/L
Density	~0.74 kg/L	~0.84 kg/L	0.789 kg/L
Octane / Cetane rating	Octane: ~91-95	Cetane: ~45-55	Octane: 108-113
CO ₂ emitted per litre burned	2.31 kg	2.68 kg	1.51 kg
Principal pollutants of concern	CO, benzene, unburnt HC	PM, NO _x , SO ₂	Acetaldehyde, SO ₂ & PM
India's installed production capacity	~258.1 Million Metric Tonnes Per Annum		20 billion L/year (2026)
India's import dependence	~88.7% (crude oil)		Near self-sufficient (negligible net imports)

Positive Agricultural Impacts

The rise of ethanol production in India has emerged as a powerful driver of rural prosperity, building a resilient bridge between agriculture and clean energy. The ethanol blending program provides a steady demand and higher incomes to

millions of farmers by creating a guaranteed, price supported market for the by-products of sugarcane, damaged food grains and maize. This regular income has enabled sugar mills to pay long overdue payments to farmers, thus promoting financial stability in rural areas. The program also promotes crop diversification into plants such as maize, boosts local employment in processing and transportation, and helps sustainable waste management by converting agricultural waste into second generation biofuels.

Second-generation ethanol which is made from crop residues such as rice husk, wheat straw, and sugarcane bagasse adds a further benefit, it converts agricultural waste that would otherwise be burned in the field into a marketable fuel, thereby easing the residue-burning problem that worsens winter air quality across northern India (Mandade et al., 2015).

Negative Agricultural Impacts

The primary concern is the classic food-versus-fuel conflict: sugarcane and maize are primary food and feed crops, and the scale at which they would have to be diverted to produce E85 puts direct pressure on food and nutritional security if the feedstock base is not expanded.

Another related concern is that of reduced crop rotation, with the feedstock-driven, monoculture intensive cultivation of sugarcane and maize leading to depletion of the soil organic carbon and vulnerability to pests and climate variability. Water stress exacerbates this, sugarcane is one of the most water intensive crops grown in India and expanding it in already stressed states like Maharashtra and Karnataka has real hydrological risk.

Positive Environmental Impacts

The most consistent finding in the literature is that high-ethanol blends offer sharp cuts to both tailpipe and lifecycle emissions relative to petrol. The increased blending leads to significant decreases of greenhouse gasses, particulate matter and toxic carcinogenic emissions from the transport systems (U.S. EPA, 2024). Each percentage point of blending creates a systematic displacement of fossil fuels and hence a direct reduction in the carbon intensity of the transport sector. The growth of the ethanol ecosystem offers two major environmental benefits, beyond simply reducing emissions:

Cleaner Urban Air: Ethanol is a natural octane booster, replacing dangerous aromatics such as benzene in fuel refining, drastically reducing urban smog.

Mitigating Stubble Burning: Agricultural residues, such as rice straw, can be converted into high-quality biofuels, providing a way to capture the rice straw and directly address the severe seasonal air pollution caused by open-field burning.

Negative Environmental Impacts

The environmental picture is not all positive. Feedstock cultivation intensifies fertilizer and pesticide use, and the literature is reasonably consistent that higher ethanol blends provide no benefit over petrol for eutrophication or freshwater ecotoxicity - the pollution burden just moves from the tailpipe to the farm (Borrión et al., 2012).

Expanding feedstock cultivation into forest margins or wetlands can also trigger indirect land-use change, a mechanism by which biofuels can, paradoxically, increase net GHG emissions once displaced-ecosystem carbon losses are counted (Searchinger et al., 2008). Finally, ethanol combustion trades one pollutant for another, it lowers benzene and carbon monoxide but raises acetaldehyde, a precursor of photochemical smog, as observed in Brazil's long experience with E100 (U.S. EPA, 2024).

Additionally, ethanol distilleries produce extremely hazardous effluent and industrial pollution that threaten regional ecosystems, posing a difficult trade-off between long-term environmental sustainability and clean energy goals.

Case Study: Byrnihat and the Ethanol-Blame

According to the IQAir World Air Quality Report, Byrnihat, an industrial town on the Assam-Meghalaya border, has an annual PM2.5 that is significantly higher than the WHO recommendation, making it the most polluted metropolitan area in the world (IQAir, 2025). Widespread criticism resulted from a viral expose in mid-2026 that blamed a single newly commissioned grain-based distillation facility for the majority of the crisis. The available evidence, however, does not support treating the ethanol plant as the principal cause.

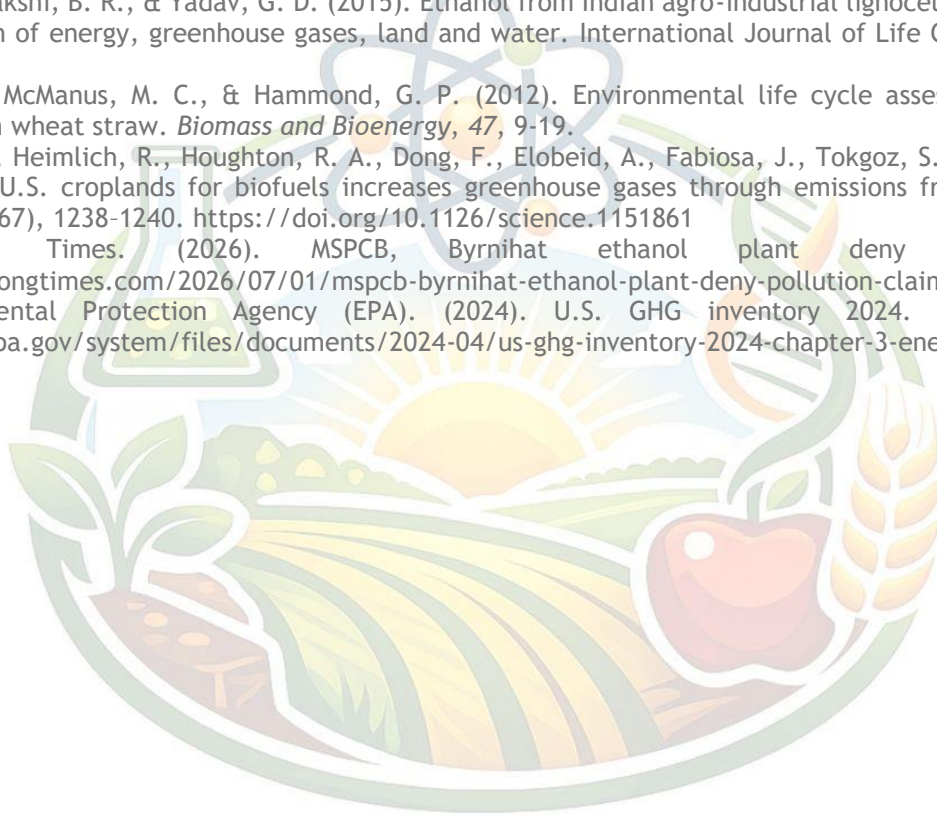
Byrnihat had already been flagged as critically polluted by the Central Pollution Control Board in 2022-23 and was ranked the world's most polluted metro area in March 2024. The ethanol unit only began commercial production in September 2024, after both milestones. However, the Meghalaya State Pollution Control Board (MSPCB) conducted a formal inspection in June 2026 found the plant's emissions within permitted limits, and the town's industrial estate hosts dozens of other significant sources such as cement plants, coal-based units, ferroalloy manufacturing, and multiple distilleries alongside heavy traffic and a valley geography that traps pollutants (The Shillong Times, 2026). Byrnihat's crisis ultimately reflects a multi-industrial, systemic failure of regulatory control and blaming a single ethanol plant only hides the larger policy failure.

Conclusion

E85 and E100 ethanol fuels offer significant potential for reducing fossil-fuel dependence, supporting farmers, utilizing agricultural residues, and lowering selected transport emissions. However, their environmental benefits are not guaranteed and depend on feedstock selection, water and land use, cultivation practices, and production efficiency. Therefore, India's transition towards higher ethanol blends should follow a feedstock-diversified and sustainability-focused approach. The Byrnihat case further demonstrates that industrial air pollution requires evidence-based assessment of multiple sources rather than attributing pollution to a single facility.

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Climate Change and Greenhouse Gas Emissions: The Global Challenge, India and China, and the Way Forward

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Climate Change: A Global Challenge

Climate change is no longer a distant environmental concern—it is a reality being experienced across the world. Rising temperatures, changing rainfall patterns, prolonged droughts, floods, melting glaciers, sea-level rise and increasingly frequent extreme weather events are affecting agriculture, water resources, biodiversity, human health and the livelihoods of millions of people.

Behind these changes lies a fundamental problem: the increasing concentration of greenhouse gases (GHGs) in the atmosphere. Carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O) and fluorinated gases trap heat and help maintain the Earth's temperature. However, human activities such as fossil-fuel combustion, electricity generation, industrial production, transportation, deforestation and agriculture have substantially increased greenhouse gas emissions, intensifying the natural greenhouse effect.

The scale of this challenge is becoming increasingly clear. According to the EDGAR 2025 assessment, global greenhouse gas emissions from anthropogenic activities reached a record 53.2 billion tonnes of CO₂ equivalent (Gt CO₂eq) in 2024, excluding land use, land-use change and forestry (LULUCF). This represented a 1.3 per cent increase over 2023, or an additional 665 million tonnes of CO₂eq. Global emissions in 2024 were nearly 65 per cent higher than in 1990.

Where Do Greenhouse Gas Emissions Come From?

Greenhouse gas emissions do not originate from a single source. Power industry is the largest contributor, accounting for nearly 30 per cent of global GHG emissions in 2024. It also recorded the largest absolute increase in emissions compared with 2023, rising by about 235 million tonnes of CO₂eq. In 2024, fossil CO₂ accounted for 74.5 per cent of global GHG emissions, followed by methane at 17.9 per cent, nitrous oxide at 4.8 per cent, and fluorinated gases at 2.8 per cent. Since 1990, global fossil CO₂ emissions have increased by nearly 75 per cent.

A Global Perspective: Who Emits the Most?

Greenhouse gas emissions are unevenly distributed across the world. Although every country contributes to climate change, a relatively small number of major economies account for a large share of global emissions because of their population size, industrial activity, energy consumption and economic development.

In 2024, China, the United States, India, the European Union (EU27), Russia and Indonesia were the six largest greenhouse gas emitters. Together, they accounted for 61.8 per cent of global GHG emissions. They also represented 64.2 per cent of global fossil-fuel consumption, highlighting the close relationship between energy use and greenhouse gas emissions.

Table 1. Top Five Greenhouse Gas-Emitting Countries in the World (2024):

Rank	Country/Region	Share of Global GHG Emissions (%)
1	China	29.2
2	United States	11.1
3	India	8.2
4	European Union (EU27)	5.9
5	Russian Federation	4.8

Source: JRC/IEA, EDGAR 2025.

Although greenhouse gas emissions are generated worldwide, they are concentrated in a few countries. In 2024, the top five emitters contributed more than half of the world's greenhouse gas emissions. China alone accounted for nearly three-tenths of global greenhouse gas emissions, while the United States and India ranked second and third, respectively. These countries play a critical role in global climate mitigation because their policies and technological advancements have a significant influence on future emission trajectories.

Why Focus on India and China?

Among the world's major emitters, India and China deserve particular attention. Both are large and rapidly developing economies with substantial populations, expanding industries, growing cities and increasing energy requirements. Over the past three decades, economic development, infrastructure expansion and rising energy demand have significantly

influenced their greenhouse gas emission trajectories. At the same time, the two countries differ considerably in their economic structure, energy systems, industrial development and per-capita emissions. Studying India and China provides valuable insights into the relationship between economic development, energy consumption and greenhouse gas emissions. Their future choices in energy, industry, transport and agriculture will have a major influence on global climate action.

How have Greenhouse Gas Emissions Changed?

Greenhouse gas emissions have increased substantially in both India and China over the past three decades. China's emissions increased from 4,059 million tonnes of CO₂ equivalent in 1991 to 15,536 million tonnes in 2024, representing more than a three-fold increase. During the same period, India's emissions increased from 1,433 million tonnes to 4,371 million tonnes of CO₂ equivalent, more than tripling over the period.

The emission trends show a particularly rapid increase in China after the early 2000s, coinciding with rapid industrialisation, expansion of manufacturing activities, increased coal-based electricity generation, urbanisation and rising energy demand. India's emissions have also shown a steady upward trend, driven by economic growth, increasing energy consumption, industrial development, urban expansion and transportation.

By 2024, China accounted for 29.2 per cent of global greenhouse gas emissions, while India's contribution reached 8.2 per cent. Together, the two countries accounted for approximately 37.4 per cent of global GHG emissions, highlighting their significant role in global climate action.

GHG Emission

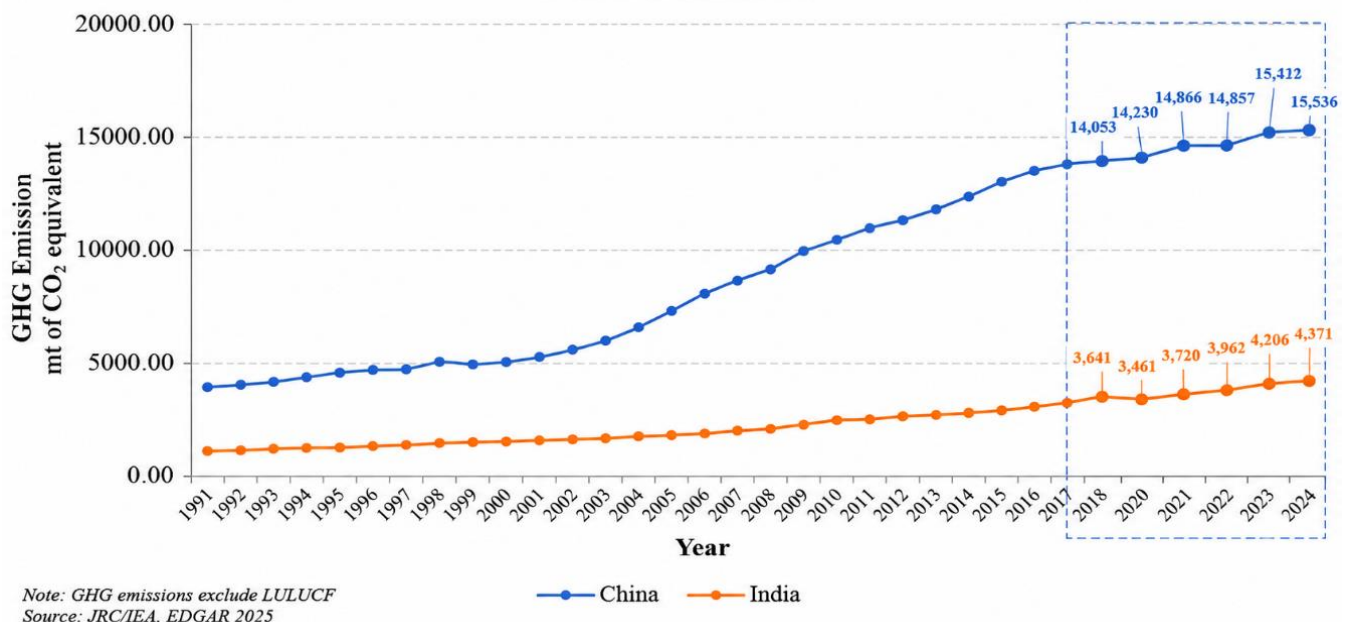


Figure 2. Trends in Greenhouse Gas Emissions in India and China (1991-2018)

Greenhouse gas emissions increased substantially in both India and China between 1991 and 2024. China's emissions grew more rapidly than India's, particularly after the early 2000s. The relatively continuous rise in emissions in both countries demonstrates the close relationship between economic development, energy demand and greenhouse gas emissions. At the same time, these trends highlight the importance of accelerating the transition towards renewable energy, improving energy efficiency, adopting cleaner technologies and promoting sustainable development pathways.

Per Capita Emissions: Looking Beyond Total Emissions

A country's total greenhouse gas emissions show its overall contribution to global emissions, but per-capita emissions provide another important perspective. A country with a very large population may have high total emissions while having relatively low emissions per person. In 2024, China's per-capita GHG emissions were approximately 10.8 tonnes CO₂eq per person, whereas India's were about 3.0 tonnes CO₂eq per person. This difference highlights the importance of considering population size, economic development, energy consumption and lifestyle patterns when comparing countries. Therefore, India's position as the third-largest emitter in total terms should be interpreted alongside its comparatively lower per-capita emissions.

Table 2. Comparison of Greenhouse Gas Emissions in India and China, 2024:

Indicator	China	India
Share of global GHG emissions	29.2%	8.2%

Per-capita GHG emissions	10.8 t CO ₂ eq /person	3.0 t CO ₂ eq/person
Change in emissions, 2023-2024	+0.8%	+3.9%
Change since 1990	More than four-fold increase	Nearly three-fold increase

Source: JRC/IEA, EDGAR 2025

Per Capita Emission

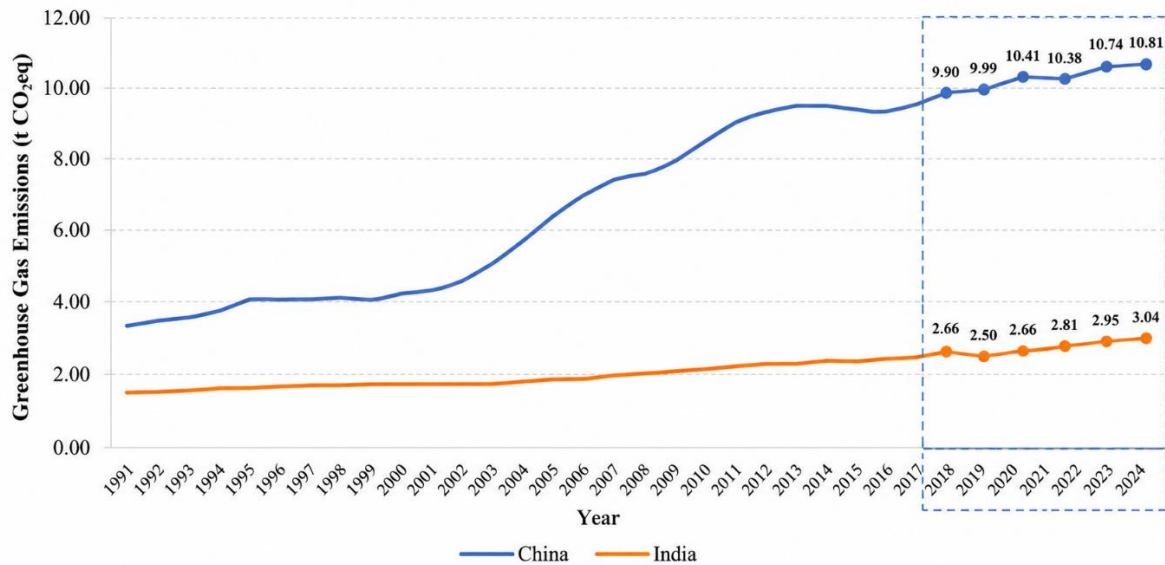


Figure 3. Per Capita Greenhouse Gas Emissions in India and China (1991-2018)

What is Driving the Increase in Emissions?

The increase in greenhouse gas emissions is influenced by several interconnected factors rather than population growth alone.

Major Driver	Impact on Greenhouse Gas Emissions
Rapid industrialization	Higher emissions from manufacturing and industries
Fossil fuel consumption	Increased carbon dioxide emissions from coal, oil, and natural gas
Urbanization	Greater demand for electricity, housing, and transportation
Economic growth	Expansion of production and energy-intensive activities
Population growth	Increased demand for food, energy, and infrastructure

The latest EDGAR assessment shows that global emissions have followed a largely upward trajectory since the beginning of the twenty-first century, with notable interruptions in 2009 during the global financial crisis and in 2020 during the COVID-19 pandemic.

Conclusion

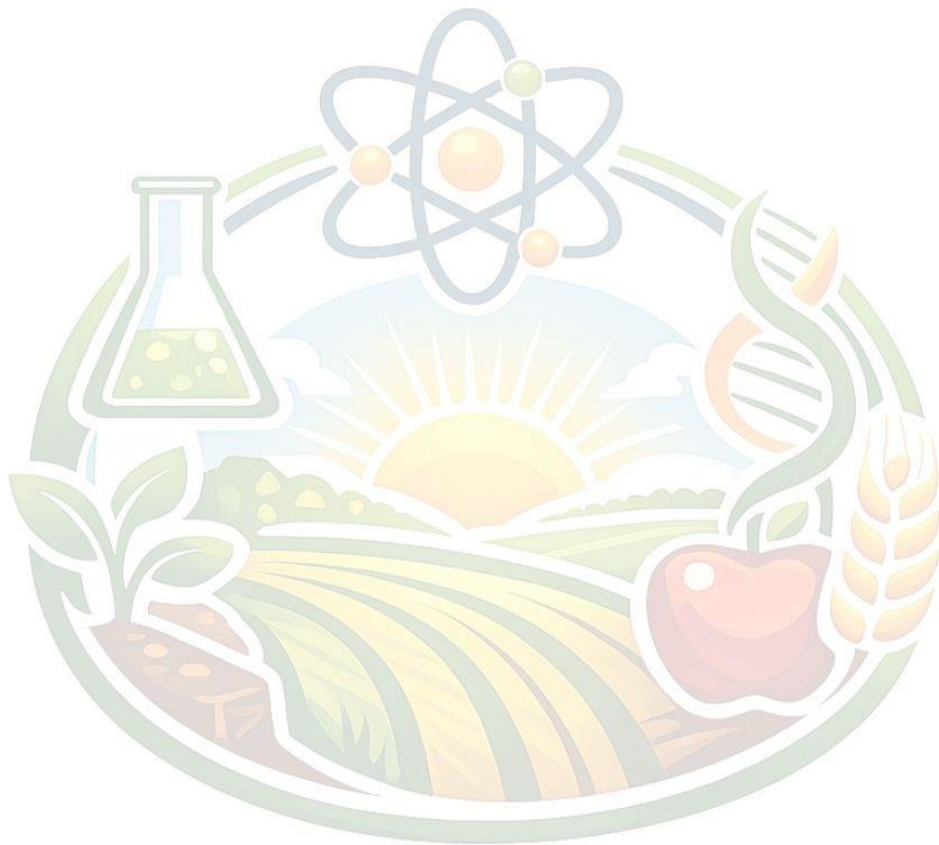
Greenhouse gas emissions have become one of the defining environmental challenges of our time. The experiences of India and China demonstrate how rapid economic growth, industrialisation and urbanisation can lead to substantial increases in greenhouse gas emissions alongside improvements in living standards. At the same time, these experiences highlight the importance of adopting cleaner technologies, expanding renewable energy, improving energy efficiency and promoting sustainable development.

As two of the world's largest economies and among the leading greenhouse gas emitters, India and China have a pivotal role to play in global climate action. Their policies, technological innovations and transition towards low-carbon development will significantly influence global efforts to reduce greenhouse gas emissions and achieve climate goals. Sustained action today can help balance economic development with environmental sustainability and secure a safer and more sustainable future for generations to come.

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Rice Earhead Bug (Gundhi Bug): An Emerging Challenge for Rice Farmers of Uttar Pradesh

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Abstract

Rice earhead bug (*Leptocorisa acuta*), commonly known as the Gundhi bug, has become an increasingly important insect pest of rice in Uttar Pradesh. The pest is particularly destructive during flowering and the milky grain stage, when both nymphs and adults extract sap from developing grains. Infested grains often become shrivelled, partially filled and lighter in weight, leading to reduced yield and inferior grain quality. The increasing frequency of warm, humid weather and changes in crop management practices have contributed to its growing importance. Sustainable management relies on an integrated pest management (IPM) approach that combines regular field monitoring, preventive cultural practices, conservation of natural enemies and judicious use of insecticides only when necessary (Heinrichs, 1994; Prakash *et al.*, 2021).

Keywords: Rice, *Leptocorisa acuta*, Gundhi bug, Earhead bug, Uttar Pradesh, IPM, Rice pests.

Introduction

Rice is the most important staple crop grown in Uttar Pradesh and plays a vital role in the state's agricultural economy. Among the insect pests affecting rice, the Gundhi bug has gained attention because of its ability to damage developing grains during the reproductive stage of the crop. Population build-up is usually observed under warm and humid conditions during panicle emergence and grain filling, resulting in measurable losses in both grain yield and market quality (ICAR-IIRR, 2023).

Taxonomy

Order: Hemiptera

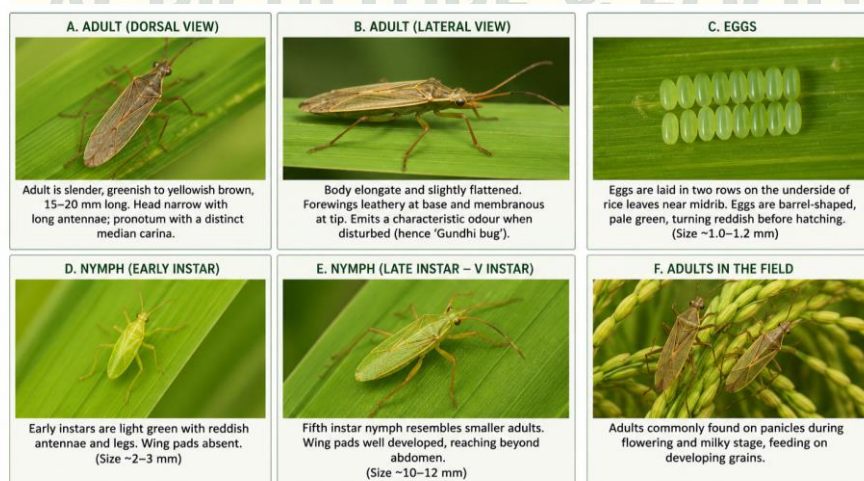
Family: Alydidae

Genus: *Leptocorisa*

Species: *Leptocorisa acuta* (Thunberg).

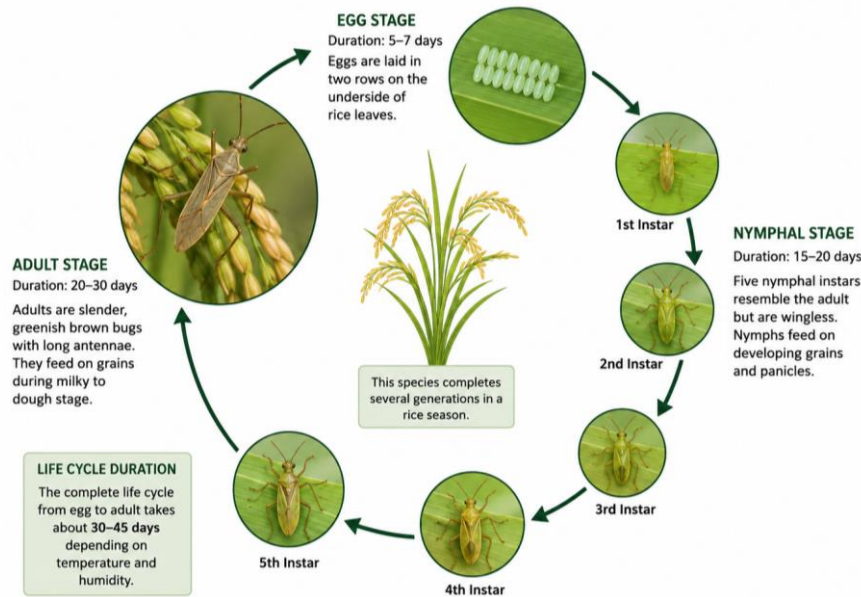
Identification

Adults are slender greenish-brown insects measuring about 15-20 mm. Eggs are laid in two rows on leaves. Nymphs resemble adults but are wingless. Adults emit a characteristic odour when disturbed, giving rise to the common name 'Gundhi bug'.



Note: Both nymphs and adults are plant sap suckers. Their piercing-sucking mouthparts are used to feed on developing rice grains. Field observation during panicle emergence to milky stage is important for proper identification.

Biology and Life Cycle



Greenhouse gas emissions have increased substantially in both India and China over the past three decades. China's emissions increased from 4,059 million tonnes of CO₂ equivalent in 1991 to 15,536 million tonnes in 2024, representing more than a three-fold increase. During the same period, India's emissions increased from 1,433 million tonnes to 4,371 million tonnes of CO₂ equivalent, more than tripling over the period.

Stage	Duration	Characteristic	Management Focus
Egg	5–7 days	Rows on leaves	Monitoring
Nymph	15–20 days	Five instars	Field scouting
Adult	20–30 days	Feeds on grains	IPM/need-based control

Nature of Damage

Feeding during the milky stage causes shrivelled grains, chaffiness, brown spots, poor seed viability and lower milling quality (Pathak & Khan, 1994).

Crop Stage	Symptoms	Expected Impact
Flowering	Panicle feeding	Reduced grain set
Milky stage	Shrivelled/chaffy grains	Yield and quality loss
Maturity	Discoloured grains	Lower market value

Integrated Pest Management

Component	Recommendation	Timing
Cultural	Synchronized planting; balanced nitrogen; weed removal	Before flowering
Monitoring	Weekly scouting and sweep net observations	Panicle emergence onward
Biological	Conserve spiders and predators	Entire season
Chemical	Need-based application only as per official recommendation	Above ETL

District-Wise Reported Occurrence in Uttar Pradesh

The following table summarizes districts where Gundhi bug has been reported or is considered a potential concern based on rice cultivation and extension advisories. It is indicative and not an incidence survey.

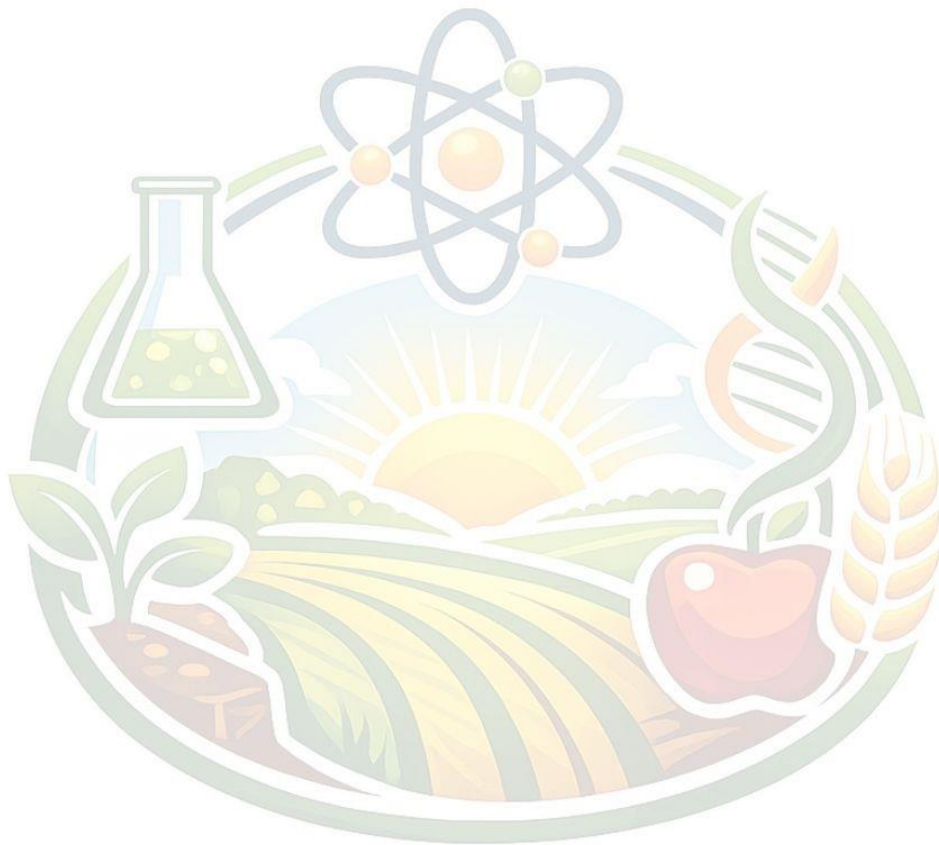
Region	Representative districts
Eastern UP	Gorakhpur, Deoria, Kushinagar, Maharajganj, Ballia, Azamgarh
Central UP	Lucknow, Barabanki, Sitapur, Hardoi, Raebareli
Terai	Lakhimpur Kheri, Bahraich, Shravasti, Balrampur, Pilibhit
Western UP	Moradabad, Bareilly, Bijnor, Rampur

Conclusion

Effective management of the rice earhead bug requires a combination of timely surveillance, synchronized crop establishment, balanced nutrient management, conservation of beneficial organisms and need-based plant protection measures. Adoption of these integrated practices can substantially reduce crop losses while promoting environmentally sustainable rice production in Uttar Pradesh.

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When the Climate Turns Hot: How El Niño Rewires Plant Physiology

Article ID: 74439

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Imagine a crop field during an unusually hot and dry season. Leaves begin to curl, stomata close, photosynthesis declines, and the plant struggles to maintain its water balance. The remarkable part is that the cause of this stress may have begun thousands of kilometres away—not in the field, but in the tropical Pacific Ocean.

El Niño, the warm phase of the El Niño-Southern Oscillation (ENSO), is a major ocean-atmosphere phenomenon that can alter temperature and rainfall patterns across different parts of the world. Its effects are not identical everywhere: some regions may experience drought and heat, while others may receive increased rainfall. For plants, therefore, El Niño is not a direct stress signal. Instead, plants respond to the **heat, drought, altered rainfall and atmospheric water demand** that may accompany regional El Niño conditions (Iizumi et al., 2014). The fascinating question is: **How does a climate event in the ocean eventually change the physiology of a plant?**

From El Niño to Plant Stress

During El Niño, weakening of the Pacific trade winds and warming of the tropical Pacific alter atmospheric circulation. These changes can influence regional precipitation and temperature through long-distance atmospheric connections known as teleconnections. For agriculture, the consequences can be substantial. Changes in rainfall may reduce soil moisture, while increased temperature raises atmospheric demand for water. When these conditions occur together, plants face a double challenge: **less water is available in the soil, while the atmosphere demands more water from the leaves.**

The combination of heat and drought is particularly important because plants do not necessarily respond to combined stresses in the same way as they respond to either stress individually. Heat and drought can interact to produce complex changes in photosynthesis, water relations, metabolism and growth (Zandalinas et al., 2018). This is where plant physiology becomes the bridge between climate variability and crop productivity.

Stomata: The Plant's First Response

One of the earliest responses to declining water availability occurs at the stomata—microscopic pores on the leaf surface that regulate gas exchange. When soil moisture decreases, plants commonly increase **abscisic acid (ABA)** signalling. ABA promotes stomatal closure, reducing the loss of water through transpiration. In simple terms, the plant partially closes its microscopic water valves to conserve moisture.

But this protection comes with a cost.

Stomatal closure also restricts the entry of carbon dioxide into the leaf. Consequently, the plant conserves water but may lose photosynthetic capacity. Under high temperature, the situation becomes even more complicated because transpiration can help cool leaves. Thus, drought encourages stomatal closure, whereas heat may increase the need for evaporative cooling (Zandalinas et al., 2018).

The plant must constantly balance two competing demands: **Save water or keep photosynthesizing and cooling the leaf.**

This trade-off is one of the central challenges of plant adaptation to climate extremes.

Photosynthesis Under Pressure

Heat and drought can reduce photosynthesis by restricting CO₂ entry through stomatal closure and impairing enzymes such as Rubisco and Rubisco activase. In rice, improving the levels of these proteins enhanced photosynthesis and biomass under heat stress (Qu et al., 2021). Heat can also damage Photosystem II, causing photoinhibition, which can be detected through chlorophyll fluorescence. Ultimately, reduced photosynthesis limits carbon availability for plant growth and reproduction, contributing to yield loss.

Protecting Water and Cells

Plants maintain cellular water status by accumulating compatible solutes such as **proline and soluble sugars**, which support osmotic adjustment and hydration. Root growth and architecture may also adapt to improve access to deeper or wetter soil, while aquaporins regulate water movement.

Heat and drought can increase **reactive oxygen species (ROS)**. At moderate levels, ROS act as signals, but excess ROS can damage cellular components. Plants counter this through antioxidants such as **superoxide dismutase, catalase and ascorbate peroxidase**, while ROS interact with hormones to coordinate stress responses (Devireddy et al., 2021). Heat also induces **heat-shock proteins**, which protect and refold damaged proteins, enabling plants to reorganize metabolism and withstand stress.

Roots and the Plant Microbiome

While drought and heat are visible aboveground, roots are fighting their own battle. Under water scarcity, roots may alter elongation, branching and root-to-shoot allocation, with deeper or more extensive roots improving access to soil moisture. Roots also interact with rhizosphere microbes that can influence growth, nutrient uptake, hormone signalling and antioxidant defence. This has increased interest in the plant microbiome as a component of climate resilience. However, these microbial benefits depend on the crop genotype and soil environment, highlighting the need for reliable plant-microbe combinations.

When Stress Reaches Reproduction

For farmers, the ultimate consequence of physiological stress is often measured not in leaves, but in **yield**. Reproductive development is particularly sensitive to high temperature. Heat can affect pollen formation, pollen viability, pollen germination, fertilization and subsequent grain or seed development (Chaturvedi et al., 2021).

This makes flowering a critical period.

A crop may maintain reasonable vegetative growth but still produce a poor harvest if heat coincides with flowering. In cereals such as maize, rice and wheat, reproductive heat stress can strongly influence grain number and grain filling. The timing of stress therefore matters as much as its intensity. A short period of severe heat during a sensitive reproductive stage may cause greater yield loss than a longer period of moderate stress during vegetative growth.

This is why understanding plant developmental physiology is essential for predicting the agricultural consequences of climate variability.

Can Plants Remember Stress?

Plants are increasingly recognised as organisms capable of displaying **stress memory or priming**.

A previous mild stress can sometimes alter the plant's response to a subsequent stress through changes in gene expression, metabolism, antioxidant capacity and chromatin regulation. Such responses may allow plants to activate protective mechanisms more rapidly when stress returns. For climate variability, this raises an intriguing possibility: previous exposure to heat or drought may influence how plants respond to future episodes. However, stress memory is complex and highly dependent on species, genotype, stress intensity and environmental conditions. It should therefore be viewed as an emerging opportunity rather than a universal mechanism of climate adaptation.

From Stress Detection to Prediction

Modern plant science is moving beyond measuring stress after damage has occurred.

Thermal imaging can identify increased canopy temperature associated with reduced transpiration. **Chlorophyll fluorescence** can reveal disturbances in photosynthetic performance. Multispectral and hyperspectral imaging can provide information about canopy structure, pigments and plant water status. When these technologies are combined with drones, large crop populations can be monitored rapidly. Artificial intelligence and machine learning can then integrate physiological, environmental and imaging data to identify stress patterns and potentially predict yield loss.

This creates an exciting future possibility: **Instead of waiting for a crop to show visible drought symptoms, we may detect physiological stress early enough to intervene.**

Designing Crops for an El Niño World

Understanding plant physiology also provides targets for crop improvement.

Future climate-resilient crops may require combinations of:

1. Efficient and deeper root systems,
2. Stable photosynthesis under heat,
3. Effective stomatal regulation,
4. Improved osmotic adjustment,
5. Stronger antioxidant defence,
6. Heat-tolerant reproductive development,
7. Efficient water use, and
8. Beneficial plant-microbe interactions.

Conventional and molecular breeding, genomic selection and genome editing can help develop climate-resilient traits, while improved irrigation, soil-water conservation, climate-informed planting and precision agriculture can reduce risks. El Niño forecasting can further guide crop selection, planting time, irrigation and climate-risk management.

From Climate Warning to Plant Resilience

El Niño begins as an ocean-atmosphere phenomenon, but its consequences can ultimately be expressed at the scale of a stomatal pore, a chloroplast, a root or a pollen grain.

The sequence is remarkably interconnected:

El Niño → altered climate → heat and water stress → physiological sensing → stomatal and photosynthetic responses → cellular protection → reproductive effects → yield consequences.

Understanding this cascade changes how we think about climate-resilient agriculture.

The goal is no longer simply to ask, “How much yield will El Niño reduce?”

A more useful question is:

“Can we understand the physiological warning signals early enough to predict stress, select resilient plants and protect yield?”

The future of climate-resilient agriculture may lie at this intersection of **plant physiology, climate science, phenomics, microbiome research, molecular breeding and artificial intelligence**. A warming ocean may be far from a crop field, but the plant can still reveal its influence on one stomatal response, one photosynthetic adjustment and one developing grain at a time.

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Empowering Turmeric Farmers Through Modern Processing Technologies: A JMKPM FPO Model

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Abstract

Turmeric farmers often market raw produce, limiting opportunities to capture value from processing and direct marketing. This article presents the JMKPM Farmer Producer Organization model in Nizamabad district, Telangana, which integrates collective processing, value addition, quality assurance, branding and direct market linkages. The organization brings together nearly 600 farmers from five villages and operates a Common Facility Centre with facilities for boiling, polishing, grading, powder preparation, packaging and turmeric leaf oil extraction. The centre provides custom-hiring services and enables farmers to convert turmeric into market-ready products while reducing dependence on intermediaries. The model reports a processing service charge of ₹1,000 per quintal and an additional ₹1,000 for powder preparation, with an estimated net surplus of ₹500 per quintal. The integrated approach strengthens value addition, market access and income generation opportunities, demonstrating a replicable pathway for farmer-led turmeric enterprises.

Keywords: Turmeric; Value addition; Farmer Producer Organization; Common Facility Centre; Marketing; Entrepreneurship

Introduction

Turmeric is an important commercial spice crop with applications in food, pharmaceuticals, cosmetics and export markets. Although farmers commonly market raw turmeric, post-harvest processing and value addition can provide opportunities to improve product quality, marketability and returns. The experience of the JMKPM Farmer Producer Organization illustrates a farmer-led approach in which collective action is combined with modern processing infrastructure, quality assurance, branding and direct marketing. The organization was established to strengthen farmers' participation beyond primary production and to promote a farmer-to-consumer model that reduces dependence on intermediaries. Its Common Facility Centre brings multiple post-harvest operations under one roof and provides custom-hiring services to member farmers. Against this background, the present article documents the operational features, processing capacities, value-added products, market linkages and economic feasibility of the JMKPM model, with emphasis on its potential as a practical approach for strengthening turmeric-based rural enterprises.

The FPO was established in 2021, the organization comprises nearly 600 turmeric farmers from the above five villages. Each member obtained membership by contributing a minimum share capital of ₹7,000. Under the leadership of Mr. P. Tirupathi Reddy, Chairman of the JMKPM FPO, the organization is committed to improving farmer's livelihoods through adoption of modern processing technologies, value-added turmeric products, quality assurance, branding and direct marketing systems that eliminate the role of intermediaries. With technical support from Prakruthi, a Non-Governmental Organization, and 90% financial assistance from the National Institute for Micro, Small and Medium Enterprises (NIMSME), the FPO has established as Common Facility Centre (CFC), providing a strong foundation for its sustainable growth and development.

Mr. P. Tirupathi Reddy, Chairman of the JMKPM FPO stated that "The primary objective of this FPO is to follow farmer - consumer concept and to ensure that turmeric farmers receive fair with remunerative prices for their produce by minimizing the involvement of intermediaries". He emphasized that farmers should not remain mere producers but should evolve into agri-entrepreneurs through value-added turmeric products and marketing them directly to consumers. The organization is committed to supplying pure and high-quality turmeric products while creating sustainable income opportunities for its members. To realize this vision, the FPO has established a Common Facility Centre (CFC) spanning approximately 6,000 square feet, which serves as a comprehensive processing hub for turmeric farmers. The centre is equipped with modern infrastructure, including four steam boilers powered by a combination of 80% electricity and 20% firewood, a polishing unit, grading machines of four different size categories, a pulverizer, powder manufacturing and packaging units, and a turmeric leaf oil extraction unit. In addition to providing advanced processing facilities, the centre also functions as a custom hiring centre, enabling farmers to access these services at affordable rates.



Farmers bring their sun-dried turmeric rhizomes and fingers to the Common Facility Centre, where the FPO manages the entire post-harvest processing chain through custom hiring. The services include unloading, single/double polishing, grading, bagging, and loading, ensuring that farmers receive a complete processing solution under one roof. The FPO charges a processing fee of ₹1,000 per quintal for these services. Farmers who wish to convert their turmeric rhizomes/fingers into powder are required to pay an additional ₹1,000 per quintal. This cost-effective processing system enables farmers to prepare high-quality, market-ready products while minimizing post-harvest handling expenses. The CFC is equipped with four boilers, each having a capacity of 250 kg per batch, capable of boiling turmeric in approximately 20 minutes. Collectively, the facility can process one tonne of turmeric per batch. The boilers operate using a combination of 80% electricity and 20% firewood, with an average monthly electricity expenditure of around ₹15,000/month. After boiling, the turmeric is sun-dried for 8-12 days before being transferred to the polishing unit.



The polishing machine has a processing capacity of one tonne per hour. A single polishing cycle requires approximately 25 minutes, whereas double polishing takes about 35-40 minutes. The polished turmeric is subsequently graded using a grading machine with a capacity of one tonne per hour, which separates the produce into four different size categories. The pulverizer can process approximately three quintals of turmeric per hour into fine turmeric powder. Following sieving, the powder is packed using an automatic packaging unit in various pack sizes ranging from 100 g to 10 kg, making the products ready for commercial marketing. The predominant “Armoor” Local turmeric variety cultivated in this region contains 1.5-3.0% curcumin making it highly preferred in the commercial market.

The FPO markets conventionally produced turmeric powder at a price ranging from ₹180 to ₹250/kg, while organically produced turmeric powder is sold at ₹300 to ₹400/kg. Maintaining uncompromising quality standards and supplying pure, adulteration-free turmeric products remain the organization's foremost priorities. By reducing the involvement of intermediaries and establishing a direct marketing system, the FPO effectively connects farmers with consumers, enabling producers to realize better returns for their produce. At present, the FPO markets its 'Indur' branded turmeric products to Self-Help Groups (SHGs), educational institutions, local consumers, private organizations, online marketing

platforms, traders from Gujarat, and exporters serving the Gulf countries. This diversified marketing strategy has significantly expanded market access while enhancing the visibility and credibility of the FPO's products.



To generate additional income opportunities for farmers, the FPO has also established a turmeric leaf oil extraction unit, enabling the utilization of turmeric leaves, which are generally considered a by-product of cultivation. The unit has the capacity to process one tonne of turmeric leaves per batch, producing approximately 4-5 litres of turmeric leaf essential oil through steam distillation using electricity and steam. However, due to the limited market demand for turmeric leaf oil, the extraction unit is operated only when sufficient demand exists, ensuring efficient utilization of resources and economic viability.



The integrated approach adopted by the JMKPM FPO, combining modern processing technologies, value addition, stringent quality standards, branding and direct marketing has transformed farmers from primary producers into successful agri-entrepreneurs. By enhancing the value of turmeric and strengthening market linkages, the FPO has created sustainable livelihood opportunities seeking to improve farmers' income through commercial agriculture.

Table 1: Economic Feasibility of the Common Facility Centre:

Particulars	Amount (₹/Quintal)
Primary processing service charge	1,000
Additional charge for powder preparation	1,000
Total amount payable by the farmer	2,000
Estimated total operational cost	1,500
Estimated net surplus	500

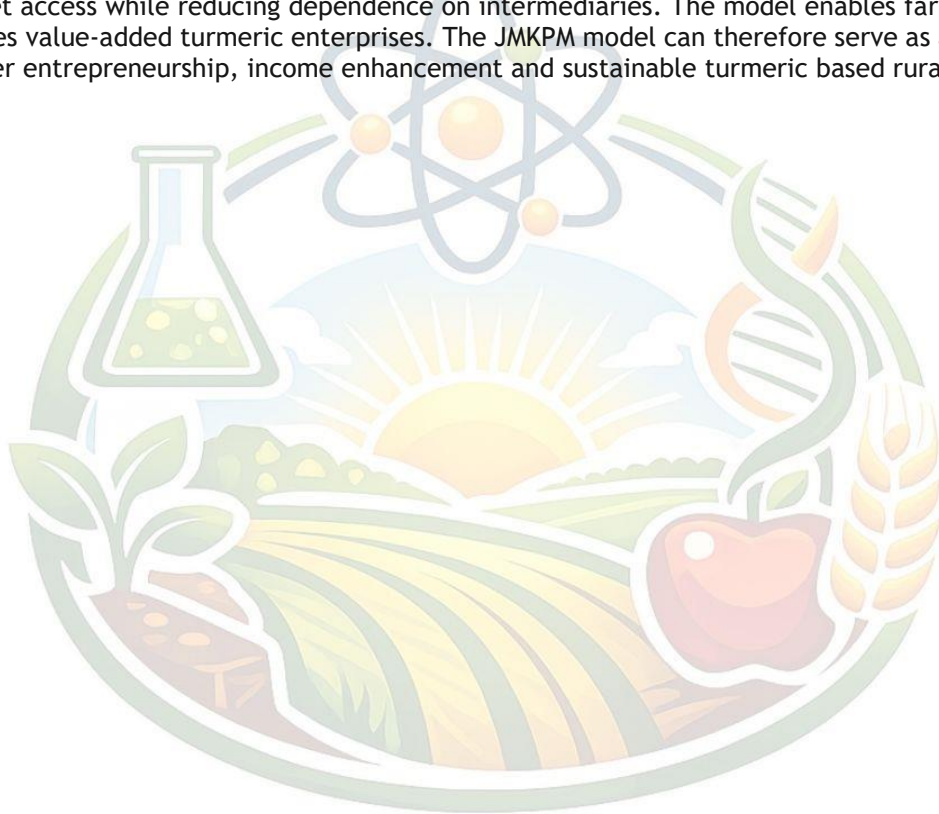
The establishment of this modern CFC has significantly benefited both the Farmer Producer Organization and turmeric farmers in the district. By providing integrated facilities for boiling, polishing, grading, powder production, and packaging under a single roof, the centre saves considerable time and labour while enabling farmers to produce high-quality,

market-ready turmeric products. Furthermore, the elimination of intermediaries allows farmers to market their produce directly to consumers, business enterprises, and exporters, thereby securing better prices and improving farm profitability.

The service charges generated through processing activities also enable the FPO to meet the operational expenses of the CFC, ensuring its long-term sustainability. The integration of value addition, quality assurance, branding, and direct marketing has established the JMKPM Farmer Producer Organization as a successful and replicable model for other Farmer Producer Organizations. Establishing similar CFC across different districts would promote value addition in agricultural commodities, reduce dependence on intermediaries, facilitate the production of high-quality marketable products, expand farmer's income, and accelerate the development of sustainable rural agro-based enterprises.

Conclusion

The JMKPM Farmer Producer Organization demonstrates the potential of value addition and modern processing technologies in improving turmeric farmers' livelihoods. The Common Facility Centre provides integrated facilities for processing, grading, powder preparation and packaging at affordable costs. Direct marketing and branding have strengthened market access while reducing dependence on intermediaries. The model enables farmers to obtain better returns and promotes value-added turmeric enterprises. The JMKPM model can therefore serve as a replicable approach for promoting farmer entrepreneurship, income enhancement and sustainable turmeric based rural enterprises.



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Empowering Smallholder Farmers for a Changing Future from Climate Risk to Resilience in Agriculture

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Abstract

Climate change is adding to the uncertainty in agriculture, due to higher temperatures, irregular rainfall, droughts, floods, increasing intensities of heat waves and changing pests and diseases distribution patterns. Smallholder farmers are especially vulnerable as they rely heavily on natural resources, and have limited access to finance, technology, irrigation, markets and timely information. Recent research conducted in India indicates that smaller land holdings, restricted livelihood options, and poor market linkages can make people vulnerable; but, livelihood diversification, and solidarity and resilience building strategies like climate-smart farming can build adaptive capacity. Climate resilience is not simply about implementing one particular technology; however, it also involves developing resilience of the farmer to foresee risks, adjust their production system and bounce back from shocks. Crop diversification, climate resilient varieties, soil and water conservation, integrated farming systems, livestock integration, financial protection and collective action can be a part of this transition. The National Innovations in Climate Resilient Agriculture (NICRA) programme has identified and tested technology for specific locations in vulnerable areas and more recent ICAR programmes focus on scaling up climate-resilient technologies and knowledge to farmers. This article explores practical avenues for smallholder farmers to shift from being vulnerable to building resilient and sustainable livelihoods.

Keywords: Climate change, smallholder farmers, climate resilience, adaptation, diversification, climate-smart agriculture, farmer resilience.

Introduction

When the Climate Changes, the Farm Changes: Climate change is not just a change in temperature at a weather station for a smallholder farmer. It can be a delayed monsoon, unexpected high temperatures during the flowering stage, sudden heavy rainfall, an outbreak of pests or water and fodder shortage. In such occasions, the repercussions may go beyond the production of the crop to household income, food security and capacity to invest in the following season. Small and marginal farmers are the majority and this is an important vulnerability in India. Rain fed agriculture is particularly vulnerable to rainfall variability and extremes. Recent ICAR research highlights the need to build resilience in rain-fed farming in the context of the challenges posed by erratic rainfall, heat/cold stress and extreme events, and points to soil-moisture conservation, resilient varieties, integrated farming systems and livestock interventions as critical pathways to resilience (Pratibha et al., 2025). So the issue isn't if, but when, climate change is going to impact agriculture. It already is. The bigger question is: What can be done to enable the smallholder farmer to be better prepared for the uncertainty which lies ahead?

Understanding Smallholder Vulnerability

The impact on the farmer is not necessarily a function of climate exposure. The impact of drought on two farmers who are otherwise identical can vary greatly due to differences in their irrigation, savings, livestock, alternative income, information, and markets and social support. This is why climate resilience is closely linked to the overall farming livelihood's resilience. A farmer who has just one crop, no opportunity for irrigation, a lack of savings and poor market access has fewer options if the crop is lost. A farmer who can grow crops and livestock, has fodder stored, water-saving practices, has some means of other income, and can access climate information will be more resilient to the same shock. A study conducted in the Indian Himalayas revealed that small-scale farms and farms with less livelihood diversification were more vulnerable, whereas agricultural livelihood diversification, market access and robust social networks were linked to better climate adaptability (2024). Resilience is not simply about the technology on the farm. It's also the choices, resources and supports that the farmer has.

From Vulnerability to Resilience

Climate resilience is simply defined as the capacity of a farming system and a household to anticipate, resist, adapt to and rebound from climatic shocks. This will also mean a change from reactive farming to anticipatory farming. Farmers should be assisted to ask themselves "How can I minimise the losses in case of a drought?" rather than just "What do I do when drought happens?" Farmers can have fodder reserve rather than expecting fodder shortage. They could diversify rather than relying solely on one crop. They can change their irrigation habits to more efficient methods and water conservation practices. Thus resilience is created in a step-by-step process that is informed by knowledge, diversified,

managed through natural resources, developed with technologies, and cultivated with financial capacity and collective action.

Diversification: Never Depend on a Single Source of Livelihood

The message to be given is to diversify, that is, not rely on one source of livelihood. Diversification is one of the most useful means to resilience. When a drought, flood, heat or price change hits a mono-crop farmer, he is almost entirely vulnerable. Crop diversification, integration of livestock, horticulture and agroforestry, and establishing allied enterprises can spread risk among various activities. For instance, if it rains on crops, livestock or other enterprises could still generate income. Crop residues may provide livestock; livestock manure may add to soil fertility and various parts of an integrated farm can help each other. ICAR's recent research has highlighted the importance of system-based strategies for mitigating the risks posed by climate change in rainfed farming, which include crop diversification, integrated farming systems, agroforestry, conservation agriculture, and the use of resilient varieties (Singh et al., 2025). Diversification does not imply the random addition of activities. It should be planned based on local climatic condition, resources, market and farmer capacity.

Protecting Soil and Water: The Foundation of Resilience

A healthy soil and a careful management of water are the first steps to a climate-resilient farm. Water scarcity and excessive runoff are issues due to erratic rains. Improved use of available water through practices like mulching, rain water harvesting, in-situ moisture conservation, farm ponds, micro-irrigation, conservation agriculture and improved soil organic matter can improve the water use efficiency of farms. ICAR has encouraged adoption of protective irrigation, micro-irrigation, in situ moisture conservation, conservation agriculture and better nutrient management in vulnerable areas (Government of India, 2025). The goal is not just to consume more water. It is to increase the value of each drop of water. Again, the farm's long-term resilience to climatic stresses is enhanced by protecting the soil from erosion and degradation.

Choosing the Right Crop for the Right Climate

Farmers need to take different approaches to what and when to plant for climate-resilient agriculture. There is a risk involved with extreme weather, but stress-tolerant varieties, appropriate sowing dates, short term crops and contingency plans can minimize it. However, the selection will be dependent on agro-climatic conditions in the area. ICAR's NICRA programme has been developing and promoting technologies for crops and livestock that are resilient to various climatic stressors like drought, flood, heat, and temperature stress, for regions prone to these conditions (Government of India, 2025). Recent ICAR research further highlights the need for site-specific and scalable nature of the technology to be climate resilient, as a practice which is useful in one agro-ecological region may not necessarily be applicable in another (Pratibha et al., 2025). This makes it very important that local extension advice is followed.

Information is Also a Climate-Resilience Resource

Information can be a valuable input during a climate emergency. Weather forecasts prior to a heat wave can enable a farmer to change the irrigation or take measures to protect livestock. A pest warning will prompt earlier monitoring. Rainfall advisory may affect sowing decisions. ICAR's 2025 agro-advisories underline the need for timely, location-specific, science-based information to act as a link between agricultural research and the decisions made for farmers in the field. Digital tools can serve to reinforce this process by offering mobile warnings, weather apps, remote sensing, and, more and more, AI-supported decision support systems. ICAR literature in recent years has given recognition to the role of AI, machine learning and drones in improving the accuracy of weather forecasts, monitoring crops, improving resource management and speeding up assessments of damage caused by climate change (Kumar et al., 2025) and, of course, the technical, skill and infrastructure and cost issues must be addressed. Technology, however, must not supplant, but rather complement, the knowledge and experience of local extension and farmer knowledge.

Building Financial Resilience

A farmer might have information about the climate-resilient technology that he or she wishes to use, but be unable to afford it. This is where financial resilience plays a crucial role in resilience to climate change. Households can mitigate the impacts of climatic shocks, without plunging themselves into an even greater debt trap, through savings, affordable credit, crop insurance, livestock insurance, diversified income and access to institutional finance. Finance and technical assistance must go hand-in-hand. It is not beneficial to place credit on a technology that is not suitable for local conditions, for it can increase vulnerability. The ambition should be to develop a farmer who is technically equipped to face the challenges of climate change, but also financially.

The Power of Collective Action

Climate risks can affect smallholders on an individual level, but can be experienced as a group. Farmer Institutions such as the farmer producer organizations, co-ops, self-help groups and others can provide access to inputs, technologies,

markets, information and financial services. Shared machinery and services can make expensive technologies more available and collective procurement can lower transaction costs. Evidence from India also indicates that institutional support through FPOs can boost the adaptability of farmers to climate change and create impact on their adaptation behaviour and resilience. Collective organizations therefore play an important role as a link between climate resilient technology and farmer adoption. The big idea is as follows: Individual farmers are at risk from climate change, collective resilience can be created.

Women and the Strength of Rural Resilience

Women play deep involvement in the farming activities, management of livestock, food processing, and nutrition and natural-resource management in the household. Their learning and choices consequently impact on the capacities of the whole household. Enhancing women's access to climate information, productive resources, finance, technology and farmer organisations can enhance the coping capacity of households to climate shocks. Resilience should consequently not be measured only through crop yield. It should also be considered in terms of who can have access to resources, who makes the decisions and who has the capacity to recover from the shock.

From Individual Practices to a Resilient Farming System

1. No single practice can make a farmer completely climate resilient.
2. A stronger approach combines several elements:
3. **Climate information** helps anticipate risks.
4. **Diversification** spreads risk.
5. **Healthy soil and efficient water management** protect natural resources.
6. **Resilient varieties and appropriate technologies** reduce production losses.
7. **Livestock and allied enterprises** provide additional livelihood options.
8. **Financial services and insurance** strengthen the ability to recover.
9. **FPOs and farmer institutions** improve access to markets, knowledge and collective resources.

Together, these create a farming system that is better prepared to absorb shocks.

India's Move Towards Climate-Resilient Agriculture

India's transition to climate-smart agriculture. India's shift towards climate resilient agriculture. India has increasingly been polishing the skills of developing location-specific solutions that are climate-resilient, as has been done in NICRA. In this context ICAR has conducted a Climate Vulnerability Assessment (CVA) in 651 major agricultural districts, 310 of which are identified as vulnerable (including 109 very highly vulnerable and 201 highly vulnerable). The district-level contingency plans have also been prepared which will provide guidance for responding at the location level (Government of India, 2026). These are crucial initiatives because there is no single national solution to build resilience. Strategies used by farmers during droughts differ from those used during floods, coastal salinity or heat stress. Climate resilience needs to be local, practice-based and farmer-centred.

The Way Forward

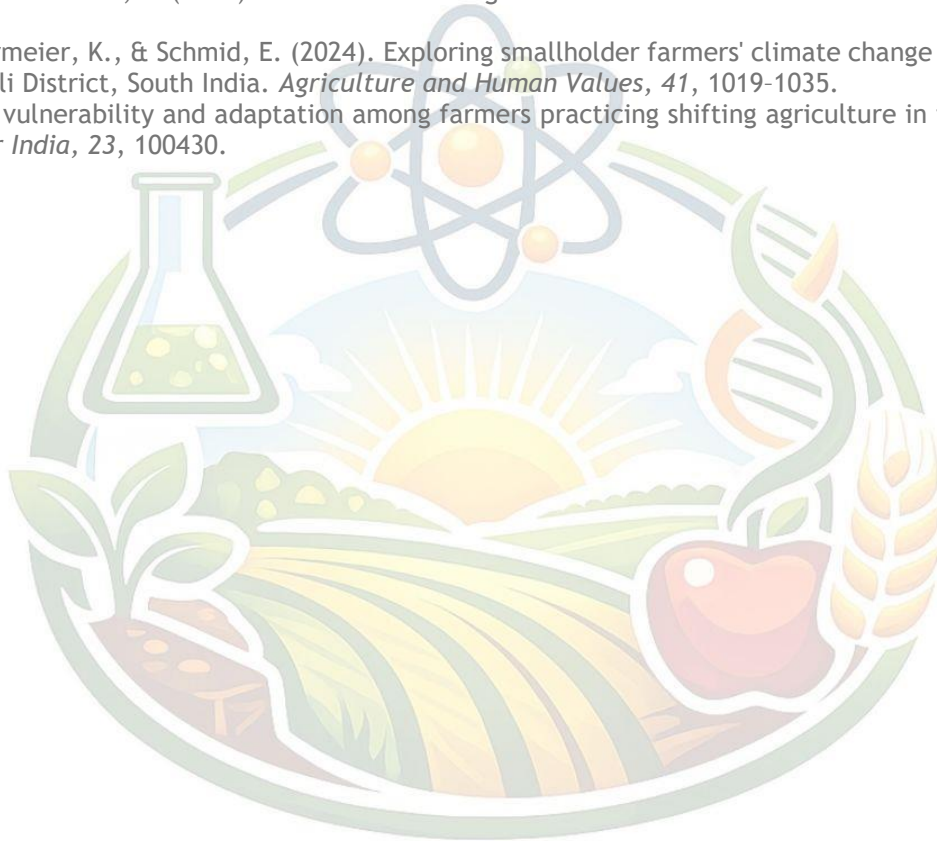
Moving forward in the fight for climate-resilient agriculture is not just about the technology, though; it's about making it accessible, comprehensible, attainable and maintainable for farmers. Research institutions must keep working on the development of technologies that are specific to the location. Extension systems have to be able to operationalise research findings into simple, timely advisories. Improved access to affordable risk-management tools is needed by financial institutions. Farmer groups can facilitate the aggregation of demand and service, link farmers to markets. Most importantly, farmers should not be just recipients of technologies but rather partners in adaptation. They are well-versed in their local knowledge, experience, and observations which can be used to augment scientific information and provide solutions that are locally appropriate and practical.

Conclusion

Adverse climate change conditions are making smallholder agriculture an uncertain future, but vulnerability need not be the norm. Don't mistake a resilient farmer for a farmer who never suffers a drought, flood, heat wave or pest attack. A resilient farmer is someone who has the information, assets, options and networks necessary to withstand the shock and bounce back from it. Translating climate risk to resilience is not just about implementing some new techniques. It demands diversified livelihoods, healthy soils, efficient water use, resilient crops and livestock, timely information, and financial protection and robust farmer institutions. Not only will the future of small holder agriculture hinge on the response to the next climate shock, but it will also be determined by how well prepared the farmers are before the shock. But it all starts with farmers acquiring the knowledge, resources and community power to adapt and change from vulnerable farms to resilient livelihoods.

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Bharat-VISTAAR: Bringing Artificial Intelligence Closer to the Indian Farmer

Article ID: 74442

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A new digital pathway for timely, personalised and science-based agricultural advice.

Abstract

Climate variability, shifting patterns of pests and diseases, market volatility and escalating production costs are increasingly affecting agriculture. In these days, timely and reliable information is an important resource for agriculture. Bharat-VISTAAR (Virtually Integrated System to Access Agricultural Resources), an AI-based, voice-enabled and multilingual Digital Public Infrastructure, was launched with the aim of using technology to deliver personalised agricultural information and advisory services to farmers in February 2026. It combines the information from government digital systems and scientific knowledge in the field of agriculture such as ICAR's recommended agricultural practices. The site would be used for information regarding crop management, weather conditions, market prices, pest and disease warnings, soil health and government schemes. The new system is an important move in agricultural extension, from providing information to providing more personalised and digitally facilitated decision support. The long-term effects, however, will rely on the quality of information, digital accessibility, farmer trust and the responsible and human use of artificial intelligence. The keywords used in this thesis are Bharat-VISTAAR, artificial intelligence, digital agriculture, agricultural extension, digital public infrastructure, farmer advisory, e-extension.

Keywords: Bharat-VISTAAR, artificial intelligence, digital agriculture, agricultural extension, digital public infrastructure, farmer advisory, e-extension.

Agriculture is Entering a New Information Era

It is not a case of a single decisive factor when a farmer makes a decision. Weather, soil, market, available resources and government support all may be factors in determining the choice of crop, sowing date, irrigation, fertilizer, and pest-management practice or time of sale. In the past, farmers relied upon extension workers, KVKs, other farmers, input dealers, television, newspapers and other sources to get such information. These days, the digital technologies are bringing a new dimension to the information system. The difficulty, however, is that agricultural information is typically dispersed in various platforms and institutions. A farmer might want to find one place for weather information, another for market prices, another for government programs and another for technical advice. Bharat-VISTAAR has been designed to overcome this disjointedness and create a single digital platform for agricultural information.

What is Bharat-VISTAAR?

Bharat-VISTAAR is Virtually Integrated System to Access Agricultural Resources. Union Budget 2026-27 announced with an outlay of ₹150 crore and Phase I was introduced on 17 Feb 2026. The Government calls it a nationwide, AI-powered, voice-first and multi-lingual Digital Public Infrastructure for Agriculture. The goal of the platform is to achieve the alignment of agricultural information with farmer's real decisions. It brings together the government digital ecosystem and scientific agri-knowledge created by the ICAR and other credible sources. Phase I offers information and advisories on crop management, weather, market prices, pest and disease notifications, soil health, and also integrates 10 major central agricultural schemes.

From Information to Personalised Advice

The key concept behind Bharat-VISTAAR is to shift from mere information to context-specific decision support. For instance, if a heat wave is anticipated, it is helpful to know this. However, a farmer should have more than a weather forecast. The farmer must understand the implications of this forecast for the crop or livestock and also what preventive action should be taken. Likewise, a market price alone might not be sufficient. Farmers require information which helps them to determine where and when to market. Where AI can give agricultural extension a boost is in the ability to help them process information from multiple sources to provide advice that is relevant to a farmer's context. This overall trend is supported by the recent research that has been conducted in the use of AI in agricultural extension. According to a 2026 bibliometric study, the research focus has also been growing for AI, machine learning and IoT in personalised, predictive and data-driven agricultural advisory systems, and hybrid systems, which integrate AI with human experience are emerging as an important future system.

A Voice-First Approach: Making Technology Simpler

The VFA is an approach designed to make technology easier to use for the majority of people. A key advantage of Bharat-VISTAAR is its voice-first functionality, making it accessible and user-friendly. Digital agriculture frequently assumes that farmers can easily use apps and type questions, and easily interpret complex digital information. This assumption can put at risk smallholder farmers who are not as technologically literate as others. This barrier can be eliminated by using voice interaction. The Government says that in the initial phase, Phase I, it is available via a dedicated telephone number, an AI-controlled voice bot, a web portal and mobile application (in Hindi and English) with further regional languages coming in in the next phases. It's a simple concept, yet strong: Rather than teaching all farmers technology, teach technology to teach the farmer.

Connecting Agricultural Science with the Farm

Another significant feature is the incorporation of the scientific agricultural information and recommended Packages of Practices of ICAR. This will provide an opportunity to reduce the gap between agricultural research and decision making at the field level. Learning doesn't always have to be a struggle through technical papers, as digital systems could simplify and make it more accessible to a farmer to receive a recommendation. This is especially important in a country characterized by a great variety of crops, soils, climate and farming system. Agricultural recommendations must be site specific, and not be a universal commandment for all other locations. The Government's target is not just to build another portal for agricultural information, but to build an integrated solution that can provide personalised agricultural advice, in real-time and with location.

Bharat-VISTAAR and Climate-Resilient Agriculture

Timely agricultural information is even more critical in the face of climate change. Farmers may need to make rapid adjustments to their decisions due to heat waves, disrupted rainfall, droughts, flooding, and shifting pest trends. A co-ordinated delivery of weather information, pest alerts and recommended management practices to the farmers using an integrated digital advisory system may be beneficial. Therefore, Bharat-VISTAAR can be a significant part of the agricultural extension in order to be climate resilient. But there's a difference between potential and impact. However, the platform has not yet been widely evaluated for impacts on productivity or farmer income or climate resilience in large-scale impact evaluations to establish the long-term impacts. The real challenge will be how the information delivered actually contributes to farm decision making in terms of improving the quality and timeliness of those decisions.

Can AI Replace the Extension Worker?

The answer should be no.

Agricultural extension is NOT just the transfer of information. It includes knowing the farmers' situations, showcasing technologies, identifying issues, building farmers' trust and assisting farmers to implement recommendations in their local context. Recent studies on the use of artificial intelligence in pest advisories bear this out. In a study published in 2025, researchers in India's National Pest Surveillance System (NPSS) report that the reach of AI-driven advisories was significant, with participation by 1,422 respondents, but overall compliance was not as high as anticipated, especially for recommendations involving expensive or complex interventions. The study highlighted the importance of improved communication and better last-mile support. This provides an important lesson for Bharat-VISTAAR: AI can broaden the scope of agricultural extension but human extension can add the trust, context and support required for action. The future looks more like an era of AI + KVK + extension worker + farmer instead of AI replacing the extension system.

The Digital Divide Must Not Become the New Agricultural Divide

The potential of technology to improve access to information is significant, but only if farmers are able to access and use it. Digital Agricultural Services will be valuable if they are connected, digitally literate, in the language(s) used, and affordable and trusted. In a 2026 study on ICT-based agro-advisory services, farmers' attitudes towards such systems were found to be influenced by various factors, such as accessibility, convenience, trust, credibility, responsiveness and personalisation. This means that advanced AI is not the only thing required for successful digital agriculture.

It requires:

1. Reliable connectivity
2. Local-language communication
3. Simple interfaces
4. Scientifically validated information
5. Farmer training
6. Human support when required
7. Strong data privacy and security.

Bharat-VISTAAR's official policy has incorporated provisions for data-security and it has been built with adherence to the data-protection and cybersecurity requirements in India.

The Road Ahead

Bharat-VISTAAR is a significant development in the agricultural extension system in India. It is more than AI, it is the provision of information that farmers need to access in one place, through a more user-friendly interface, for example, information on science, weather, markets, schemes, farm-management advice. Such a system can contribute to the shift from wide-spread 'one size fits all' dissemination of agricultural extension to time-sensitive, personalized, and farmer-centered decision support if implemented effectively, as it can. However, technology is a tool, not a goal. If it is to be judged successful, its success should be weighed by whether or not farmers are given accurate, understandable, timely, and useful information for improved real decisions on their farms.

Conclusion

Traditional extension and artificial intelligence are not the only choices for the future of agricultural extension. This could be a combination or both. The emerging platform Bharat-VISTAAR offers a platform on which the scientific and agricultural knowledge and digital infrastructure of India can reach the farmers much more integrated. It also offers a voice-first, multilingual approach that could help to make digital advisory more accessible for smallholders. What will make a real change is when a farmer can go from "I have a problem" to "I can get reliable advice and I know what to do next" -- quickly, simply and in a language that is easily understood. Bharat-VISTAAR is not just introducing AI to the agriculture sector, but also making agricultural knowledge more accessible and available for the farmer.

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Participatory Integrated Climate Services for Agriculture (PICSA): Putting Climate Information into Farmers' Hands

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How participatory climate services can help farmers make better decisions in an uncertain climate.

Abstract

Smallholder farmers are facing challenges in decision-making regarding agriculture due to climate variability. Weather and climate are closely related to decisions regarding sowing time, selection of crops and varieties, livestock and other livelihood activities, investment and management. However, climate information is frequently given in general terms that do not necessarily help farmers make decisions. The participation is made possible by the integration of historical climate data, season and short-term climate forecasts, participatory planning tools and farmer knowledge, and is alternative approach available under the umbrella of participatory integrated climate services for agriculture (PICSA). PICSA is an initiative of the University of Reading, in collaboration with partners, under the CGIAR climate research programme, and it puts farmers at the heart of decision making, not providing one-off solutions. Results from several countries suggest that it has caused farmers to take action on changing crop, livestock and livelihood practices and increased confidence in decision making on climate change. In a multi-country assessment conducted in 2022, 87% of the 4,299 farmers assessed reported positive changes as a result of PICSA engagement. Some more recent studies in Malawi also indicate that impacts of PICSA can be seen in crop-variety decisions, but in varying degrees. The article examines how PICSA can improve the capacity to get climate information from a technical forecast to a useful decision-making tool for farmers.

Keywords: PICSA, climate services, climate change, agricultural extension, farmer decision-making, climate-resilient agriculture, adaptation.

When the Weather Becomes Uncertain

If the weather changes, leave the area. If weather conditions turn uncertain, you must leave the area. Weather is a farmer's more than just everyday forecast. It decides how much land to be sowed, when to fertilize, when to crop and how to care livestock. These decisions are more difficult when the rain becomes unpredictable and the temperatures go up. The ability to understand weather conditions has always been the farmer's experience and knowledge. However, rising variability in climate conditions can sometimes make it difficult to rely on traditional indicators for the guidance needed. Farmers must be able to access reliable climate information, but they must also be able to interpret the information and understand how it relates to their farm. PICSA has an interesting approach here.

What is PICSA?

Participatory Integrated Climate Services for Agriculture (PICSA) is an approach developed to assist farmers' decision making on crops, livestock and livelihoods with climate and weather information. PICSA engages farmers in their own analysis of situation, rather than merely providing them with information. Extension workers or trained facilitators meet with farmer groups to discuss the past climate, seasonal predictions, short-term weather forecasts and the resources the farmers have and their livelihood options. The motto is straightforward: "The farmer decides." PICSA doesn't recommend all farmers the same treatment. Instead, it assists farmers to become aware of the risks of climate change they face and to understand the different choices and options available and select what is appropriate for them. This is especially relevant as two farmers in the same village may differ significantly in their land holdings, input resources, availability of labour, attitudes to risk, and expectations of their livelihoods.

From Climate Data to Farm Decisions

Without farmer knowledge of how to use climate information it has little value. Seasonal forecast could suggest that rainfall may be deficient. However, the farmer's next question is of course: "Now what do I do about this?" PICSA is trying to fill this gap in. Farmers review past climate trends and engage in participatory activities like seasonal calendars and resource allocation maps and participatory budgeting to gain an understanding of the suitability of various production and livelihood options to their situation. These plans can be reviewed and modified as necessary in the context of seasonal and short-term forecasts.

For instance, if the climate or resources are different in the area, farmers might want to make changes such as:

1. Sowing dates,
2. Fertilizer usage, and
3. Fertilizer decisions,
4. Livestock activities,
5. The mix of enterprises on the farm, or
6. Other livelihood activities.

Of key importance is that, once climate information affects a decision, it becomes useful.

Why Participation Matters

Traditional extension has often followed a linear pathway:

Research → Extension → Farmer: PICSA tries to make a more participatory roadmap: Farmer decision relies on Climate information + Scientific knowledge + Farmer experience → Discussion → Options

Farmers take their own expertise of their land, resources and past experiences with them. Climate scientists provide historic and forecast data, and extension workers provide interpretation and application of historic and forecast data to farmers. This is because farmers are not passive recipients of information, thus making the approach relevant to climate adaptation. They start to make decisions and to be experimenters. A study in Ghana revealed that 97 % of the farmers surveyed implemented changes in their practices and on average 3 changes per farmer. These involved changes in farm enterprises and management as well as increased farmers' income, food security and confidence in coping with climate variability.

The Power of Historical Climate Information: In particular, the use of historical climate information is a distinguishing characteristic of PICSA. Farmers will tend to remember good or bad seasons, but historical climate information can help provide a longer-term context to these experiences. Knowledge of the timing of the typical start of rains, variability in rainfall and frequency of dry spells can help farmers determine the risk associated with different decisions. This is especially important since adaptation is not just about addressing the past weather. It's all about preparing for the next step in the process. Historical patterns can be reviewed prior to the season starts to give farmers the opportunity to think through various scenarios and plan accordingly for the local climate.

Forecasts Become More Useful When Farmers Have a Plan: Forecasts of seasons are never certain. A forecast should not be read as a prediction or an assurance of what will happen. PICSA can help deal with this by having farmers prepare plans ahead of the forecast and then revisit those plans and plans actions with the forecast. This is a behavioural change that is important. Instead of asking: What should I do according to the weather forecast? farmers can ask: With this prediction, which of my options makes the most sense? This gives farmers the option to choose, while recognising uncertainty.

PICSA and Climate-Resilient Agriculture: Climate-Resilient Agriculture is part of the PICSA programme. PICSA includes Climate-Resilient Agriculture. There is no single technology that can be used for climate-resilient agriculture. Farmers should have a choice of options they can choose based on their local risks and resources. PICSA is an ideal fit because the tool connects contextually, climate information with options. The farmer facing periodic dry periods may be interested in other alternatives than the one facing excessive rainfall. A farmer who has animals may react differently to a farmer who produces only crops. PICSA thus facilitates climate adaptation from a One Size Fits All recommendation to context specific decision making.

Evidence from the Field: PICSA is now in over 20 countries. In 2022, a synthesis of experiences in Africa, Latin America and the Caribbean and South Asia found that over 200,000 farmers had been trained in 23 countries. In the seven countries evaluated, 87% of 4,299 farmers reported positive change in crops, livestock or livelihood enterprises. A survey in Rwanda showed that 96% of the farmers surveyed were more confident in planning and decision making, and 93% more capable of dealing with poor weather years. There's also some nuance to the evidence in more recent quantitative studies. Results of a study in 2025 in Malawi showed an association with an increased odds of using OPM varieties with PICSA participation, with no clear association for all adaptation outcomes. The researchers said additional in-depth testing would be required to determine widespread impacts. This is a crucial scientific principle: although PICSA provides some good evidence, it is not necessarily the same everywhere, for every crop or result.

PICSA and Agricultural Extension: PICSA can reinforce and not supplant agricultural extension. Extension workers serve as facilitators to help farmers grasp the climate information and participate with the use of participatory tools. Climate data is supplied by meteorological agencies and scientific knowledge is offered by research and technical institutions. This forms a network: The extension of meteorological services to farmer groups to farmer decisions. Climate information can be very technical and that is why it is important to collaborate. This type of forecast is most useful when translated into a language and format that farmers can understand and relate to their own decisions.

Could PICSA Work in India?

The concepts behind PICSA are very applicable to the world of Indian agriculture, especially in areas where farmers rely heavily on rain and are experiencing higher climate variability. The country already has comprehensive weather forecasting systems, agro-meteorological advisory and agricultural extension systems. Studies from Haryana have shown how weather alerts via SMS, WhatsApp and mobile apps can affect farm operations and save wheat and rice farmers money on inputs. PICSA can be implemented to fit into such systems and can provide the missing link: Assisting farmers to understand climate information for decision making. Extension programmes could instead employ participatory tools to enable farmer groups to reflect on their own past weather, resources and management options. But for successful implementation in India, adaptation to local crops, languages, agro climatic condition, extension system and farmer institutions are required.

The Role of FPOs and Farmer Groups

PICSA is a curriculum that can easily be used for group based learning. This affords an opportunity to the FPOs, co-operatives, self-help groups and other farmer institutions to enhance climate-informed decision making. An FPO may provide the platform for climate learning sessions, link farmers with meteorological and extension services, distribute predictions and enable members to talk about potential impacts of climate conditions on the collective procurement, production, and marketing. This could transform the FPO from being a market institution into a more. Can be a local climate information and decision-support hub.

From Forecasts to Confidence

The biggest advantage of PICSA may not be a specific technology or crop suggestion. It is confidence. Weather is beyond the control of farmers. They can do more to prepare for uncertainty, though. By knowing their own climate track record, looking at other choices and reviewing plans with the help of climate forecasts, farmers can shift from a reactive to a proactive approach to climate change. The core of climate resilience is: Not being able to control the climate, but making good decisions in spite of uncertainty.

Challenges and the Way Forward

PICSA is promising but making it a success demands more than one training of farmers. Climate data quality is important, but so are the capacity of the facilitators and communication channels, as well as a sustained institutional support. Sustainability and improving the quality and extent of implementation were identified as on-going priorities in the 2022 multi-country assessment.

Future implementation should therefore focus on:

1. Strengthening collaboration between meteorological and agricultural institutions.
2. Training extension personnel as climate-information facilitators.
3. Providing local and understandable climate information.
4. Combining scientific forecasts with farmers' local knowledge.
5. Using digital tools alongside face-to-face extension.
6. Evaluating outcomes across different crops, regions and farmer groups.

The aim should not be to increase the number of farmers receiving the forecasts. It should increase the number of farmers who can use those forecasts to make better decisions.

Conclusion

The uncertainty of agriculture is increasing with climate change. Information is needed but this is insufficient to help farmers. PICSA is a new approach to thinking about climate services: farmer-centred. It is a tool for farmers to consider their choices and make decisions that are appropriate for their situation by using historical climate data, forecasts and farmer knowledge and participatory planning. The method also offers a valuable enlightenment for agricultural extension: Climate services should not dictate what actions farmers should take, but rather provide information and tools to support farmers' decisions on what is suitable for them. With changing climate, the capacity to make informed decisions can be one of most important resiliency traits a farmer can possess.

Understanding Farmers' Adaptation Behaviour in a Changing Climate Scenario

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Abstract

Climate change is changing the circumstances in which farmers do their farming. Changes in temperature, rainfall patterns, drought, flood, heat waves and the changes in pest and disease patterns are adding to uncertainty and new risks for agricultural livelihoods. Smallholder farmers are especially vulnerable as their ability to respond is both a function of their exposure to climatic risks, as well as their access to land, water, finance, technology, information and institutional support. Adaptation behaviour is thus not merely about taking up a specific climate resistant practice, but it is the social and economic consequences of farmers' interpretations of climate risks, and their assessment of and decision making in relation to possible options. Studies conducted recently in India reveal that farmers are making some efforts like change of planting time, diversification of crops, using the resistant varieties, water management and soil-management practices, and the gap between awareness and actual practice is still significant. Farm income, information-seeking behaviour, education, and livelihood diversification and access to agro-meteorological advisories are important factors identified that affect adaptation decisions. This behavioural aspect is critical for the design of agriculture programmes to address climate change impacts in a way that is accessible and viable by farmers. This article examines the drivers of the farmers' adaptation behaviour and identifies barriers to transitioning from awareness to action and towards sustainability.

Keywords: Climate change, farmer behaviour, climate adaptation, climate-resilient agriculture, adoption, smallholder farmers, agricultural extension.

Climate Change is Changing the Farmer's Decision-Making Environment

The climate change environment is impacting the decision-making environment of farmers. For centuries farmers have adapted to local environmental conditions and weather. The uncertainty and strength of climatic changes are growing in the present situation. Unexpectedly dry spells, heat waves, extended periods of heavy rainfall or shifts in pest population can throw off the decisions that are normally made based on experience. These changes are already having an impact on farmers. The ICAR literature in recent times indicates that agricultural practices, such as land use, labour use, irrigation, cropping systems and crop varieties have also been changing to cope with the new climate conditions. However, adaption is not a process of automatic change. A farmer can feel the effects of climate change, be aware of the impacts and know of an alternative practice but not choose to implement it. This is where adapting behaviour is important.

What Does Adaptation Behaviour Really Mean?

Adaptation behaviour is defined as actions by farmers to minimize the adverse impacts of climate-related risk and/or capitalize on shifts in climate. Some of these include shifting sowing dates, growing resilient varieties, diversifying crops, better irrigation, better water management, integration with livestock, and seeking other sources of income. But adaptation is not to be taken as a technical choice. It's a behavioral choice as well. The farmer essentially considers a number of questions: What is the threat of climate change? Does it really help to practice? Can I afford it? Is there any way to use it without me knowing how? Will there be enough benefit for the price? Is there access to the inputs or services that are needed? Such decisions help to account for the different reactions of two farmers who are exposed to the same climate.

Awareness Is the Beginning, Not the End

A key message from recent studies is that simply knowing is not enough to ensure adoption. A study in 2025 in farmers of Uttar Pradesh in eastern region revealed that farmers were very aware and perceived climate change, but comparatively lower in the adoption of adaptation strategies, which means there is a gap between Knowledge-Attitude-Practice (KAP). Crop diversification was reported as a key adaptation response and was also identified as being important but the perception and adoption of crop diversification was a key concern. This has a significant impact on agricultural extension. Just informing farmers about the climate change is not sufficient. The farmers should be informed what they can do, how, what it will cost and what benefit they can expect to gain.

The trip must then proceed from: Awareness - Understanding - Confidence - Adoption - Sustained practice.

What Makes a Farmer Adapt?

Adaptation behaviour of the farmers is influenced by individual, economic, technological and institutional factors. A recent study, involving 240 rice farmers in Andhra Pradesh, showed that education, farm income and information-seeking positively impact adaptation behaviour, while constraints like lack of variety, quality seed, technical knowledge and weather-based insurance shaped a farmer's adaptation limited. This illustrates an important point: Farmers do not decide to adapt alone. If a farmer has access to information and resources, then he may have more opportunities at experimenting with a new practice. The same practice can be understood by another farmer, but that farmer may not have the financial resources or the irrigation, labour or inputs to do the practice. Hence, to be more effective in improving adaptations behavior, it is not just the farmer's knowledge that needs to be improved but the circumstances surrounding the farmer.

Perception of Risk Influences Action

How farmers perceive climate risk is a key element of their decision-making on whether they need to adapt or not. When a climatic event is not seen as a real or regular threat for the farmer, he or she may have little motivation for altering current activities. On the other hand, there can be a greater felt need for adaptation as a result of repeated losses of crops or livestock. A recent study on smallholder farmers in India highlighted the significance of the cognitive aspects and farmers' perceptions in explaining the intentions to adapt. Interestingly, farmers don't only read the scientific information about climate change. They also have their own observations, memories and experiences of changing rainfall, temperature and crop behaviour, which can also impact their understanding. In the year 2025, a study in Assam concluded that Indigenous Knowledge was still being used in farmers' adaptation decisions, and farmers preferred using both Indigenous and modern adaptation methods. This indicates that it is not enough to merely substitute farmers' knowledge with that of extension. Should relate local experience to scientific knowledge.

Adaptation is Not the Same for Every Farmer

No standard adaptation package will be suitable for all farmers. A rainfed farmer who is experiencing drought conditions may need to focus on water saving and drought-tolerant crops. A farmer in a flood prone area can need drainage, raised bed or flood tolerant varieties. When a dairy farmer is under extreme heat stress, shade, water, cooling and heat stress management may be his/her first priorities. Different strategies can be selected within the same village as farmers have different priorities and resources. For instance, it was found that the rural women farmers in Uttar Pradesh and Haryana had different groups with different preferences for the agronomic practices, mechanization, soil and water management and sustainable practices. The researchers recommended an extension intervention specific to these groups of farmers, instead of a one-size-fits-all approach. An Extension lesson to note: Adaptation should be farmer-centred, location specific and need-driven.

From Individual Practices to Adaptation Portfolios

Adaptation Portfolios are derived from and build on Individual Practices. A single adaptation measure is not generally relied on by farmers. They will frequently make multiple answers. A farmer can change sowing dates, adopt a different variety and diversify crops and conserve soil moisture simultaneously. Likewise, integration of livestock with crop production to utilise crop residues and derive additional income from livestock can be achieved. Studies conducted in India indicate that farmers often implement multiple adaptation measures, such as shifting crops, using tolerant crops, implementing water management and soil management practices. In a large-scale study, involving 1274 farmers across all the disaster-prone districts, it was seen that over 90 per cent of the farmers implemented at least one climate smart practice. This indicates that adaptation should be thought of as a set of choices - not a single technology.

Information Can Change Behaviour

One of the best resources for helping with adaptation is timely information. Climatic services such as weather and pest forecasting, and seasonal climate and location-specific agricultural advisories, can guide decisions prior to the onset of a climatic event that may cause damage. ICAR's Kharif Agro-Advisories underscore the need for scientific information that is available to end users on-time and in the right location, as a link between agricultural research and field-level decision making. But information is useless – it needs to be actionable. Rather than stating a rise in temperature, an advisory should help farmers to understand what they can do to remedy this situation. For example: Expect heat wave: adjust irrigation; protect livestock; modify field operations; monitor crops more closely. It is in this context that climate information is made an instrument of adaptation and not just a message about climate.

The Role of Extension: From Teaching to Enabling

Agricultural Extension is undergoing transformation. In the past, extension typically concerned itself with bringing recommended technologies to the farmers. Extension needs to play a more important role in helping farmers evaluate risk, consider options, try practices and make decisions as climate change becomes a more prevalent phenomenon. Uncertainty about new practices can be lowered through demonstrations, farmer field schools, participatory trials,

digital advisories, exposure visits and peer learning. Farmers are more inclined to embrace a technology when they understand how it is relevant to their operation and can become familiar with how it works and that support will be provided if issues arise. Thus, the extensionist of the climate resilient times is not a technology voucher. The extension worker turns into an adaptation facilitator.

Institutions Can Make Adaptation Easier

Even with the interest of farmers, adaptation can be very difficult if there are no supportive institutions. New evidence from 1274 farmers in disaster-prone regions of India revealed that livelihood diversification and assets of the household also played an important role in determining the adoption of climate-smart practices; and soil-health information and agro-meteorological advisories also influenced the uptake of some adaptation options. This implies that reducing the adaptation gap requires more than the technology.

Farmers require access to:

1. Quality seed and planting material
2. Affordable credit and insurance
3. Irrigation and water-management facilities
4. Climate information
5. Extension services
6. Markets and remunerative prices
7. Machinery and custom-hiring services
8. Farmer organizations and collective institutions.

When these systems work together, the cost and uncertainty of adaptation can be reduced.

FPOs and Collective Adaptation

Farmer Producer Organizations can provide a vital link between farmers and technology to enhance climate resilience. A single small farmer may find it hard to get machinery, bulk quality inputs, reach extended markets or specialized technical services. The farmers can enjoy the benefits of inputs, machines, information, training, markets and value addition opportunities through an FPO. Collective action can thus shape adaptation behaviour by facilitating and making practices more economically viable. This is also true for dairy farmers. Individual burden of adaptation can be reduced through collective procurement of feed and fodder, co-sharing of veterinary services, climate advisory services and through common cooling or fodder infrastructure. So, resilience is not just a personal behavioural product. It can also be a team effort.

The Behavioural Gap: Why Farmers Sometimes Do Not Adopt

It's important to know why some farmers do not adopt as well as why others do. A farmer might not choose a climate resilient practice because of the expense, lack of labour, lack of information, poor returns, poor availability of inputs or previous bad experiences. The 2025 Andhra Pradesh study highlighted some of the major adaptation constraints including the lack of suitable varieties and quality seed, price volatility in the market, lack of technical knowledge and inadequate weather-based insurance. Thus, rather than asking: Why the failure of farmers to implement? we should ask: What are the barriers for farmers to adoption? A change of attitude can make for a lot better extensions and policies.

Building a Culture of Adaptation

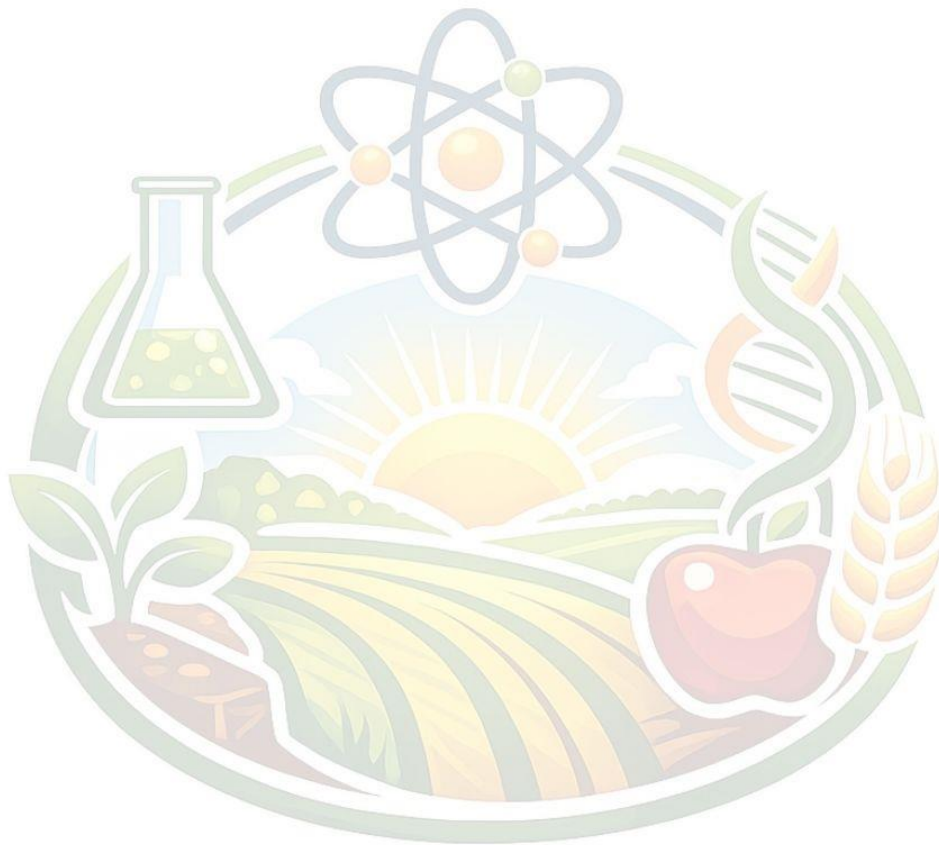
The long-term climate resilience needs to be integrated into the farm decision making process and not as an emergency measure. Farmers can be encouraged to regularly consider: What climate risks are likely this season? What are areas of my farm most at risk? What can I do that can reduce the chance of that occurring? What can I afford to do? How can I get technical and financial assistance? This will make climate adaptation an ongoing learning process. Farmers observe, experiment, evaluate and modify their practices. Adaptation is not a single solution or event, but is a continuous learning and adjustment process.

The Way Forward

Climate-smart farming is synonymous with the gap between knowing and doing and the future of climate resilient agriculture relies on bridging this gap. In the future, research institutions should keep developing technologies according to the location. These technologies need to be broken down into easy and practical recommendations by extension systems. The economic barriers need to be lessened by financial institutions and government programmes. Collective access to resources and markets can be enhanced by FPOs and other farmer organizations. First and foremost, farmers are active agents in climate adaptation and they should be treated as such. Observations and their experiences contribute to the knowledge about the local changes of climate and this knowledge from scientific sources can be used to validate and support that experience. Farmer knowledge + scientific evidence + institutional support can result in more practical and sustainable adaptation pathways.

Conclusion

Change is something that farmers have always been able to cope with. The only thing that has changed today is the pace, unpredictability and magnitude of climate change. An understanding of farmers' adaptation behaviour must not only consider the question of whether a farmer has adopted a specific practice, but also whether a farmer has adopted a practice and how he is adapting. It demands an understanding of farmers' attitudes to risk, sources of information, resources available to them, people they trust and expected gains and constraints. There is ample recent evidence that awareness doesn't translate to adoption. Farmers' capacity and willingness to adapt can be affected by what they learn and are urged to learn, what they know, their income, and their livelihood assets, and institutional support and access to appropriate technologies. Climate-resilient agriculture should not be merely about creating more technologies, however. It is meant to provide a platform for farmers to grasp the risk, select suitable answers, obtain the resources they need, and be confident to implement the answers. Technology is the first step to climate resilience, but the most powerful way is through farmers' empowerment to take action.

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Precision Agriculture for Enhanced Vegetable Production

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Introduction

Precision agriculture is an integrated approach to agricultural production that aims to improve productivity and resource-use efficiency by combining crop information, modern technologies, and appropriate management practices. It is not limited to activities carried out in the field; rather, it begins with crop planning and continues through cultivation, harvesting, post-harvest handling, processing, and marketing. In this approach, accurate information, suitable technology, and effective management work together to support better decision-making at every stage of production.

A broader approach to agriculture involves the use of information technology to collect and combine data from different sources. These data can then be used to make informed decisions related to crop production, transportation, marketing, financial management, and farm labour. In precision horticulture, several technological and management interventions are being adopted, including genetic resource conservation, genetic improvement, integrated nutrient management, protected cultivation, micro-irrigation, fertigation, and modern post-harvest technologies.

The adoption of these practices can improve production efficiency, enhance the quality of agricultural produce, and promote the judicious use of fertilizers and crop protection chemicals. At the same time, precision-based management can help conserve water and energy while reducing negative impacts on the environment. Practices such as field scouting, field mapping, variable-rate application, yield mapping, and improved post-harvest handling can also be incorporated into vegetable production systems. However, some precision-farming technologies still require further development and refinement to make them more affordable, practical, and effective for farmers. Growing environmental concerns have also increased interest in site-specific application of agricultural inputs, as applying fertilizers and chemicals according to the actual requirements of different areas can reduce unnecessary use, minimize leaching, and lower the risk of environmental contamination.

Precision agriculture is commonly referred to by several related terms, including precision farming, precision horticulture, site-specific farming (SSF), site-specific management (SSM), site-specific crop management (SSCM), and variable-rate application (VRA). Despite differences in terminology, all of these approaches are based on the common principle of using information, technology, and precise management to improve the efficiency, productivity, profitability, and sustainability of agricultural production.

Objectives of Precision Farming

1. Increased profitability and sustainability: Maximum profit can be obtained in each zone or site in a field by balancing precise amounts of inputs (seeding rate, variety, herbicide and insecticide) with crop needs, which can be determined by weather, soil characteristics (nutrient availability, texture and drainage) and historic crop performance. At the very same time, precision farming aims at sustaining this profitability.

2. Optimising production efficiency: In general, the aim of precision farming is to optimise returns across a field. Unless a field has a uniform yield potential (and therefore, a uniform yield goal), the identification of variability in yield potential may offer possibilities to optimise production quantity at each site or within each “zone” using differential management.

3. Optimising product quality: Precision farming also aims at optimisation of product quality by way of using sensors which detect the quality attributes of the crop and thus inputs are to be applied accordingly. In production systems where quality premiums exist, this may alter the amount of input required to optimise profitability and agronomic response.

4. Most efficient chemical and seed use: PA involves efficient use of inputs i.e., chemicals, seeds etc. according to the yield potential of the soil.

5. Effective and efficient pest management: One goal of precision farming is to cut crop production inputs, which result in cost and environmental savings. Whereas conventional farming methods apply herbicides, insecticides etc. to the entire field, site-specific variable rate application puts these chemicals (i.e., herbicides, insecticides) where the problem appears.

6. Energy, water and soil conservation: A comprehensive approach to PA begins from crop planning and thus includes such tillage practices which conserve the soil or disturb the soil to its minimum. Besides, water is efficiently applied by using techniques like drip irrigation etc. In all these cases, very less energy is used and thus PA leads to conservation of energy also.

7. Surface and ground water protection: PA aims at safeguarding the environment by way of efficient use of inputs like chemicals etc. This prevents their leaching through ground water or as runoff through surface water.

8. Minimising environmental impact: If better management decisions are being made to tailor inputs to meet production needs, then by default there must be a decrease in the net loss of any applied input to the environment. This is not to say that there is no actual or potential environmental damage associated with the production system, however, the risk of environmental damage is reduced.

9. Minimising Risk: Risk management is a common practice today for most farmers and can be considered from two points of view - income and environmental. In a production system, farmers often practice risk management by erring on the side of extra inputs while the unit cost of a particular input is deemed 'low'. Thus, a farmer may put an extra spray on, add extra fertilizer, buy more machinery or hire extra labour to ensure that the produce is produced/harvested/sold on time thereby guaranteeing a return.

Potential Benefits of Precision Farming

1. Increased profits through increased efficiency: With PA, one can use farming inputs more efficiently by applying more of them where more are needed and less where less are needed.

2. Reduced agronomic inputs: Many producers who adopt PA technologies find their overall use of production inputs (fertilizer, lime and chemicals) decreases because they can better adjust to a field's fertility level, the number of inputs applied.

3. Better record keeping: PA technology generates large amounts of data that are spatial records of inputs and outputs for fields. These data can help to create more accurate management plans.

4. Improved production decisions: PA can be used to make land use decisions. Profit maps, which show the spatial distribution of a field's profitability can help to make decisions about which cropping systems work best. We may also be able to identify areas that should be enrolled in government programmes such as the federal Conservation Reserve Programme (CRP) or removed from production, if low yields cannot be profitably corrected.

5. On-farm research: The ability to quantify the spatial performance of crops allows to conduct more comparison trials within fields. For example, it is relatively simple to compare the performance of different varieties on different soil types, when practising PA.

6. Reduced environmental impact: If we apply and use production inputs more efficiently, less material will leave the field through surface water and ground water. Reduced environmental impact can only improve the public's perception and acceptance of producer's agricultural practices.

7. Property advantages: Many landlords are giving preference to farmers who can create yield maps and other files of spatial data for the fields they farm. This spatial history may also increase the value of cropland.

8. More ground farmed: The records generated can allow to effectively manage more cropland than we had in the past.

Limitation of Precision Farming

1. Small land parcels: Over 58 percent of active land plots in India are smaller than one hectare in size, and these fragments of land are further divided.

2. Expensive technology: The adoption of precision agriculture requires the utilization of various costly technologies.

3. Diverse cropping methods: Agricultural practices vary widely, posing challenges due to their heterogeneity.

4. Absence of regional know-how and expertise: There is a deficiency in local technical knowledge and proficiency.

5. Technological disparities: Gaps exist in the availability and accessibility of appropriate technologies.

Elements of Precision Farming

1. Information

2. Technology

3. Decision support (management)

Information includes data on:

- a. Crop characteristics like stage of crop, crop health, nutrient requirement etc.
- b. Detailed soil layer with physical and chemical properties, depth, texture, nutrient status, salinity and toxicity, soil temperature, productivity potential etc.
- c. Microclimate data (season and daily) about the canopy temperature, wind direction and speed, humidity etc.
- d. Surface and sub-surface drainage conditions
- e. Irrigation facilities, water availability and other planning inputs of interest.

B. Technology: PA is an integrated agricultural management system incorporating several technologies. The technological tools often include:

a. Global positioning system (GPS):

- i. A global positioning system (GPS) is one of the cutting-edge technologies of the information age. It asks the basic question “where is it”? It is a versatile navigational aid.
- ii. It is computer based and the key components in this technology are satellites.
- iii. GPS depends on 24 satellites that are strategically positioned in orbits such that, at any given time and place on earth, one can have a line of sight to atleast four of these satellites.
- iv. Using the technique of “Trilateration”, a user is able to access atleast three satellite signals, each producing a surface that will overlap each other to locate the site in question, providing both longitude and latitude.
- v. A fourth satellite signal allows the altitude of the site to be calculated.

b. Geographical information system (GIS):

- i. A geographic information system (GIS) is a computer-based system for storing very large amounts of data (collected based on spatial location), retrieving, manipulating, and displaying them for easy interpretation.
- ii. The term “geographic” should be interpreted to mean “space” or “spatial”.
- iii. For crop production, some of the data of importance are soils, land use, vegetation, fertility, hydrology, and rainfall averages.
- iv. GIS has the capability of linking multiple sets of data (in layers) to study relationships among various attributes and creating new relationships.
- v. GIS is an aid for decision making.
- vi. It can be used to answer the location question “what is there”? It can also be used to study trends that is, answer the question “what has changed since a certain point in time.”
- vii. Another application of GIS is in the area of prediction of change or modelling.

c. Yield monitors:

- i. Yield monitors are crop yield measuring devices installed on harvesting equipment.
- ii. The yield data from the monitor is recorded and stored at regular intervals along with positional data received from the GPS unit.
- iii. GIS software takes the yield data and produces yield maps.

d. Variable Rate Technology:

- i. Consists of farm field equipment with the ability to precisely control the rate of application of crop inputs and tillage operations.
- ii. Typical VRT system components include a computer controller, GPS receiver, and GIS map database.
- iii. The computer controller adjusts the equipment application rate of the crop input applied.
- iv. The computer controller is integrated with the GIS database, which contains the flow rate instructions for the application equipment.
- v. A GPS receiver is linked to the computer. The computer controller uses the location coordinates from the GPS unit to find the equipment location on the map provided by the GIS unit.
- vi. The computer controller reads the instructions from the GIS system and varies the rate of the crop input being applied as the equipment crosses the field.
- vii. The computer controller will record the actual input being applied as the equipment crosses the field.

e. Remote Sensing:

- i. It is the art and science of obtaining information from a distance, i.e. obtaining information about objects or phenomena without being in physical contact with them.
- ii. The science of remote sensing provides the instruments and theory to understand how objects and phenomena can be detected.
- iii. The art of remote sensing is in the development and uses analysis techniques to generate useful information.

Application of Remote Sensing in Precision Agriculture

- a. Soil and drainage maps
- b. Soil maps:

- i. The grid sampling technique takes separate soil samples from uniform sized grids laid out over the field.
- ii. A problem with this type of sampling is the variability that can exist in soil types within each grid.
- iii. This variability makes it much tougher to determine soil characteristics within the grid for crop input management purposes.
- iv. To minimise this problem smaller grids are required which then requires many more soil samples to be taken for a larger number of grids.

c. Drainage maps:

- i. Colour infrared (CIR) aerial photographs have been shown to be an effective tool in locating unknown subsurface tile lines.
- ii. The image data is digitised for pre-processing and then geo-referenced using ground control points.
- iii. The CIR photographs show different tones of grey depending on soil type and moisture.
- iv. By filtering out spectral reflectance differences due to soil type, soil moisture content in dry soils that have a higher reflectance can be identified from lower reflectance wet soils.
- v. The resulting image shows where the tile lines are located and whether they are working properly.
 - Monitor crop health
 - Water stress
 - Weed management
 - Insect detection
 - Nutrient stress
 - Yield forecasting

d. Decision support (management): Just having information about variability within the field does not solve any problems unless there is some kind of decision support system (DSS) in order to make VRT recommendations.

- i. Identify environmental and biological states and processes in the field that can be monitored and manipulated for the betterment of crop production.
- ii. Choose sensors and supporting equipment to record data on these states and processes.
- iii. Collect, store and communicate the field recorded data.
- iv. Process and manipulate the data into useful information and knowledge.
- v. Present the information and knowledge in a form that can be interpreted to make decisions.
- vi. Choose an action associated with a decision to change the identified state or process in a way that makes it more favourable to profitable crop production.

Methods for Implementing a Precision Farming Strategy

1. Map based technologies -

- a. This is currently the most widely used method. It may involve a GIS-based method of pre-sampling and mapping of the field.
- b. The computer-generated maps are then converted into a form that can be used by the variable rate applicator.
- c. The applicator's controller then calculates the desired amount of an agronomic input to apply at each moment in time as the equipment traverses the field.
- d. The farmer knows how much of the agronomic input is needed before starting the application.
- e. A DGPS (Differential Global Positioning System) must be used to constantly evaluate the location in the field with a coordinate on the map and the desired application rate for that coordinate.

2. Sensor-based technologies:

- a. This method offers real time sensing and variable rate control.
- b. The strategies provide on -the - go sensing of field characteristics, thereby eliminating the need for a positioning system.
- c. The sensors must be mounted strategically (e.g. at the front of the tractor) to allow the variable rate applicator's controller adequate time to adjust the rate of the agronomic input accordingly, before it passes the sensed location.

Steps Involved in Precision Agriculture Adoption

1. Purchase a mapping programme
2. Collect spatial data
3. Map field boundaries
4. Keep records
5. Obtain remote images
6. Purchase a yield monitor
7. Purchase a DGPS differential global positioning system receiver
8. Generate yield maps

9. Use yield maps for scouting
10. Generate profit maps
11. Use yield and profit maps for land use decisions
12. Take site-specific soil fertility samples
13. Manage subfields
14. Adopt variable rate technology (VRT).

Precision Agriculture: Is Really Needed in India's Context

1. On the one hand there are depletions of ecological foundations of the agro-ecosystems, as reflected in terms of increasing land degradation, depletion of water resources and rising trends of floods, drought and crop pests and diseases. On the other hand, there is imperative socio-economic need to have enhanced productivity per units of land, water and time.
2. At present, 3 ha of rainfed areas produce cereal grain equivalent to that produced in 1 ha of irrigated. Out of 142 m ha. Net sown areas, 92 m ha are under rainfed agriculture in the country.
3. From equity point of view, even the record agricultural production of more than 200 Mt is unable to address food security issue. A close to 60 Mt food grains in the storehouses of Food Corporation of India (FCI) is beyond the affordability and access to the poor and marginalized in many pockets of the country.
4. Globally, there are challenges arising from the globalisation especially the impact of WTO regime on small and marginalized farmers.
5. Some other unforeseen challenges could be anticipated. Global warming scenario and its possible impact on diverse agro-ecosystems in terms of alterations in traditional crop belts, micro-level perturbations in hydrologic cycle and more uncertain crop weather interaction, etc.

Precision Farming Development Centres (PFDC) in India

There are about 16 Precision Farming Development Centres (PFDC) in India namely:

1. PFDC Jorhat Assam.
2. PFDC Samastipur Bihar.
3. PFDC HAU Hissar.
4. PFDC Bikaner Rajasthan.
5. PFDC Raipur Chhattisgarh.
6. PFDC Hyderabad.
7. PFDC IARI.
8. PFDC KAU Kerala.
9. PFDC Bhubaneswar Orissa.
10. PFDC Bangalore.
11. PFDC Rahuri Maharashtra.
12. PFDC Navsari Gujarat.
13. PFDC Lucknow.
14. PFDC Pant Nagar.
15. PFDC Coimbatore (TN).
16. PFDC IIT Kharagpur W. Bengal.

Conclusion

A truly comprehensive approach to precision agriculture must cover all phases of production from planning to post-harvest. Information, technology and management are combined into a production system that can increase productivity, improve product quality, allow more efficient chemical use conserve energy and provide for soil and ground water protection. Technology and management practices such as field scouting, field mapping, variable rate control, yield mapping and post-harvest processing can readily be adapted to vegetable crop production. However, the technology related to precision farming needs refinement to realize benefits. Questions remain about cost effectiveness and the most effective ways to use the technological tools we now have, but the concept of doing the right thing in the right place at the right time has a strong initiative appeal. Ultimately, the success of precision agriculture depends largely on how well and how quickly the knowledge needed to guide the new technologies can be found.

Glycemic Index: The Science Behind Smart Food Choices

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Introduction

Carbohydrates are one of the major sources of energy in our diet. They are found in cereals, millets, fruits, vegetables, pulses, milk and many processed foods. However, all carbohydrate-rich foods do not affect the body in the same way. Some foods cause blood glucose levels to rise rapidly after consumption, whereas others produce a slower and more gradual increase. This difference is where the **Glycemic Index (GI)** becomes useful.

The glycemic index is a measure that indicates how quickly a carbohydrate-containing food raises blood glucose compared with a reference food (Jenkins et al., 1981). Foods are generally classified as low GI (55 or less), medium GI (56-69) and high GI (70 or more) (Atkinson et al., 2008; Atkinson et al., 2021). A low-GI food tends to release glucose more gradually, while a high-GI food can result in a faster increase in blood glucose. Understanding GI does not mean that people need to completely avoid carbohydrates. Instead, it provides another useful tool for making **smarter food choices**. Choosing appropriate carbohydrate sources, combining foods wisely and paying attention to portion size can contribute to better dietary quality and metabolic health.

What Exactly is the Glycemic Index?

The glycemic index was developed to compare the effects of carbohydrate-containing foods on blood glucose. During digestion, carbohydrates are broken down into glucose and other simple sugars. Glucose is then absorbed into the bloodstream and used by cells for energy. The speed and extent of this process vary considerably between foods. For example, highly processed carbohydrates such as some refined cereals and sugary foods can be digested and absorbed relatively quickly. In contrast, foods containing intact grains, legumes, fibre and resistant starch may result in a slower release of glucose.

GI is expressed on a scale from **0 to 100**, with pure glucose traditionally assigned a value of 100. A food with a GI of 70 would generally raise blood glucose more rapidly than a food with a GI of 40, when comparable amounts of available carbohydrate are consumed.

However, GI should not be interpreted as a simple ranking of foods from "good" to "bad." A food's nutritional value depends on many factors, including its fibre, protein, fat, micronutrient content and degree of processing.

Low, Medium and High GI Foods

1. Low-GI foods: Low-GI foods generally produce a slower rise in blood glucose. Examples include many pulses and legumes, such as chickpeas, lentils and beans. Some fruits, vegetables and minimally processed whole grains may also have relatively low GI values. These foods can be particularly useful as part of meals designed to provide sustained energy.

2. Medium-GI foods: Foods with a medium GI fall between low- and high-GI categories. Their effect on blood glucose is moderate and can vary depending on preparation, variety and the foods eaten with them.

3. High-GI foods: High-GI foods are rapidly digested and absorbed, producing a comparatively quick increase in blood glucose. Some refined grain products, certain processed foods and sugar-rich foods may have a high GI. However, a high-GI food is not necessarily unhealthy in every situation. For example, rapidly available carbohydrates can sometimes be useful during or immediately after prolonged physical activity when quick energy replenishment is required.

Why Does GI Matter?

Repeated consumption of meals that produce large and rapid increases in blood glucose may be undesirable for metabolic health, particularly when the overall diet is high in refined carbohydrates and added sugars and low in fibre. A diet emphasizing lower-GI carbohydrate sources has been associated with improvements in several aspects of metabolic health. Research has particularly examined the role of low-GI dietary patterns in relation to blood-glucose management and type 2 diabetes risk (Livesey et al., 2019).

For individuals with diabetes or impaired glucose regulation, understanding the carbohydrate quality of foods can be useful when planning meals. However, GI should not replace individualized medical or nutritional advice. For healthy individuals, the concept can also be valuable because it encourages greater attention to **food quality, fibre, processing and balanced meals** rather than simply counting calories.

GI is Not the Same as Sugar Content

One of the most common misunderstandings is that a food containing sugar must automatically have a high GI. The glycemic response depends on the overall composition and physical structure of the food. Fibre, acidity, fat, protein, starch structure and processing can all influence how quickly carbohydrates are digested. Similarly, a food can have a relatively low GI but still be high in calories or contain substantial amounts of fat. Therefore, **low GI does not automatically mean low calorie or unlimited consumption**. This is an important reason why GI should be considered as one component of a healthy dietary pattern rather than used as the only criterion for selecting foods.

What Determines the Glycemic Index of a Food?

Several factors influence the GI of a food.

- 1. Type of carbohydrate:** Different carbohydrates are digested at different rates. The structure of starch and the proportion of rapidly digestible and slowly digestible carbohydrates influence the resulting blood-glucose response.
- 2. Fibre content:** Dietary fibre can slow digestion and carbohydrate absorption. Foods rich in fibre, particularly intact plant foods and legumes, often produce a more gradual glucose response.
- 3. Food processing:** Processing can alter the physical structure of food and make starch more accessible to digestive enzymes. Finely milled flour and highly processed cereal products may therefore behave differently from intact or minimally processed grains (Atkinson et al., 2021).
- 4. Cooking method:** Cooking can influence starch digestibility. The degree of cooking, temperature and cooking time can all affect the structure of starch and consequently the glycemic response.
- 5. Ripeness:** The ripening process can change the carbohydrate composition of fruits. As some fruits ripen, starch is converted into simpler sugars, potentially influencing their glycemic response.
- 6. Food combinations:** This is particularly important in real-life meals. Foods are rarely eaten in isolation. Protein, fat, fibre and acids present in a mixed meal can alter the overall glucose response.

Therefore, the GI of an individual food should not always be assumed to represent the glycemic response of the complete meal.

Glycemic Load: The Missing Piece

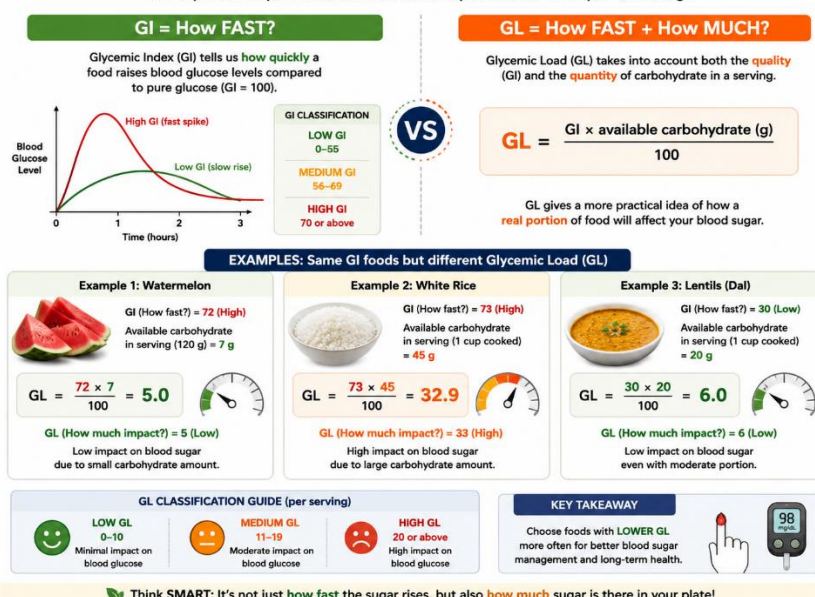
GI tells us how rapidly carbohydrate can raise blood glucose, but it does not tell us how much carbohydrate is present in the portion consumed (Brand-Miller et al., 2003).. This is where **Glycemic Load (GL)** becomes important. GL considers both the GI of the food and the amount of available carbohydrate in a serving. It can be expressed as:

$$GL = GI \times \text{available carbohydrate per serving} \div 100$$

A food with a relatively high GI may produce a modest glucose response when consumed in a small portion, while consuming a large quantity of a moderate-GI food may result in a substantial carbohydrate load. Thus, GI tells us about quality or speed, while GL incorporates quantity. For practical food choices, considering both the type and amount of carbohydrate provides a more complete picture.

GI vs GL: Understanding the Difference

Two important ways to understand how carbohydrate foods affect your blood sugar



Think SMART: It's not just how fast the sugar rises, but also how much sugar is there in your plate!

Indian Foods and the Glycemic Index

For Indian consumers, GI becomes particularly interesting because the traditional diet contains a wide variety of cereals, millets, pulses, vegetables and fruits. Rice and wheat are major staple foods, but their glycemic responses can vary depending on variety, processing and cooking method. Similarly, foods prepared from millets are not automatically low-GI simply because they are millets. The final glycemic response depends on the grain, milling, cooking, recipe and portion size. Pulses and legumes are generally valuable components of a healthy diet because they provide protein, fibre, minerals and complex carbohydrates. Combining cereals with pulses is also a traditional dietary practice that can improve the overall nutritional quality of a meal. Traditional meals can therefore provide useful lessons in dietary balance.

For example, instead of consuming a large portion of refined cereal alone, a meal can include:

1. Whole or minimally processed cereals
2. Pulses or legumes
3. Plenty of vegetables
4. Curd or another appropriate protein-rich food
5. Nuts or seeds in suitable quantities
9. Whole fruits rather than sugar-sweetened beverages

The goal is not to eliminate rice, wheat or other staple foods. Rather, it is to improve the overall composition and portion size of meals.

How Cooking Can Change the Glycemic Response

The way food is prepared can be almost as important as the food itself. Cooking softens food and makes starch more accessible to digestive enzymes. Longer cooking and greater processing can sometimes increase the rate at which carbohydrates become available. Interestingly, cooling and subsequently reheating certain cooked starch-containing foods can increase the formation of resistant starch. Resistant starch is less readily digested in the small intestine and can behave in some ways like dietary fibre. This does not mean that every cooled carbohydrate food automatically becomes a low-GI food. However, it demonstrates how food structure and preparation can influence the body's response. For everyday eating, practical strategies include avoiding excessive cooking of vegetables, choosing less processed grains and incorporating whole foods wherever possible.

Smart Food Pairing: Eat Better, Not Just Less

One of the most practical lessons from GI research is that foods are usually eaten as part of meals rather than alone. Consider a meal consisting primarily of a refined carbohydrate. It may produce a different glucose response from a balanced meal containing carbohydrate together with vegetables, pulses, protein and healthy fats. Combining carbohydrate-rich foods with fibre, protein and healthy fats can slow gastric emptying and carbohydrate absorption and may result in a more gradual post-meal glucose response. For example, instead of focusing only on reducing the quantity of rice, a person could improve the meal by increasing the proportion of vegetables and pulses and controlling the rice portion. This approach is more realistic and sustainable than unnecessarily eliminating entire food groups.

GI and Weight Management

The relationship between GI and body weight is complex. Low-GI foods can often be rich in fibre and less processed, which may contribute to greater satiety and improved overall diet quality. However, weight management depends on the overall balance between energy intake and expenditure, food quality, physical activity, sleep and other lifestyle factors. A low-GI food can still contribute substantial calories if consumed in excessive quantities. Therefore, the better strategy is to focus on nutrient-dense, minimally processed foods and appropriate portions, rather than simply searching for foods labelled "low GI."

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Common Myths About Glycemic Index

Myth 1: All high-GI foods are unhealthy: Not necessarily. The nutritional value of a food cannot be determined by GI alone. Overall composition, portion size and dietary context are important.

Myth 2: Low-GI means unlimited: Absolutely not. Low-GI foods can still contain significant calories, fats or carbohydrates.

Myth 3: People should avoid all carbohydrates: Carbohydrates are an important source of energy and are present in many nutrient-rich foods. Whole grains, legumes, vegetables and fruits can contribute valuable fibre, vitamins, minerals and other bioactive compounds.

Myth 4: Millets always have a low GI: Millets are nutritious whole grains, but their GI can vary depending on variety, processing, milling, cooking and recipe formulation.

Myth 5: GI alone can determine a healthy diet: GI is useful, but it is only one piece of the nutritional puzzle.

Five Simple Rules for Making Smarter Food Choices

- 1. Choose whole and minimally processed foods more often:** Whole grains, pulses, vegetables, fruits, nuts and seeds provide a combination of nutrients and bioactive compounds.
- 2. Increase dietary fibre:** Vegetables, fruits, legumes and whole grains can help improve overall dietary quality and support healthy digestion.
- 3. Watch portion size:** Even a nutritious carbohydrate source can contribute a substantial glycemic load when consumed in excessive quantities.
- 4. Combine carbohydrates with protein and vegetables:** Balanced meals generally provide better nutritional value than meals dominated by a single carbohydrate source.
- 5. Limit highly processed and sugar-rich foods:** Foods high in added sugars and refined carbohydrates should generally be consumed less frequently and in appropriate portions.

Beyond GI: Think About the Whole Food

The growing interest in GI reflects an important shift in nutrition science: **what we eat matters, but how foods behave in the body also matters.**

Nevertheless, nutrition is more complicated than a single number. Two foods with similar GI values may differ substantially in fibre, protein, vitamins, minerals and phytochemicals. Likewise, the same food can produce different glucose responses depending on the person, meal composition, preparation and portion size. For this reason, the healthiest approach is not to create a rigid list of "good" and "bad" foods. Instead, people can use GI as one tool alongside other principles such as dietary diversity, nutrient density, portion control and minimal processing.

The Future of Smart Eating

Modern nutrition is increasingly moving toward personalized approaches. Advances in continuous glucose monitoring, nutrition research and digital health technologies are helping scientists understand why individuals can respond differently to the same foods. This suggests that the future of smart eating may go beyond generic food rankings. Personal characteristics, lifestyle, physical activity, meal timing, gut microbiota and overall dietary patterns may all contribute to an individual's metabolic response. However, the basic principles remain remarkably simple: eat more whole foods, include plenty of vegetables and pulses, choose high-fibre carbohydrate sources, control portions and minimize highly processed foods.

Conclusion

The glycemic index provides a useful scientific framework for understanding how carbohydrate-containing foods influence blood glucose. It reminds us that carbohydrates are not nutritionally identical and that the speed of glucose release can be influenced by food structure, fibre, processing, cooking and meal composition. The real value of the glycemic index lies in helping people make smarter food choices rather than simply fewer food choices. A balanced meal containing whole grains, pulses, vegetables, fruits and appropriate sources of protein can be both nutritious and satisfying. Ultimately, healthy eating is not about finding one perfect food or avoiding one particular nutrient. It is about creating a sustainable dietary pattern that supports energy, nutrition and long-term health.

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Doubled Haploidy in Vegetables: Current Status and Future Prospects

Article ID: 74447

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Abstract

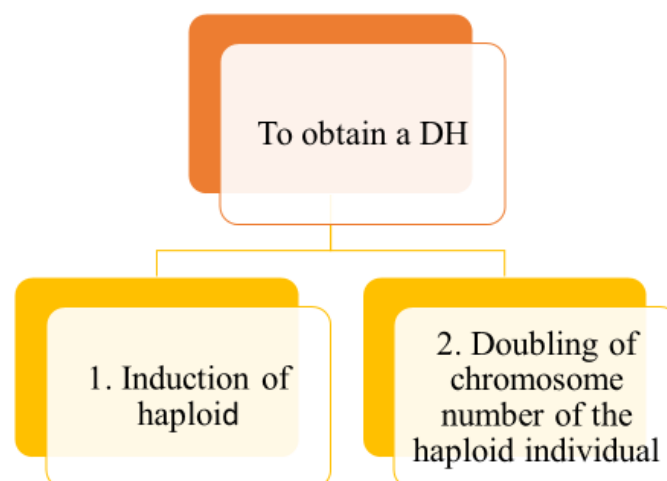
Doubled haploidy (DH) is an important breeding technique for the rapid development of completely homozygous lines. A doubled haploid plant is obtained by chromosome doubling of a haploid plant and is homozygous at all loci. The development of DH lines generally involves two major steps: induction of haploids followed by chromosome doubling. Haploids can be produced through in-vivo methods such as distant hybridization and parthenogenesis, or through in-vitro methods such as androgenesis and gynogenesis. The DH technique has important applications in vegetable breeding, including rapid development of homozygous lines, genetic mapping, QTL analysis, molecular studies and cultivar development. Although the technique can reduce the time required for pure-line development from several generations to a single generation, its efficiency is affected by genotype, low haploid frequency and difficulties in chromosome doubling. This article discusses the methods, applications, advantages, limitations and future prospects of doubled haploidy in vegetable crops.

Keywords: Doubled haploid, haploid, androgenesis, gynogenesis, chromosome doubling, vegetable breeding, homozygous lines.

Introduction

Haploids are plants possessing the gametophytic chromosome number (n) in their sporophytic cells. Haploids derived from diploid plants are known as monoploids, whereas haploids obtained from polyploid species are referred to as polyhaploids. Doubled haploid plants are produced by doubling the chromosome number of haploid plants, resulting in complete homozygosity at all loci. The first report of a haploid plant was made in *Datura stramonium* by Blakeslee et al. (1922). Subsequently, important developments included in-vitro anther culture by Guha and Maheswari, the bulbosum technique by Kasha and Kao, and gynogenesis in barley by San Noeum. DH methodologies have subsequently been applied to more than 250 species.

In order to obtain a DH, two main steps should be usually considered



Importance of Doubled Haploids in Vegetable Breeding

The major advantage of DH technology is the rapid development of completely homozygous lines. Conventional breeding requires several generations of selfing to achieve genetic fixation, whereas DH technology can produce homozygous lines in a much shorter period. DH lines are also useful in genetic mapping, genomics, transgenesis, mutation studies, stress resistance breeding and cytogenetic research. The probability of obtaining a desirable genotype in a DH population is presented in the PPT as $(1/2)^n$, compared with $(1/4)^n$ in a conventional diploid population, where n represents the number of segregating loci.

Methods of Haploid Production

Haploids can be produced through **in-vivo** and **in-vitro** methods. In-vivo methods include distant hybridization, parthenogenesis, pseudogamy, semi-gamy, apogamy, the bulbosum technique and inducer-based techniques. In-vitro methods mainly include androgenesis and gynogenesis.

1. Androgenesis: Androgenesis is the production of haploid plants from male gametic cells. It can be achieved through anther culture or isolated microspore culture, in which microspores undergo embryogenesis or organogenesis. Haploid plants have been successfully produced through androgenesis in several vegetable crops, including potato, brinjal, chilli, cabbage, cauliflower, asparagus and tomato. A sweet pepper variety, Haihua-3, was also developed through anther culture in China. The general process includes collection of flower buds, surface sterilization, plating of anthers on culture media, embryo or callus development, regeneration of haploid plants, chromosome doubling and acclimatization of DH plants.

2. Gynogenesis: Gynogenesis involves the in-vitro production of maternal haploids from female gametic cells. It can be achieved by culturing unpollinated ovaries, ovules, placenta-attached ovules or whole flower buds. This method has been successfully used in vegetable crops such as onion, beetroot, cucumber and squash.

Identification and Chromosome Doubling

Haploid plants can be identified by direct and indirect methods. Direct methods include chromosome counting in root-tip cells and flow cytometry, while indirect identification can be based on stomatal size, chloroplast number in guard cells and morphological characteristics. Chromosome doubling is essential because haploid plants generally have reduced fertility or may fail to produce seeds. Although spontaneous chromosome doubling can occur, artificial chromosome doubling is generally required to restore fertility. Colchicine is one of the commonly used chromosome-doubling treatments. Other agents mentioned in the PPT include acenaphthene, chloramphenicol, nitrous oxide, parafluorophenylalanine and 8-hydroxyquinone. The mechanisms associated with chromosome doubling include endomitosis, endoreduplication, C-mitosis and nuclear fusion.

Applications of Doubled Haploids

DH technology has several applications in modern vegetable breeding. It is useful for:

1. Development of homozygous parental lines.
2. Rapid cultivar development.
3. QTL mapping.
4. Construction of genetic maps.
5. Bulk segregant analysis (BSA).
6. Backcross breeding.
7. Elite crossing.
8. Molecular marker identification.
9. Genomic and cytogenetic studies.

DH populations are particularly valuable because they are permanent and can be repeatedly evaluated for genetic studies.

Doubled Haploid versus Conventional Breeding

One of the major benefits of DH breeding is its ability to shorten the breeding cycle. According to the PPT, development of pure lines may require approximately one year or one crop season through DH breeding, compared with 6-7 years through conventional breeding. Development of cultivars may take approximately 3-5 years using DH methods, compared with 8-12 years through conventional breeding.

Particular	Doubled Haploid Breeding	Conventional Breeding
Pure-line development	1 year/one crop season	6-7 years
Cultivar development	3-5 years	8-12 years
Fixation of heterosis	Possible	Not possible
Cost	Higher	Lower
Recessive mutant identification	Easy	Difficult
Mapping population	Permanent	Temporary

Advantages

The major advantages of DH technology include rapid development of homozygous lines, shortening of breeding cycles, efficient identification of molecular markers and development of parental inbred lines for hybrid breeding. DHs are also valuable for evolutionary and cytogenetic studies and can be particularly useful where conventional inbred-line development is difficult.

Limitations

Despite its advantages, DH technology has several limitations. The frequency of haploid production may be low, and success is often unpredictable and strongly genotype-dependent. The technique may also reduce genetic variation, and selection cannot always be imposed effectively on the haploid population. Health and legal concerns may further influence its application. The current status of DH production also varies among crops. Cabbage and brinjal commonly use anther culture, onion and beetroot use gynogenesis, asparagus uses anther culture, while potato may utilize distant crosses and anther culture. Genotype dependence, low fertility and difficulties in chromosome doubling remain important constraints.

Future Prospects

Future research should focus on developing standardized protocols for DH production in a wider range of vegetable crops. Identification of genes controlling haploid formation from male and female gametes may help improve efficiency. Genotype-independent protocols would further increase the usefulness of DH technology. Molecular marker and flow-cytometry-based approaches can facilitate rapid identification of ploidy status. Development of non-toxic, inexpensive and efficient chromosome-doubling agents is also an important research priority.

Conclusion

Doubled haploidy is a powerful tool for accelerating vegetable breeding and rapidly fixing desirable genetic combinations into completely homozygous lines. The technique combines haploid induction with chromosome doubling and can substantially shorten the breeding cycle compared with conventional breeding. DH lines have important applications in hybrid breeding, cultivar development, genome mapping, QTL analysis and molecular genetics. However, low haploid induction frequency, genotype dependence and unpredictable chromosome doubling remain major challenges. Development of genotype-independent protocols, reliable ploidy identification methods and safe, economical chromosome-doubling techniques will further enhance the application of DH technology in vegetable breeding.

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Role and Mode of Action of Morphactins, Antitranspirants and Antiauxins in Plants

Article ID: 74448

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Abstract

Plant growth and development are regulated by several growth regulators and physiological processes. Morphactins, antitranspirants and antiauxins are important substances that influence plant growth, transpiration, branching, flowering and other physiological responses. Morphactins affect seed germination, seedling growth, stem elongation, apical dominance, root development, flowering and sex expression. Antitranspirants reduce water loss mainly by modifying stomatal conductance, forming reflective surfaces or producing thin and thick films over plant surfaces. Antiauxins interfere with auxin activity and can influence stem growth, flowering and morphogenesis. This article briefly discusses their roles, modes of action and applications in horticultural crops.

Keywords: Morphactin, antitranspirant, antiauxin, plant growth regulator, transpiration, auxin, horticultural crops.

Introduction

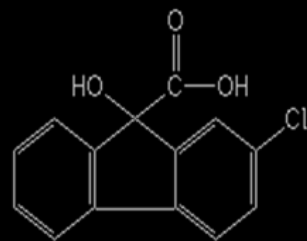
Plant growth regulators play an important role in controlling physiological and developmental processes in plants. Different growth-regulating substances can modify seed germination, vegetative growth, flowering, sex expression, water relations and fruit production. Morphactins, antitranspirants and antiauxins represent important groups of compounds that influence these processes.

The presentation describes the importance of these substances in relation to seed germination, flowering, sex expression, transpiration, stomatal conductance and plant growth.

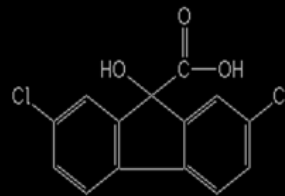
Morphactins

Morphactins are synthetic growth-regulating compounds that influence several aspects of plant growth and development. Examples mentioned in the presentation include chlorflurenol, dichlorflurenol, flurenol and methyl benzilate.

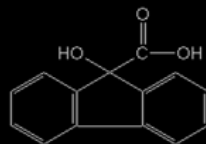
SOME STRUCTURES OF MORPHACTINS



CHLORFLURENOL



DICHLORFLURENOL



FLURENOL

1. Role of Morphactins: Morphactins can influence a wide range of physiological processes, including:

- Seed germination
- Seedling growth
- Stem elongation
- Apical dominance and branching
- Bud dormancy
- Root growth and root branching
- Flowering

h. Sex expression

The response to morphactins depends on the crop, concentration and physiological stage of the plant.

2. Effects on Horticultural Crops: The PPT reports different responses of crops to morphactin treatments. In okra, morphactin application was associated with loss of moisture and chlorophyll. In ridge gourd, application was reported to reduce staminate flowers and increase pistillate flowers, thereby influencing sex expression.

3. Mode of Action: According to the presentation, chlorflurenol and methyl benzilate can move both **basipetally** and **acropetally**. Morphactins can interfere with auxin transport, particularly by inhibiting basipetal transport of auxin. They also interact with protein and enzyme systems and may influence growth-regulating processes.

Antitranspirants

Antitranspirants are substances used to reduce excessive water loss from plants by influencing transpiration and stomatal behaviour. Their importance is mainly associated with **stomatal conductance and transpiration rate**. Examples given in the PPT include ABA, BA, PMA, HDSA, 2,4-D and HQ.

Antitranspirants can be particularly useful under water-stress conditions because regulation of transpiration can help plants conserve water.

Role of Antitranspirants: The response of plants depends on the type of antitranspirant. According to the presentation, BA can increase stomatal conductance and transpiration, whereas ABA, PMA and 2,4-D can reduce stomatal conductance and transpiration. ABA and PMA are particularly associated with lowering stomatal conductance and transpiration.

Antitranspirants can therefore contribute to regulation of plant water relations, particularly under water-stress conditions. The presentation also relates their use to crop productivity and regulation of transpiration.

Antitranspirants in Brinjal

Different antitranspirant treatments have been reported to influence growth, photosynthesis and yield in brinjal. Kaolin, PMA and salicylic acid were associated with effects on growth and yield. A 7.5% kaolin spray was reported to influence biomass and number of flowers, while combinations of kaolin with liquid paraffin affected photosynthetic rate and transpiration. Kaolin combined with salicylic acid was associated with fruit yield.

Mode of Action of Antitranspirants

Antitranspirants can function through different mechanisms. The PPT groups them into four major categories:

1. Stomatal Closure: Certain chemicals reduce transpiration by promoting stomatal closure. These include some herbicides, fungicides, metabolic inhibitors and growth regulators such as ABA and related compounds.

2. Reflectant Materials: Reflectant materials reduce the energy absorbed by the plant surface and can help reduce water loss. Examples include:

- Kaolin
- China clay
- Calcium bicarbonate
- Lime water

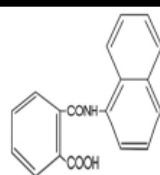
3. Thin-Film Forming Chemicals: Some chemicals form thin films over plant surfaces and thereby reduce water loss. Examples include hexadecanol, cetyl alcohol, methanol, paclobutrazol, brassinolide and resorcinol.

4. Thick-Film Forming Materials: Polyethylene-based materials can form relatively thick films over plant surfaces. Examples mentioned in the presentation include Mobileaf, Folicot, Waxol, S-800 and Hico-110R.

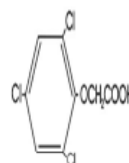
Antiauxins

Antiauxins are substances that interfere with the action or transport of auxin. They are important for regulating vegetative growth and developmental processes. Examples mentioned in the PPT include TIBA, NPA, DCA and 2,4-D.

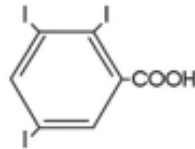
• SOME STRUCTURES OF ANTIAUXINS



(8) naptalam or NPA
[N-1-naphthyl]phthalamic acid]



(12) 2,4,6-T
[2,4,6-trichlorophenoxyacetic acid]



(11) TIBA

[2,3,5-triodobenzoic acid]

1. Role of Antiauxins: Antiauxins can:

- Retard stem growth
- Influence plant number
- Promote certain developmental responses
- Induce flowering
- Inhibit auxin action

2. Mode of Action: Antiauxins influence plant development primarily by modifying auxin activity. They may alter the effects of endogenous or externally supplied auxin and thereby modify morphogenesis. TIBA has also been associated with callus formation and embryogenesis.

Advantages and Applications

Morphactins, antitranspirants and antiauxins have potential applications in horticultural crop production because they can modify important physiological processes.

Morphactins can be used to study or regulate branching, flowering, root development and sex expression.

Antitranspirants can help regulate transpiration and water loss, particularly under water-stress conditions.

Antiauxins can be useful for modifying auxin-mediated growth, stem elongation, flowering and morphogenetic responses.

Thus, these compounds can be considered useful tools for understanding and manipulating plant growth and development.

Limitations

Despite its advantages, DH technology has several limitations. The frequency of haploid production may be low, and success is often unpredictable and strongly genotype-dependent. The technique may also reduce genetic variation, and selection cannot always be imposed effectively on the haploid population. Health and legal concerns may further influence its application. The current status of DH production also varies among crops. Cabbage and brinjal commonly use anther culture, onion and beetroot use gynogenesis, asparagus uses anther culture, while potato may utilize distant crosses and anther culture. Genotype dependence, low fertility and difficulties in chromosome doubling remain important constraints.

Future Prospects

The response of plant growth regulators can vary considerably with **crop, concentration, developmental stage and environmental conditions**. Excessive or inappropriate application may produce undesirable physiological effects. Therefore, proper concentration and timing are important for obtaining beneficial responses.

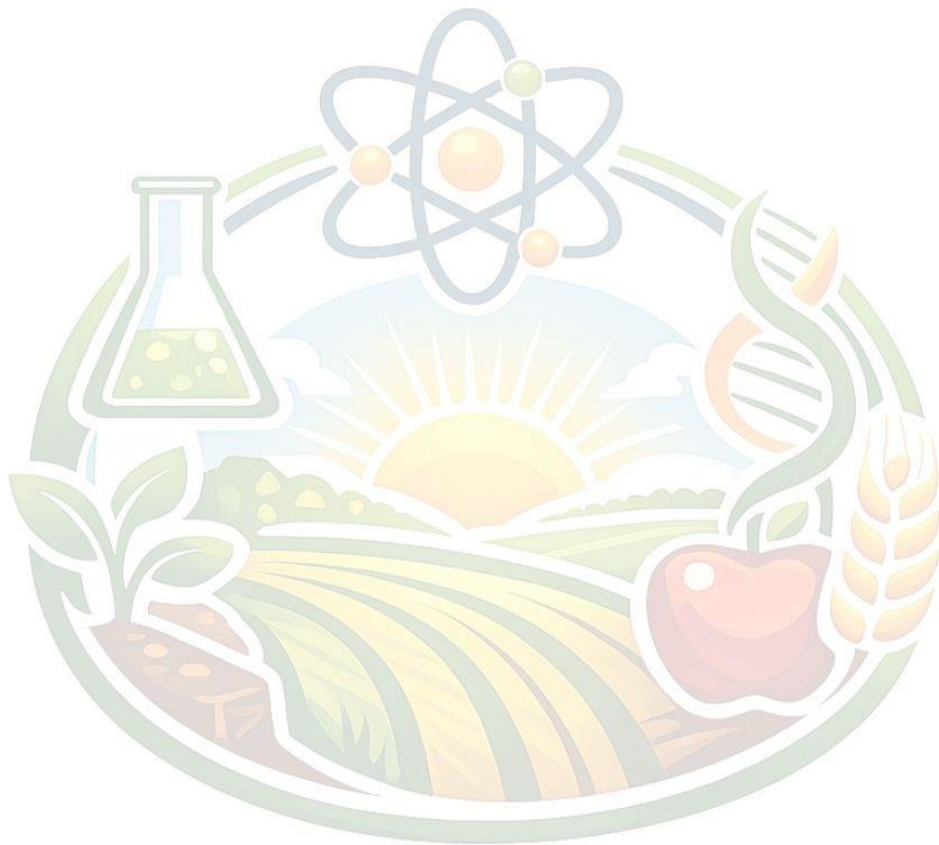
Conclusion

Morphactins, antitranspirants and antiauxins are important growth-regulating substances capable of modifying several physiological processes in plants. Morphactins influence germination, stem growth, branching, roots, flowering and sex expression, while antitranspirants primarily regulate stomatal conductance and transpiration. Antiauxins modify auxin-mediated growth and morphogenesis. Their appropriate use may provide useful opportunities for manipulating plant growth, improving water-use management and regulating developmental processes in horticultural crops. However, crop-specific evaluation and proper concentration and application timing are essential for successful use.

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Nano Edible Coatings and their Applications in Horticultural Crops

Article ID: 74449

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Abstract

Horticultural crops are highly perishable due to high respiration rate, moisture content, physiological changes and microbial attack. Considerable post-harvest losses occur because of inadequate infrastructure and limited use of modern post-harvest technologies. Edible coatings can reduce moisture loss, delay senescence and control microbial deterioration. The incorporation of nanotechnology into edible coatings further improves their barrier, antimicrobial and functional properties. Nanoemulsions, nanoparticles and nanocomposites have shown promising results in maintaining quality and extending the shelf life of horticultural produce. This article summarizes the importance, applications, advantages, limitations and future prospects of nano-edible coatings in horticultural crops.

Keywords: Nanotechnology, edible coating, nanoemulsion, nanoparticles, post-harvest, shelf life, horticultural crops.

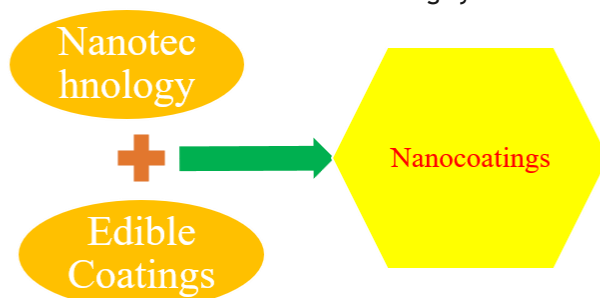
Introduction

India is one of the world's major producers of fruits and vegetables. However, around 20-30% of horticultural produce may be lost annually because of inadequate infrastructure and limited adoption of modern post-harvest technologies. Fresh fruits and vegetables are particularly vulnerable to post-harvest deterioration because of their high moisture content, high respiration rate, physiological activity, bulky nature and susceptibility to pathogenic attack. At the global level, approximately 1.3 billion tonnes of food are reported to be wasted or lost annually. The reduction of these losses is therefore essential not only for increasing food availability but also for improving farmer income, resource-use efficiency and food security. Post-harvest life can be extended by reducing moisture loss, slowing maturation and senescence, and reducing the onset and development of microbial growth. Conventional technologies such as heat treatment, irradiation, gaseous treatments, antimicrobial treatments, anti-browning agents and waxing have been used for this purpose. Edible coatings represent another important approach, particularly because they can form a protective layer directly on the surface of fruits and vegetables. The development of nanotechnology has further expanded the possibilities of edible coatings. Nanotechnology involves the design, characterization, production and application of structures and systems by controlling materials at the nanometre scale. The term nano refers to 10^{-9} m, and nanomaterials are generally considered to possess dimensions in the range of approximately 1-100 nm. At this scale, materials can exhibit distinctive physical, chemical and biological properties compared with their bulk counterparts.

Nanotechnology and its Importance in Post-Harvest Management

Nanotechnology provides new opportunities for improving the efficiency of food preservation and post-harvest management. Nanomaterials possess a high surface-to-volume ratio, which can enhance their diffusion, reactivity and interaction with surrounding materials. These characteristics can be exploited in food packaging, antimicrobial systems, sensors and edible coating formulations.

The increasing importance of nanotechnology in post-harvest technology is associated with the need to improve the efficiency of existing preservation methods, reduce the quantity and cost of additives, minimize dependence on potentially phytotoxic chemicals and develop environmentally sustainable alternatives. Some conventional ethylene inhibitors and other chemical treatments can be expensive or may have undesirable effects. In addition, environmental concerns associated with certain chemicals emphasize the need for safer and more sustainable technologies. Nanotechnology can contribute to this objective by allowing active compounds to be incorporated into coatings in very small quantities while maintaining functional effectiveness. Nanomaterials can also improve barrier properties, antimicrobial activity and controlled release characteristics of coating systems.



Edible Coatings and Nano Coatings

An edible coating is a thin layer of edible material applied to the surface of a food product to provide protection against environmental and physiological deterioration. Edible coating materials may be obtained from polysaccharides, proteins and lipids. Surfactants and plasticizers can also be incorporated to improve the physical and mechanical characteristics of the resulting film or coating. Examples of surfactants include Tween 20 and Span 80, while glycerol and sorbitol are commonly used plasticizers. Water can also act as a natural plasticizer. Nano coatings represent an advancement over conventional edible coatings in which nanoscale systems such as polymeric nanoparticles, Nano emulsions or solid lipid nanoparticles are incorporated into edible coating formulations. The seminar material describes Nano coatings as thin layers associated with nanoscale coating systems, while Nano emulsions contain lipid nanodroplets dispersed in an aqueous phase. The functional characteristics of coating materials vary according to their composition. Polysaccharides primarily act as gas barriers, lipids help reduce water transmission, and proteins contribute to mechanical stability. Lipid-based films can suffer from fragility, instability and rancidity, whereas hydrocolloid films generally have a more neutral taste. Composite coatings combine lipid and hydrocolloid components to obtain the advantages of both materials.

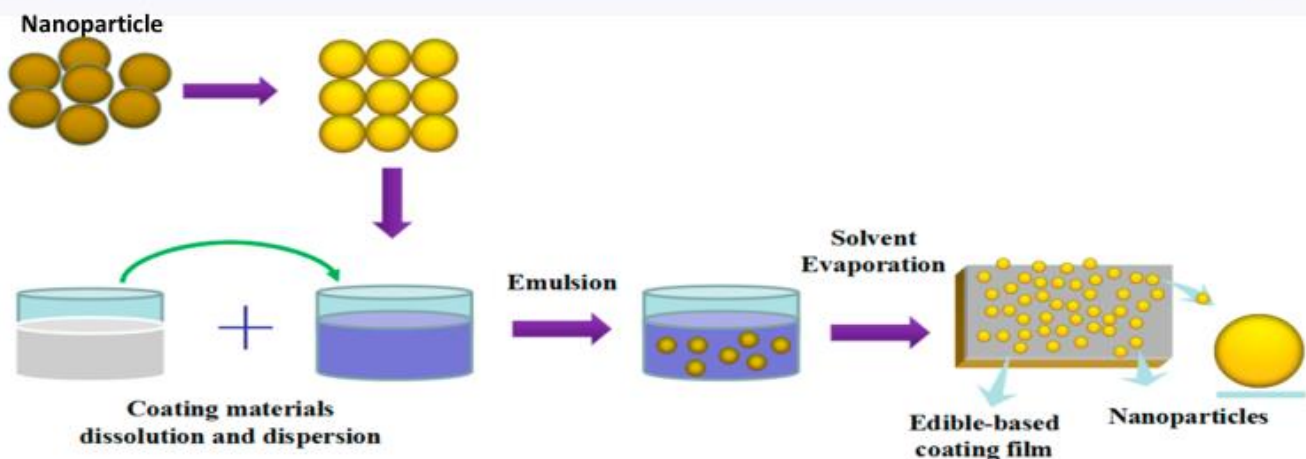
Need for Nano-Edible Coatings

Post-harvest loss refers to measurable quantitative and qualitative losses occurring throughout the supply chain from harvest until consumption or other end uses. In horticultural crops, deterioration can occur rapidly because of moisture loss, respiration, senescence, microbial infection and physical damage. The seminar presentation highlights considerable losses due to spoilage in several vegetables, including potato, cauliflower, carrot, lettuce, cabbage, onion and tomato. For example, the reported spoilage losses in the presentation range from 16-35% in onion, 37% in cabbage, 44% in carrot, 49% in cauliflower and 62% in lettuce. Such losses demonstrate the importance of effective technologies that can slow deterioration after harvest. Nano-edible coatings can act as semi-permeable barriers around fresh produce. They can reduce moisture transfer, regulate gas exchange, slow respiration and provide protection against microorganisms. The incorporation of antimicrobial compounds into nanoscale systems may further improve their effectiveness.

Components Used in Nano-Edible Coatings

- 1. Polysaccharides:** Polysaccharides such as alginate, chitosan and other hydrocolloids are important coating materials because of their film-forming properties. They can provide gas-barrier characteristics and can serve as matrices for incorporating antimicrobial and antioxidant compounds.
- 2. Proteins:** Proteins can contribute to the mechanical stability of edible films and coatings. Their ability to form cohesive films makes them useful components of composite coating systems.
- 3. Lipids:** Lipids are particularly useful for reducing water transmission because of their hydrophobic nature. However, lipid-based coatings may suffer from greasiness, thickness and rancidity, which can negatively affect sensory quality.
- 4. Nano-composites:** Nanocomposites are multiphase solid materials in which at least one phase has nanoscale dimensions, generally below 100 nm (Alexandre and Dubois, 2000). In food packaging, nanocomposites can improve mechanical strength and barrier properties against oxygen, carbon dioxide, moisture, ultraviolet radiation and volatile compounds. They can also reduce packaging weight, improve heat resistance and contribute to ethylene-related technologies.

NANO COATING FORMATION



Nanoemulsion-Based Edible Coatings

Nano emulsions are among the most promising nano-enabled systems for horticultural applications. They consist of very small lipid droplets, generally in the nanoscale range, dispersed in an aqueous phase and stabilized by surfactant molecules (Acosta, 2009). Their small droplet size can provide distinctive physicochemical and functional characteristics. Nano emulsions can be used to deliver bioactive compounds such as essential oils into edible coating matrices. Their applications in horticultural commodities include antimicrobial protection, reduction of moisture loss and maintenance of quality. The seminar material presents several examples of Nano emulsion-based coatings. Mandarin essential oil incorporated into chitosan was reported for beans, while carvacrol-based systems were investigated in cabbage and cucumber. These examples demonstrate the potential of combining natural antimicrobial compounds with biopolymer matrices.

Nanosensors for Post-Harvest Management

Nanotechnology is not restricted to edible coatings. Nano sensors can also play an important role in intelligent food packaging and post-harvest quality monitoring. Ethylene is a major physiological signal involved in ripening and senescence of many horticultural commodities. Nanoscale sensing materials can be incorporated into resistor-based devices, where changes in electrical conductivity occur in response to different ethylene concentrations. Such systems may provide an indication of produce maturity and can potentially trigger changes in package appearance to alert consumers. Materials such as tin dioxide, tungsten trioxide, palladium, platinum and zinc oxide have been considered for Nano sensor applications. The integration of nanosensors with active and edible packaging could therefore provide a more intelligent post-harvest management system in which packaging not only protects the commodity but also provides information regarding its physiological condition.

Nano-Silver and Other Nanoparticles

Nano-silver is among the commonly discussed nanoparticles for antimicrobial applications. Its proposed mode of action includes contact-based antimicrobial activity, and the seminar material reports its potential as an anti-ethylene agent and its use for extending shelf life in crops such as capsicum, tomato and carrot. Other nanoparticles such as titanium dioxide and zinc oxide have also been investigated because of their antimicrobial properties. According to the seminar material, TiO_2 nanoparticles have shown bactericidal and fungicidal effects against several microorganisms, while ZnO has activity against both Gram-positive and Gram-negative bacteria. However, the application of metallic nanoparticles in food systems requires careful assessment because their biological activity can be beneficial at appropriate concentrations but potentially harmful at elevated exposure levels.

Advantages of Nano-Edible Coatings

Nano-edible coatings possess several potential advantages over conventional preservation systems:

- 1. Control of microbial growth:** Nanoparticles and incorporated bioactive compounds can provide antimicrobial activity.
- 2. Controlled release of functional agents:** Nano-systems can facilitate incorporation and controlled delivery of active compounds.
- 3. Moisture preservation:** Coatings can reduce water loss and maintain freshness.
- 4. Quality preservation:** They can help maintain colour, texture, flavour and nutritional attributes.
- 5. Improved barrier properties:** Nano-enabled systems may provide improved barriers against oxygen, carbon dioxide, moisture and volatile compounds.
- 6. Low quantity requirement:** Because of the high surface area and functional efficiency of nanoscale materials, relatively small quantities may provide useful effects.
- 7. Biodegradability:** Many edible coating matrices are biodegradable and can provide an environmentally favourable alternative to conventional packaging.

Limitations and Safety Concerns

The major limitations include difficulty in measuring coating thickness, high production cost and complicated preparation procedures. Safety is another important concern because some metallic nanoparticles may cause adverse effects at elevated concentrations, including cytotoxicity, genotoxicity, oxidative stress and inflammation. Therefore, safe concentrations and threshold limits of nanoparticles need to be standardized before their widespread application in food and agriculture.

Future Prospects

Future research should focus on developing safe, economical and biodegradable nano-edible coating formulations. The efficiency and economics of combining nanotechnology with other post-harvest technologies should be evaluated in

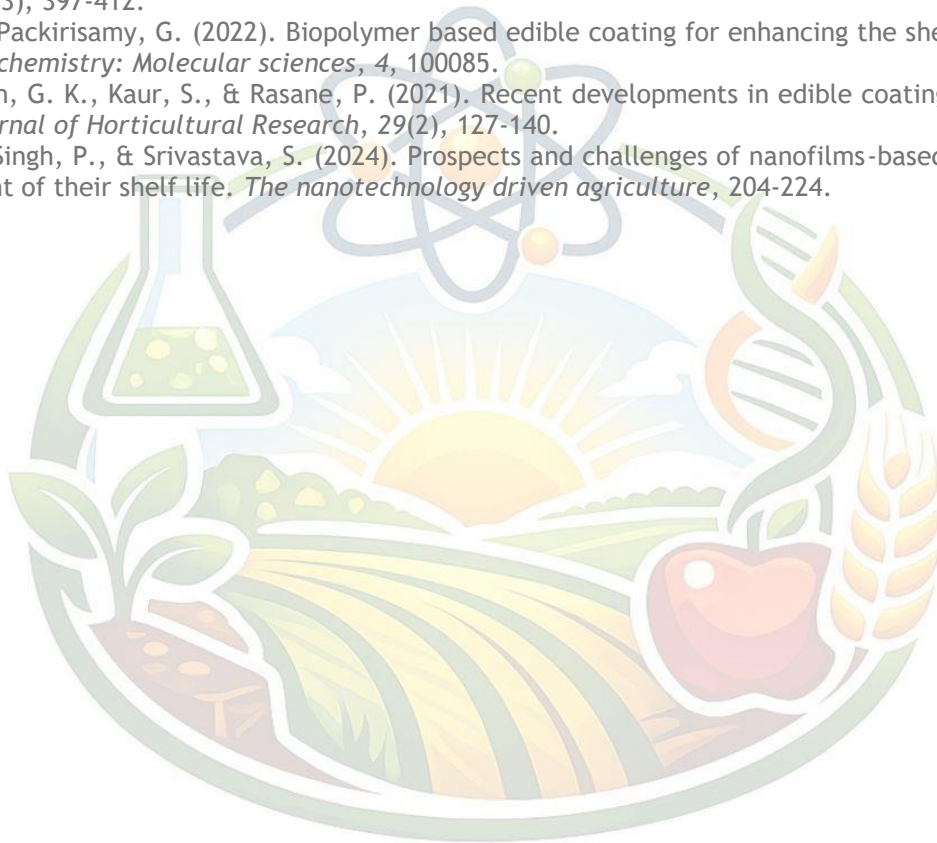
different horticultural crops. Standardization of nanoparticle concentrations and consumer safety assessment are also essential for commercial adoption.

Conclusion

Nano-edible coatings have considerable potential for reducing post-harvest losses and extending the shelf life of horticultural crops. Nanoemulsions, nanoparticles and nanocomposites can improve antimicrobial protection, moisture retention and overall quality. Studies on okra, green bell pepper, fresh-cut green beans and cantaloupe demonstrate their promising role in post-harvest management. However, safety, cost, consumer acceptance and regulatory standardization must be addressed for their successful commercial application.

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Millets under El Niño Conditions: A Farmer's Guide to Climate-Smart Crops

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Introduction

Climate variability is a major challenge for rainfed agriculture. Delayed monsoon onset, uneven rainfall, prolonged dry spells and high temperatures can adversely affect crop establishment, growth and productivity. El Niño-Southern Oscillation (ENSO) is an important climate phenomenon influencing weather patterns. El Niño events are generally associated with a tendency towards weaker Indian summer monsoon rainfall, although the relationship varies among years and regions. Millets, including sorghum, pearl millet, finger millet and small millets, offer an important opportunity for climate-resilient agriculture because many are adapted to dryland environments, relatively low water availability and high temperatures. Their short duration, drought adaptation, nutritional value and suitability for marginal environments also support nutritional security (Saha et al., 2018; Hill et al., 2024; Bezbaruah & Singh, 2024; Jacob et al., 2023).

Understanding El Niño and Its Implications for Agriculture

El Niño is characterized by abnormal warming of the central and eastern tropical Pacific Ocean with associated atmospheric changes. For Indian agriculture, strong El Niño conditions may be associated with delayed or irregular monsoon rainfall, prolonged dry spells, higher temperatures, moisture stress, reduced water availability and uncertainty in crop establishment. El Niño does not necessarily mean drought in every region because the Indian monsoon is influenced by several interacting climate systems, including the Indian Ocean Dipole and intraseasonal variability. Therefore, rainfall intensity and distribution can vary considerably across India (Saha et al., 2018; Hill et al., 2021).

Why are Millets Climate-Smart Crops?

Millets can grow under relatively low rainfall, high temperatures and marginal production conditions. Pearl millet is particularly adapted to hot and dry environments. Several small millets are short-duration crops that can complete their life cycle within a relatively short growing period and thereby escape severe terminal drought. Millets generally require less water than rice and contribute to efficient use of limited water resources. Their nutritional characteristics further support dietary diversification and nutritional security (Muneeb et al., 2026; Jacob et al., 2023; Bezbaruah & Singh, 2024).

Millets as an Alternative under Rainfall Uncertainty

Although millets are not immune to drought or heat stress, sorghum, pearl millet and finger millet may be less affected by climate variability than rice. When monsoon rainfall is delayed or uncertain, farmers can consider short-duration millet crops or varieties based on soil type, available moisture, local agro-climatic conditions and market demand. Crop diversification can reduce production risk while supporting food, fodder and nutritional security.

Selection of Suitable Millet Crops and Varieties

Sorghum is suitable where both grain and fodder are important, and early- or medium-duration varieties may be preferred. Pearl millet is especially suitable for hot and dry environments. Finger millet provides good nutritional value and can be cultivated using suitable early varieties. Foxtail, little, kodo, barnyard and proso millet offer options for rainfed and marginal environments; short-duration types are particularly useful when delayed rainfall shortens the growing period. Farmers should select early-maturing, drought- and heat-tolerant, locally adapted varieties with resistance or tolerance to important pests and diseases, using high-quality seed with good germination and vigour. Variety choice should be based on expected growing period and available soil moisture rather than only the normal sowing calendar.

Ensuring Good Crop Establishment

Farmers should use quality or certified seed with good germination and vigour, adopt locally recommended seed treatments, maintain appropriate seed rates and sow at the recommended depth. Sowing should be undertaken when adequate soil moisture is available for rapid and uniform germination. A healthy plant population improves utilization of available soil moisture, nutrients and sunlight. In sorghum, timely establishment is particularly important because shoot

fly (*Atherigona soccata*) can cause serious seedling damage; timely sowing, optimum plant population and tolerant or resistant varieties should be integrated with other pest-management practices.

Save Every Drop of Rainwater

In-situ moisture conservation can increase water availability during dry spells and improve yield stability. Contour bunding reduces runoff and improves infiltration; compartment bunding retains rainfall within field sections; conservation furrows improve moisture availability in the root zone; and, where suitable, Broad Bed and Furrow (BBF) can improve soil-water management. Farm ponds can harvest excess runoff for limited supplemental irrigation during critical stages. Crop-residue mulching reduces evaporation and helps conserve soil moisture. Integrated land and water conservation, balanced nutrition and climate-adapted varieties are important components of resilient millet production (Muneeb et al., 2026).

Crop Management under Delayed Monsoon

Farmers should avoid sowing in inadequate soil moisture because poor germination and weak establishment can cause severe yield losses. Once sufficient moisture is received, short-duration and locally adapted varieties should be considered. Where locally recommended, foxtail, little, barnyard or proso millet may provide useful alternatives. Long-duration crops that may face severe terminal moisture stress should be avoided. Crop selection should consider the remaining growing period, soil type, available moisture and local weather information. After establishment, intercultivation, conservation furrows, mulching and timely weed management should be adopted.

Nutrient and Weed Management under Moisture Stress

Fertilizer application should be based on soil-test results, crop requirement and expected moisture availability. Balanced nitrogen (N), phosphorus (P) and potassium (K) is preferable to excessive nitrogen. Well-decomposed organic manures and locally recommended organic inputs can improve soil structure, water-holding capacity and nutrient availability. Under severe moisture stress, excessive nitrogen should be avoided because nutrient uptake is restricted. Where recommended, nitrogen may be applied in split doses. The principle is “right nutrient, right dose, right time and right placement.” Weeds compete for water, nutrients, light and space, and this competition is particularly damaging under moisture stress. Intercultivation, hand or mechanical weeding, mulching and crop-specific recommended herbicides should be used according to locally approved guidelines.

Pest and Disease Management

Climate variability can influence the incidence and severity of pests and diseases. Important pests include shoot fly, stem borer, fall armyworm, aphids and other sucking pests, and earhead pests. Farmers should follow Integrated Pest Management (IPM): Monitor → Identify → Assess → Manage. Management should combine resistant or tolerant varieties, timely sowing, recommended seed treatment, field sanitation, conservation of natural enemies, biological control and need-based application of approved pesticides. Important diseases include sorghum grain mold, downy mildew, anthracnose and rust, and finger millet blast, brown spot and foot rot. Disease-resistant or tolerant varieties should be combined with healthy seed, balanced nutrition, appropriate sowing time, optimum plant population, field sanitation and need-based approved treatments.

Millets and Nutritional Security

Millets provide carbohydrates, protein, dietary fibre, minerals, B vitamins and bioactive compounds. Their nutritional richness, adaptability to difficult production environments and relatively lower water requirements make them valuable under climate change. Promoting millet cultivation and consumption can contribute simultaneously to climate resilience, nutritional security and agricultural diversification.

Value Addition and Farmer Income

Millet value addition can strengthen economic resilience and farmer income. Grains can be processed into flour, roti, porridge, malt, popped products, biscuits, snacks, ready-to-cook foods and breakfast cereals. Value addition can improve marketability, extend shelf life, create employment and provide better returns than raw grain. It creates opportunities for Farmer Producer Organizations, rural youth, women entrepreneurs, processors and local food enterprises. A sustainable value chain should extend from Seed → Production → Processing → Value Addition → Marketing → Consumer.

Future Research Priorities

Future research should adopt a multidisciplinary approach. Plant breeding should focus on drought and heat tolerance, early maturity, high grain yield and stable performance across variable environments. Biofortification should prioritize higher iron (Fe) and zinc (Zn), improved protein quality and nutrient bioavailability. Entomology should emphasize resistance or tolerance to shoot fly, stem borer and fall armyworm. Plant pathology should focus on blast, grain mold, downy mildew and other locally important diseases. Agronomy should address efficient moisture conservation, balanced

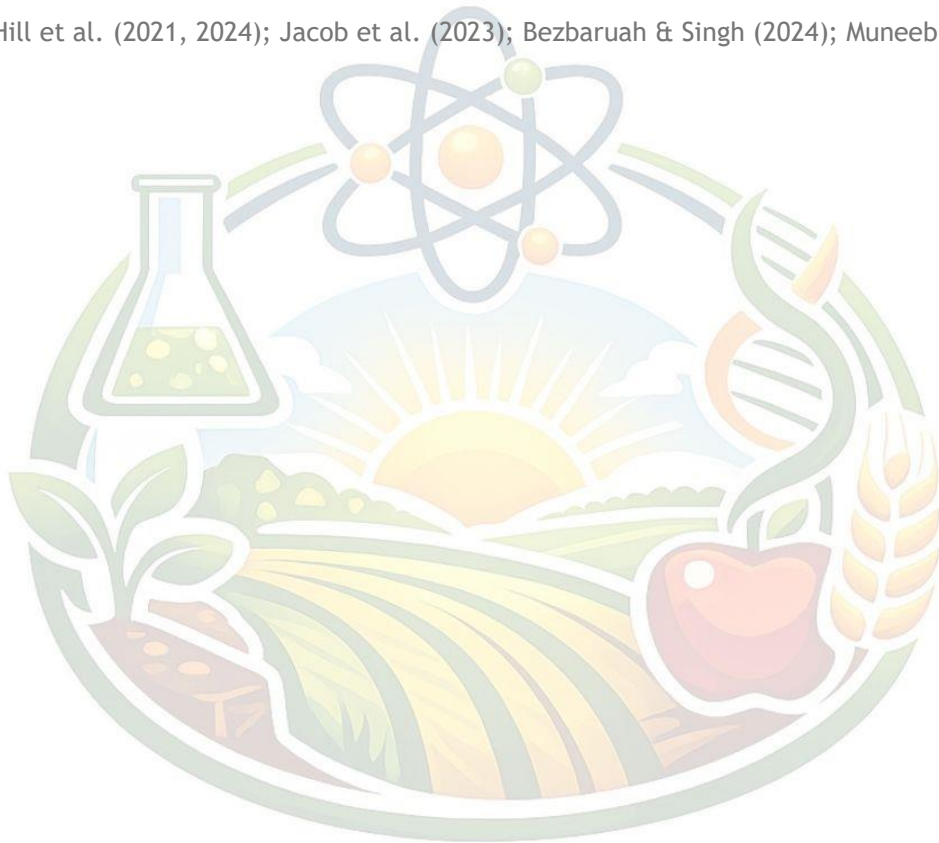
nutrient management, delayed sowing under uncertain rainfall and integrated weed management. Research should also promote improved processing technologies, nutritious food products, shelf life, packaging and stronger market linkages (Muneeb et al., 2026).

Conclusion

El Niño and increasing climate variability present important challenges to rainfed agriculture through uncertain rainfall, prolonged dry spells and high temperatures. Sorghum, pearl millet, finger millet and small millets offer important opportunities because of their dryland adaptation, relatively lower water requirements, nutritional value and potential for short-duration production. The objective should not simply be to grow millets, but to develop a complete climate-smart production system based on: Right Crop + Right Variety + Right Sowing Time + Rainwater Conservation + Balanced Nutrition + Timely Pest and Disease Management + Value Addition. Thus, millets can become an important component of climate-resilient agriculture, nutritional security, production diversification and sustainable farmer livelihoods.

Reference

Saha et al. (2018); Hill et al. (2021, 2024); Jacob et al. (2023); Bezbaruah & Singh (2024); Muneeb et al. (2026).

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From Smart Farming to Autonomous Agriculture: The Role and Impact of Artificial Intelligence in Modern Farming

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Introduction

Agriculture is an important part of the global economy. Agri-technology and precision farming, often called agriculture are new areas of science that use a lot of data to increase the amount of food produced while making less harm to the environment. Artificial intelligence is a tool for sustainable agriculture because it can improve precision agriculture, smart farming, water and energy use and other farming parts. AI in agriculture helps farmers make choices produce more use resources more efficiently and be more ready for climate changes by using machine learning, computer vision, sensors, drones, satellite data and robots. A lot of weather, soil, crop and market data are turned into advice for researchers and farmers. With the help of machine learning, deep learning, IOT sensors and robots' artificial intelligence is changing agriculture in areas like crop management, animal monitoring, resources use and moving goods from to markets. Predictive analysis, farming robots and checking soils and crops are some of the ways AI helps make decisions based on data, which increases production and uses fewer resources (Elbasi *et al*; 2022, Liakos *et al*; 2018).

Table1: Core AI applications used in agriculture:

Application Area	Key AI Methods	Demonstrated Outcomes
Yields prediction	ML/DL on climate, soil, and crop-growth data	Accurate forecasts for proactive planning (Ajith <i>et al</i> ; 2025, Ali <i>et al</i> ; 2025).
Pest & disease diagnosis	CNN-based image classification	Early detection reduces crop loss and pesticide use (Ajith <i>et al</i> ; 2025).
Precision irrigation	Real-time soil-moisture + weather models	6-11% water reduction in strawberry crops. (Ajith <i>et al</i> ; 2025, Linaza <i>et al</i> ; 2025)
Soil fertility mapping	ML spectral analysis at high resolution	Targeted nutrient application, less pollution (Ajith <i>et al</i> ; 2025)
Food quality assessment	Hyperspectral imaging + ML	Automated grading, adulteration detection (Ajith <i>et al</i> ; 2025)

Major Contributions

1. Drones for field operation: Agricultural drones or unnamed aerial vehicles can reduce reliance on human workers through:

- Crop scouting and field mapping
- Detecting drought, lack of nutrients, weeds, pests and diseases.
- Using rates of spraying pesticides, micronutrients and biostimulant.
- Monitoring how crops grow the number of plants when they flower if they fall and when they are ready to harvest.
- Estimating the amount of plant material and traits related to yield.

Drone based monitoring is especially helpful when manual scouting is slow takes much timer or is not consistent. In India not having enough workers affects tasks like spraying and putting in fertilizer and drones can do these things faster while also making sure workers are not exposed to chemicals. However high costs for equipment not training, lack of infrastructure and rules about using drones are still big problems for people to use them (Singh *et al*; 2025).

2. Autonomous ground machinery: Autonomous or semi- autonomous machine learning:

- GPS- guided tractors
- Robotic
- Planters
- Automated weeders
- Robotic sprayers
- Harvesters
- Robotic sprayers
- Harvesters
- Robotic platforms for checking plants and monitoring crops.

j. Helps for drivers during tilling, planting and working between rows.

These machines help with not having workers by doing tasks usually need many workers or experiences tractor drivers. They can work for times keep the same depth and spacing when they work and need less help from workers who are only around during certain times of the year. Agricultural robotics research shows that robots can do sensing and work in the fields at specific times and places while using less human help (Vougioukas *et al*; 2019).

Importance for Climate-Resilient Farming

Not having enough workers becomes harder when the weather changes because hot days, unexpected rain and sudden pest problems often give farmers very little time to do work in the fields. Autonomous systems can help farmers.

1. Finish planting before the soil gets too dry.
2. Put on chemicals right after finding a disease or pests.
3. Put on chemicals right after finding after finding a disease or pests.
4. Manage watering during dry times.
5. Check areas after bad weather
6. Add things to parts of the field that are under stress or have pests.
7. Finish harvesting on time during times when it might rain or get too hot.

Using thermal or RGB pictures can help look at how hot the plants are ow green they are, how much plant material is there is, when they flower, if they fall over and how long they stay green. Autonomous machines can then take pictures from places where people usually look but they don't need as much help from people. This kind of robot checking can help test different types of plants to find which ones can handle tough conditions.

Challenges and Future Directions

1. High costs for buying equipment, software and training are all still too much for medium sized farms (Taneja *et al*; 2023, Nautiyal *et al*; 2025)
2. Scaling us is not easy: small farmers often don't have internet, good equipment or the skills to use fancy computer models (Ali *et al*; 2025).
3. Keeping data safe is a problem when companies that use AI collect farm data, which might let others use it in ways (Ali *et al*; 2025, Padhiary *et al*; 2024).
4. Algorithms might not help everyone as they are usually made using data from farms, not small or organic ones (Ali *et al*; 2025).
5. Not being able to use the system in different places is a big challenge since each field is different making it hard to collect data and use models (Linaza *et al*; 2025).

Lightweight models, edge AI and shared learning are suggested to make it easier for farmers who don't have money (Ali *et al*; 2025). Future research wants to look at how to use learning from one place to order robots that understand farming using different ways to see the world and big computer models that are made just for farming (Ge *et al*; 2025). Human-centered AI systems want to keep farmers in charge of decisions because some things that are easy for people are still hard for AI. This is an idea for the new agriculture 5.0 idea (Holzinger *et al*; 2024).

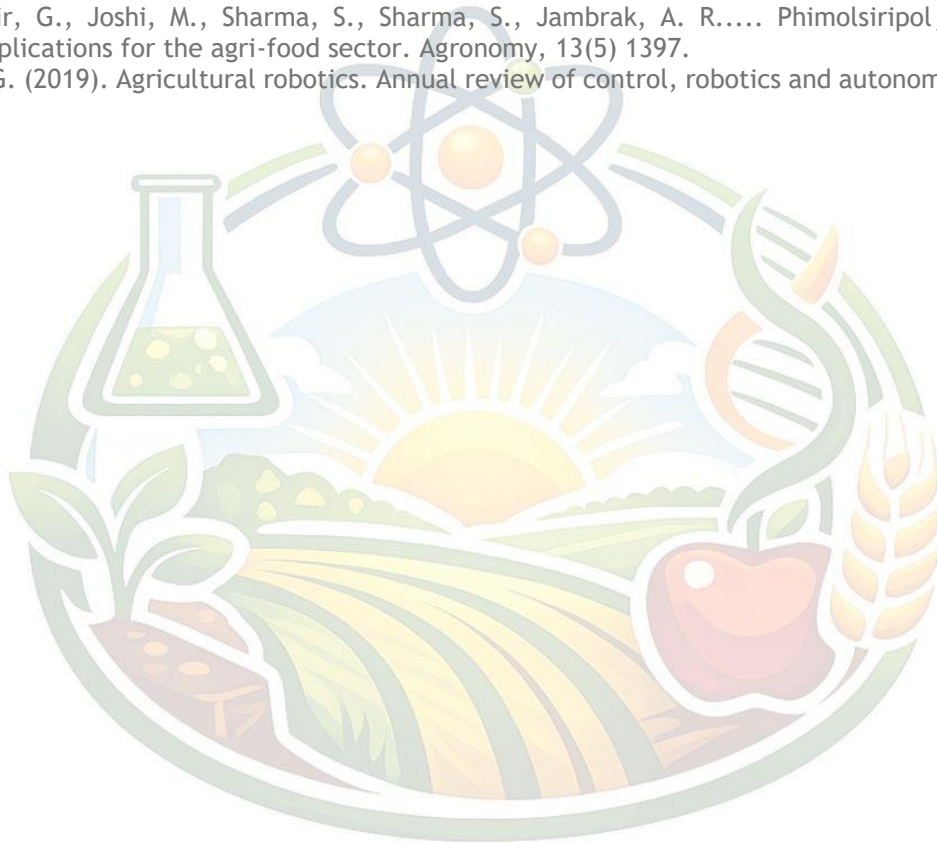
Conclusion

Instead of individual ownership, technology as a service is typically the most inclusive option for small holder agriculture. Drones and autonomous equipment are available to farmers through agricultural universities, cooperatives, farmer-producer associations, custom- hiring centers or qualified private service providers. Drone pilots, machinery technicians, data analysts, and agricultural advisors all gain new jobs as a result of lower expenditures. Therefore, autonomous machinery and drones should be seen as instruments for precision, timeliness and labor augmentation. Rather than relying solely on automation, their success will depend on cost effective service models, farmer training, trustworthy local validation, ad integration with agronomic expertise.

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Agricultural Waste Valorization and Resource Recovery: Advancing Agroecological Sustainability

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Abstract

As a vital component of circular bioeconomy, agricultural wastes play a crucial role. The present article, therefore, describes a suitable waste-to-wealth framework by valorizing the agricultural wastes and subsequent resource recovery. By utilizing different physical, chemical, and biological processes, these underutilized biomasses can be converted into biochar, biofuel, etc. or can be processed into valuable inputs/products like nano-silica, nutraceuticals, etc. However, full-scale adoption relies heavily on overcoming logistical constraints like feedstock seasonality through emerging technologies and biorefinery integration.

Introduction

The generation of large volume of agricultural wastes has become a global serious concern nowadays. This is due to the problems of existing traditional disposal methods like open burning and land filling, etc. which are responsible for ecological degradation (Khan et al., 2024; Yadav et al., 2024). Therefore, utilization of these agricultural wastes to develop some products and technologies useful for attaining agricultural and environmental sustainability adopting the "waste to wealth" approach is a need of the hour (Mukhopadhyay et al., 2024). This strategic move actually shows a new path toward a circular bioeconomy where the underutilized biomass will be converted into valuable assets for sustainable farming as well as other sectors.

The present article gives an insight into these diverse agro-wastes rich in lignocellulosic matrices including crop husks, straws, peels and agro-industrial byproducts. The conversion of these materials through integrated chemical, thermochemical and biochemical pathways into different value-added products have also been highlighted (Mehdizadeh et al., 2025). The value-added products such as biochar, bioplastics, biofuels, etc. have been reported along with their production and application protocols. Several resources such as cellulose nanocrystals, lignin and silica nanoparticles, and different nutraceuticals can also be obtained from these agro-wastes utilizing suitable extraction protocols (Chakraborty et al., 2023). Therefore, subsequent resource recovery strategies have been outlined in the present article with the aim of developing low cost technologies. Furthermore, the techno-economic assessments and life-cycle analyses to demonstrate the feasibility of "zero-waste" systems in reducing carbon footprints and enhancing rural economic resilience have been evaluated. By bridging the gap between waste management and industrial biotechnology, this article provides a strategic framework for stakeholders to optimize resource efficiency and promote sustainable agricultural intensification, addressing fundamental processes involved, management strategies, along with highlighting the challenges and future outlooks to ultimately ensure the enhancement of agricultural productivity without compromising the ecological integrity.

Types and Compositions of Agricultural Wastes

Agricultural wastes are generated after harvesting and post-harvesting operations. This may include crop residues, fruit peels, agro-industrial by-products. These materials are rich mainly in cellulose, hemicelluloses, lignin, and in some cases nutraceuticals. Based upon the compositional variations, agricultural residues are used for various operations.

Biomass Valorization Techniques

It refers to the conversion of agro-wastes into useful products, energy, and materials through various physical, chemical, and biological processes (Kataya et al., 2023), which are as follows:

Table 1: Representative examples of biomass valorization techniques:

Name of process	What is it?	Techniques	Applications
Physico-chemical Conversion	It refers to the utilization of the physical and chemical methods together to convert the agricultural biomass in to valuable products.	- Hydrolysis - Acid/alkali treatment - Solvent extraction - Densification	These techniques are widely used to extract cellulose, lignin, and nutraceuticals from agro-residues.

Thermo-chemical Conversion	These techniques use heat in presence or absence of oxygen to transform the biomass in to energy and carbon-rich materials.	• Pyrolysis • Torrefaction • Combustion • Gasification	These techniques are used for production of the biochar, bio-oil, syn gas.
Biological Conversion	These methods utilize micro-organisms or enzymes to degrade or decompose biomass.	• Vermicomposting • Anaerobic digestion • Fermentation	These techniques are used for production of vermicompost, biogas, bioethanol, organic acids.

Value Added Products and Resource Recovery from Agricultural Wastes

To date, numerous value added products as well as resources recovery strategies have been developed from agricultural crop residues/ wastes (Kover et al., 2022), the representative examples of which have been summarized in the table below.

Table 2: Representative examples of value added products and resource recovery from agricultural wastes:

Type	What is it?	Applications
Value-added Product		
Biochar	Carbon-rich charcoal-like material, produced by heating the biomass in nearly anaerobic environment	Soil amendment, carbon sequestration, environmental remediation
Agri-residue reinforced hydrogel	Super-absorbent polymers reinforced with agri-wastes	Soil amendment
Biofuel	Any fuel which has been derived from biomass.	Transportation fuel, industrial and domestic heating
Resource Recovery		
Cellulose nano-crystals	Nano sized cellulose mainly in crystalline condition, generally obtained from agri-wastes by chemical or biological modifications	Smart packaging, environmental cleanup, rheology modifier
Nano-silica	Silica in nano sized form, generally obtained from rice straw and husk	Reinforcing agent, nano-fertilizer
Lignin particles	Natural biopolymer, obtained from agri-wastes	Anti-oxidant additive, carbon fiber feedstock, asphalt extender
Nutraceuticals	Health-promoting bioactive compounds, obtained from fruit peels, husks, pomace, crop residues	Immune modulation, functional food

Environmental and Economic Benefits

The agro-waste valorization and subsequent resource recovery is a step forward toward agro-ecological sustainability. These approaches not only reduce the environmental pollution, but also improve the resource use efficiency, carbon sequestration, and renewable energy production (El-Ramady et al., 2022). It also creates additional income source for the farmers, supports rural agro-based industries, reduces waste management costs, and finally accelerates circular bioeconomy.

Challenges

The major challenges in successful utilization of agricultural wastes for valorization and resource recovery purposes are as follows:

1. Seasonal availability of biomass
2. Collection of biomass and its transportation costs
3. Variability in feedstock compositions
4. Technological limitations
5. Economic feasibility at large scales.

Conclusion and Future Outlook

Agricultural wastes should be considered as valuable renewable sources rather than disposal problems. Successful utilization of these materials may lead to generate several valuable agri-inputs. However, more focus should be given on different aspects such as integrated biorefineries, green extraction techniques, nanotechnology-based interventions, artificial intelligence-assisted process optimization, etc. for large scale adoption of these waste valorization and resource recovery technologies.

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Cashew Apple for Food Reformulation: From an Underutilized Fruit to a Functional Food Ingredient

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Introduction

Food reformulation is increasingly being used as a strategy to develop healthier and more sustainable foods. The World Health Organization (WHO) describes food reformulation as altering the processing or composition of a food or beverage to improve its nutritional profile or reduce ingredients or nutrients of concern (World Health Organization [WHO], 2022). Reformulation may involve reducing saturated fat, trans-fat, sugars or salt while maintaining desirable sensory, technological and safety characteristics (WHO, 2022). In recent years, the concept has expanded towards the use of naturally derived ingredients that can improve nutritional quality while providing technological functionality. In this context, the cashew apple represents an interesting and underutilized resource.

Cashew is primarily cultivated for its kernel, while the fleshy cashew apple attached to the nut remains comparatively underutilized. The pseudofruit contains sugars, dietary fibre, vitamin C, minerals and phenolic compounds (Reina et al., 2022; van Walraven & Stark, 2024). During juice extraction, a considerable quantity of fibrous pomace is generated, which can be converted into a value-added food ingredient (Aidoo et al., 2022; van Walraven & Stark, 2024). Thus, cashew apple can be positioned not simply as a fruit or processing residue, but as a multifunctional ingredient for food reformulation.



Cashew apple



Cashew apple pomace



Cashew apple pomace powder

What Does Food Reformulation Mean?

Food reformulation involves modifying the composition or processing of an existing food to achieve a desirable nutritional or functional outcome while maintaining product quality. Importantly, changes in formulation can affect processing behaviour, physicochemical characteristics, sensory quality and food safety (WHO, 2022). For example, a conventional product may be reformulated by replacing part of a conventional ingredient with a nutritionally or technologically advantageous ingredient. With increasing emphasis on sustainable food production, circular economy and healthier food choices, cashew apple is receiving renewed attention as a raw material for food reformulation. Cashew apple offers several possibilities through its different fractions, including juice, pulp, powder, fibre and cashew apple pomace powder (CAPP) (Aidoo et al., 2022; van Walraven & Stark, 2024).

Why Cashew Apple for Food Reformulation?

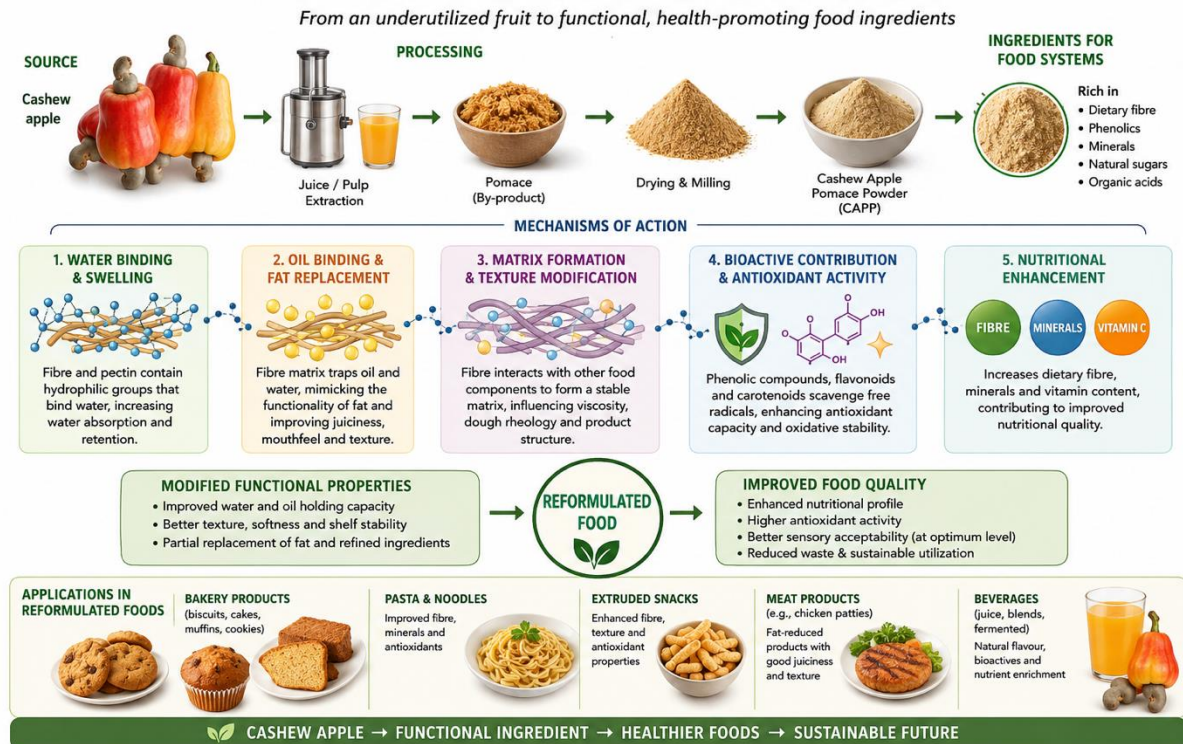
Cashew apple contains dietary fibre, sugars, vitamin C, minerals and phenolic compounds, while its pomace retains substantial quantities of fibre and other bioactive constituents. The fibre-rich nature of CAPP is particularly important from a food-formulation perspective. CAPP has demonstrated appreciable water-absorption and oil-absorption capacities, which can influence hydration, moisture retention and the structure of formulated foods. Therefore, cashew apple-derived ingredients may contribute simultaneously to:

1. Dietary fibre enrichment;
2. Phenolic and bioactive compound enrichment;
3. Water binding;
4. Oil binding;
5. Texture modification;
6. Partial ingredient replacement; and

7. Utilization of a food-processing by-product (Aidoo et al., 2022; van Walraven & Stark, 2024).

This multifunctionality makes cashew apple particularly attractive for food reformulation.

CASHEW APPLE IN FOOD REFORMULATION: MECHANISM OF ACTION



Cashew Apple as a Potential Fat-Replacement Ingredient

One of the most promising applications of cashew apple in food reformulation is fat replacement. Fat provides several technological functions, including mouthfeel, tenderness and structural modification. Therefore, successful fat reduction requires an ingredient capable of compensating for some of these functions.

Cashew apple fibre has been investigated as a fat replacer in meat products. Pinho et al. (2011) evaluated cashew apple residue as a fibre source in low-fat hamburgers and reported that its incorporation influenced dietary fibre content, cooking yield and lipid-related characteristics. Similarly, Guedes-Oliveira et al. (2016) investigated washed cashew apple fibre as a fat replacer in chicken patties. The fibre demonstrated useful water-binding characteristics and supported the development of reformulated products with acceptable sensory properties. Nishad et al. (2026) investigated cashew apple pulp and cashew apple juice as natural fat replacers in muffins. Fat replacement levels of 25, 50, 75 and 100% were evaluated, and incorporation of cashew apple ingredients resulted in substantial reductions in fat content while modifying the nutritional, physicochemical, and sensory characteristics of the muffins. These findings demonstrate that cashew apple can function not only as a nutritional ingredient but also as a matrix-modifying ingredient in reduced-fat foods. Its fibre and water-binding characteristics can contribute to moisture retention and structural development (van Walraven & Stark, 2024). Thus, the objective of cashew apple-based fat reformulation should not be simply to remove fat, but to replace part of the fat functionality while simultaneously improving the nutritional profile of the product. The appropriate replacement level, however, needs to be optimized for each food matrix because excessive incorporation may adversely affect texture, flavour, colour and consumer acceptability (Osei et al., 2025).

Table 1. Applications of cashew apple-derived ingredients in food reformulation:

Part of cashew used	Matrix in which used	Findings	Reference
Cashew industrial product	agro-by-Sponge cake	Cashew agro-industrial by-product, with cashew tree gum, was evaluated as a fat replacer. Partial and complete fat replacement maintained acceptable physicochemical and sensory characteristics, demonstrating its potential for developing lower-fat sponge cakes.	Nascimento et al. (2026)
Cashew apple pulp and juice	Eggless muffins	Cashew apple juice enabled up to 25% fat replacement in muffins while maintaining acceptable sensory quality.	Nishad et al. (2026)

Cashew pomace (CAPP)	apple powder	Biscuits	Incorporation of CAPP improved nutritional and antioxidant properties of biscuits. Up to 10% CAPP replacement of wheat flour maintained high consumer acceptability.	Osei et al. (2025)
Cashew apple flour		Cookies	Incorporation of cashew apple flour into wheat-based cookies increased dietary fibre and improved nutritional value without adversely affecting sensory acceptability.	Gunasekara et al. (2025)
Cashew powder	apple powder	Cookies	Replacement of maida with 5% cashew apple powder produced cookies with favourable sensory characteristics, although increased substitution affected browning index and hardness.	Thul et al. (2025)
Cashew apple fibre		Plant-based foods	Cooking treatments, particularly frying and combination-oven cooking, influenced retention of bioactive compounds in cashew apple fibre. Its incorporation into plant-based foods provided antioxidant functionality.	Sucupira et al. (2020)
Cashew apple fibre (CAF)		Chicken patties	CAF functioned effectively as a fat replacer while maintaining appearance, texture, flavour, juiciness and overall acceptability. Moisture, protein and ash contents were not significantly affected.	Guedes-Oliveira et al. (2016)
Cashew apple residue powder		Low-fat hamburgers	Partial replacement of meat/fat components with cashew apple residue increased dietary fibre and produced a lower-fat hamburger with good nutritional quality.	Pinho et al. (2011)
Cashew apple by-products		Doughnuts	Cashew by-products were incorporated into doughnuts as a fat-replacement ingredient, demonstrating the potential for converting cashew processing residues into value-added food products.	Gyedu-Akoto (2011)

Challenges before Commercial Application

Despite its potential, several challenges need to be addressed before commercial application. Variability in cashew apple composition due to cultivar, maturity and processing conditions necessitates raw material and process standardization. Astringency can limit incorporation levels and consumer acceptance. The high perishability of fresh cashew apple also requires effective preservation and drying technologies. In powders, particle size and processing conditions can affect hydration, texture and sensory quality. Finally, nutritional and antioxidant properties demonstrated in laboratory studies should not be directly equated with clinical health benefits, which require further validation.

Conclusion

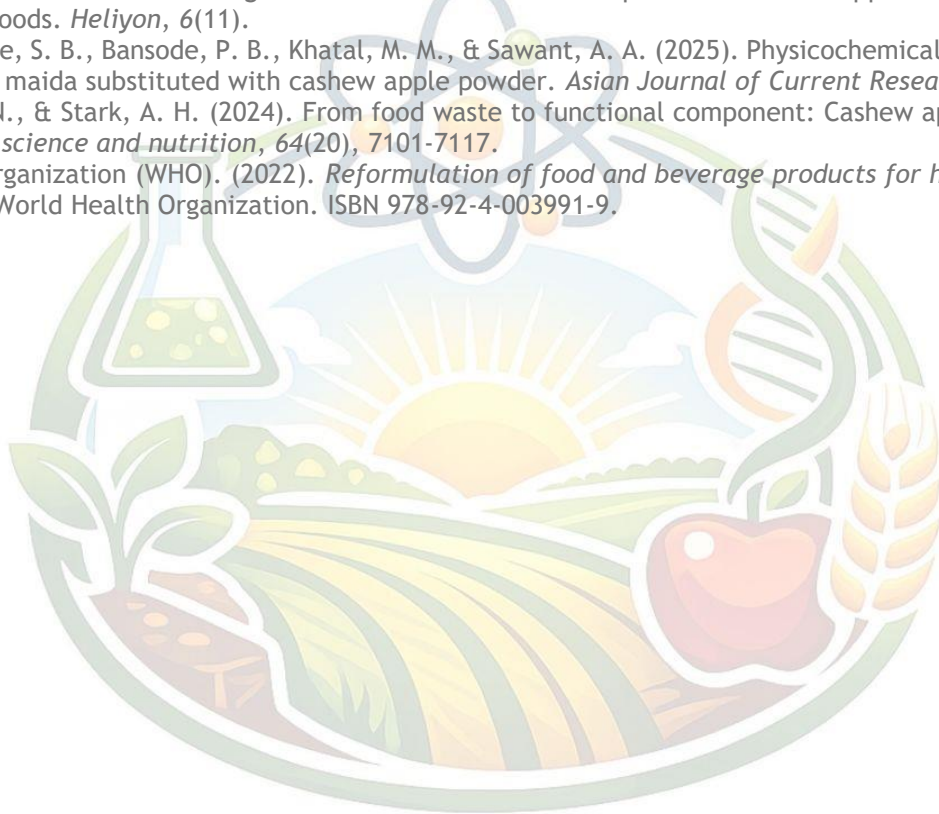
Cashew apple represents an underutilized component of the cashew value chain with considerable potential for food reformulation and ingredient innovation. Its conversion into pulp, juice, powder and pomace powder creates multiple opportunities for improving the nutritional and functional characteristics of foods. The emerging research demonstrates that cashew apple-derived ingredients can be used in bakery products, snacks and other food systems and can contribute fibre, minerals and bioactive compounds. Its potential as a fat-replacement ingredient further expands the scope of reformulation. The challenge now is to develop standardized, sensory-acceptable, shelf-stable and economically viable processing technologies that can transform this seasonal resource into commercially useful food ingredients. The cashew apple therefore represents much more than the fruit attached to a cashew nut. It is an opportunity to redesign the cashew value chain-one ingredient, one product and one formulation at a time.

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From Ocean to Medicine: How Seaweeds are Changing Healthcare

Article ID: 74454

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Introduction

Some of the most promising therapeutic compounds are found not on land, but beneath the waves. Covering more than 70% of the planet, oceans are home to extraordinary forms of life, including coral reefs, seaweeds, micro and macro algae, which have supported the marine ecosystem and coastal communities for centuries as food and traditional remedies.

Today, seaweeds are gaining widespread recognition as a natural reservoir of bioactive compounds with immense potential in modern health care. These compounds are rich in polysaccharides, polyphenols, and pigments, which exhibit a wide range of uses and biological activities, including anti-inflammatory, antioxidant, antimicrobial, antiviral, and neuroprotective properties. Researchers around the world have exploited the use of these compounds for developing safer and more effective therapies that can benefit the treatment of chronic diseases and improve overall health.

Besides their health benefits, seaweeds play a meaningful role in nutrition; they even help with environmental sustainability, and they support the emerging blue economy, which makes them, in practice, one of the most multifaceted marine resources. In a way, seaweeds are already changing how we think about healthcare and sustainable medicine, from functional foods and nutraceuticals all the way to advanced medication delivery systems and tissue engineering.

This article focuses on the surprising evolution of seaweeds from the ocean's depths into the leading edge of biomedical innovation, and it highlights how these marine organisms are pushing forward the future of global healthcare.

Meet the Ocean's Green Gold: What are Seaweeds?

Seaweeds often get mixed up with seagrasses, yet they are different in a basic sense. Seagrasses are real flowering plants; they have roots, stems, leaves, and even make flowers and seeds. Seaweeds, however, reproduce by spores, and they have a simpler body structure, including a thallus. While seagrasses form underwater meadows that provide habitats for marine organisms, seaweeds create dense forests and beds that serve as ecological hotspots, supporting countless species of fish, invertebrates, and microorganisms.

So, depending on their pigments as well as biochemical makeup, seaweeds are generally grouped into three major categories:

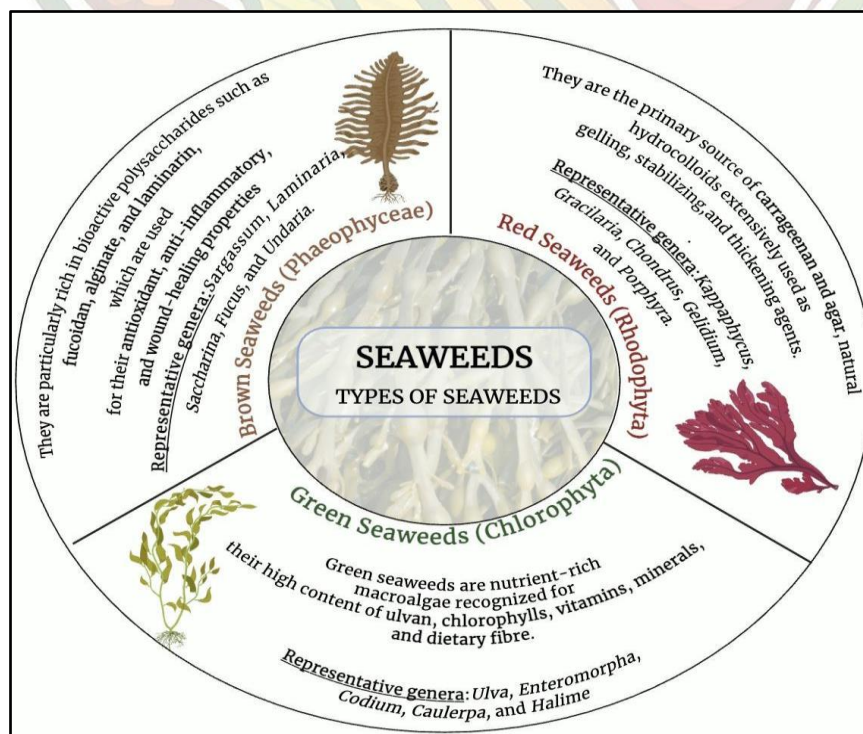


Figure 1: Diagrammatic representation of types of seaweeds

Brown seaweeds (Phaeophyceae) - generally known for a higher content of fucoidan, alginate, and laminarin. Brown types such as *Sargassum*, *Laminaria*, and *Undaria* are among the most thoroughly investigated for pharmaceutical and biomedical uses.

Red seaweeds (Rhodophyta) - Examples such as *Kappaphycus*, *Gracilaria*, and *Chondrus* are valued because they can make carrageenan and agar; these materials are commonly used across food, medicine, and biotechnology areas.

Green seaweeds (Chlorophyta) - species in the genus *Ulva*, also called sea lettuce, tend to be rich in ulvan plus vitamins, minerals and antioxidants. That combination makes them useful for nutraceutical and biomedical work.

Nature's Pharmacy: The Bioactive Wealth of Seaweeds

The rising curiosity about seaweeds goes way beyond just ecological and nutritional values; rather, their real scientific value is in how well they can synthesise a whole range of bioactive molecules. Since seaweeds are fixed marine organisms, they live in settings where salinity keeps shifting, temperature fluctuates, ultraviolet radiation is intense, nutrients can become scarce, and they are constantly surrounded by microbial communities. In order to cope and survive these hard circumstances, they generate secondary metabolites and also some structurally unique biomolecules, which act as natural armour against environmental pressure, pathogens, and herbivores. These adaptive compounds have attracted significant scientific interest due to their diverse biological activities and potential applications in human healthcare.

Marine macroalgae potentially serve as a vast source of biologically active compounds, which typically include polysaccharides, polyphenols, pigments, proteins, peptides, lipids, vitamins, minerals, and essential fatty acids. Together, these substances showcase a wide range of pharmacological benefits, including antioxidant, anti-inflammatory, antimicrobial, antiviral, anticancer, antidiabetic, and neuroprotective properties. As a result, seaweed has become a significant source of natural products for creating pharmaceuticals, nutraceuticals, cosmeceuticals, and advanced biomaterials.

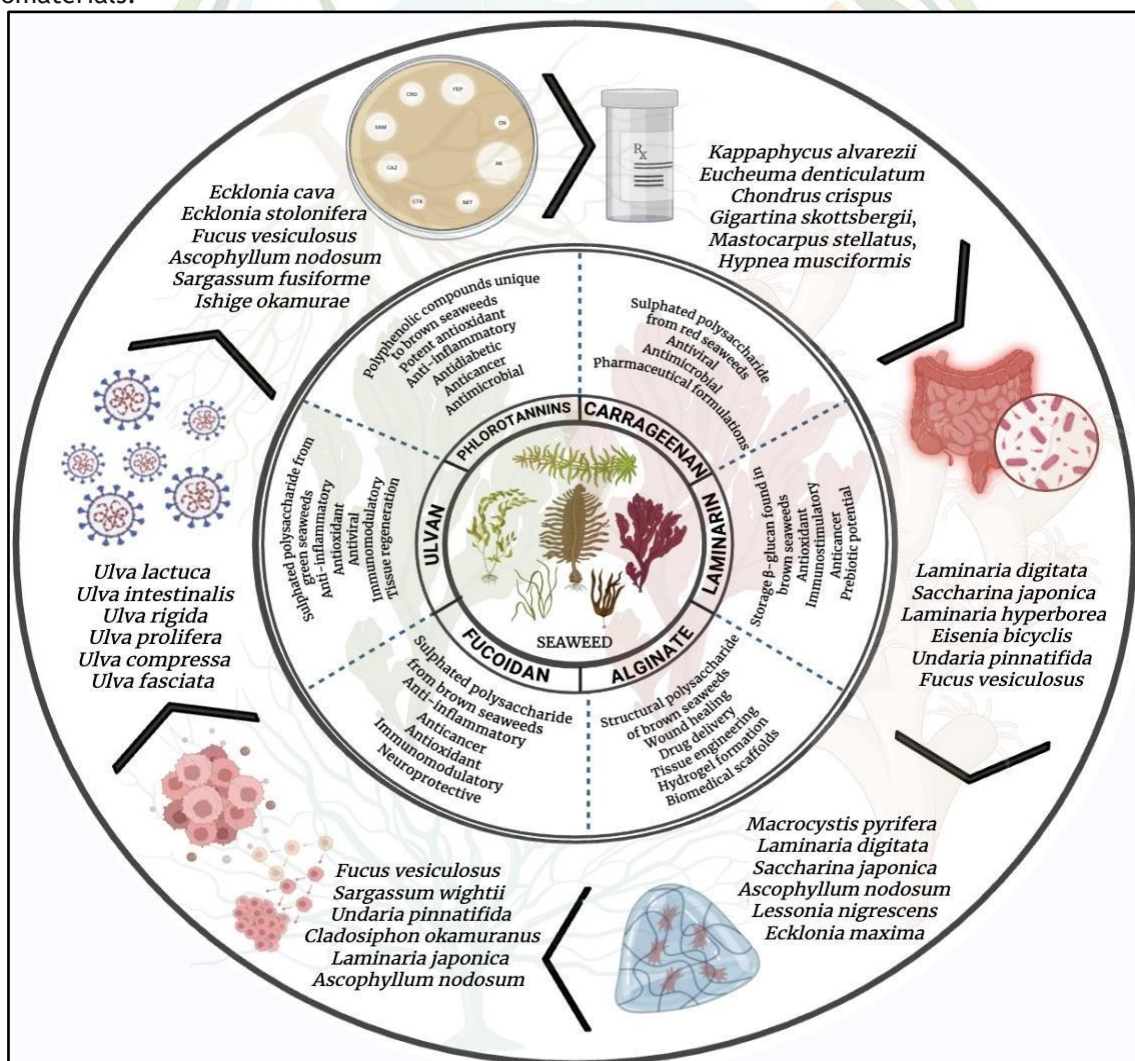


Figure 2: Major bioactive compounds derived from seaweeds, their representative marine sources, and principal biomedical applications.

Among the diverse classes of marine metabolites, sulphated polysaccharides have received the most scientific attention, mostly because their structural complexity is remarkable and they show varied multifunctional biological properties. Brown seaweeds are generally rich in fucoidan, alginate, and laminarin, while carrageenan comes mainly from red seaweeds and ulvan is typical of green seaweeds. Then, there are also brown seaweeds, which are a notable source of phlorotannins, a distinctive family of marine polyphenols that are well known for strong antioxidant activity and a broad therapeutic promise. Each of these compounds possesses distinct physicochemical characteristics that contribute to their specific biological functions and biomedical applications.

The rather impressive range of bioactive compounds that come from marine sources has put seaweeds on the map as a very promising natural resource for today's biomedical research. Their specific chemical structures and their multifunctional properties have driven a lot of studies that look into their role in wound healing, targeted drug delivery, regenerative medicine, immune modulation, cancer care and even the management of several ongoing or degenerative illnesses. And as marine biotechnology continues to advance, it's expected that these naturally produced compounds will play an even bigger role in developing safer, more sustainable approaches and, more generally, innovative treatments.

Conclusion

Seaweeds have moved on from being treated as plain marine resources to becoming really valuable reservoirs of bioactive compounds, with huge promise for helping human health. They harbour a varied collection of polysaccharides, polyphenols, pigments, proteins and other biologically active molecules, which has opened up new breakthroughs in pharmaceuticals, nutraceuticals, regenerative medicine, drug delivery, and functional foods. Meanwhile, their contribution to environmental sustainability, climate resilience, and the whole blue economy also makes them matter well beyond healthcare.

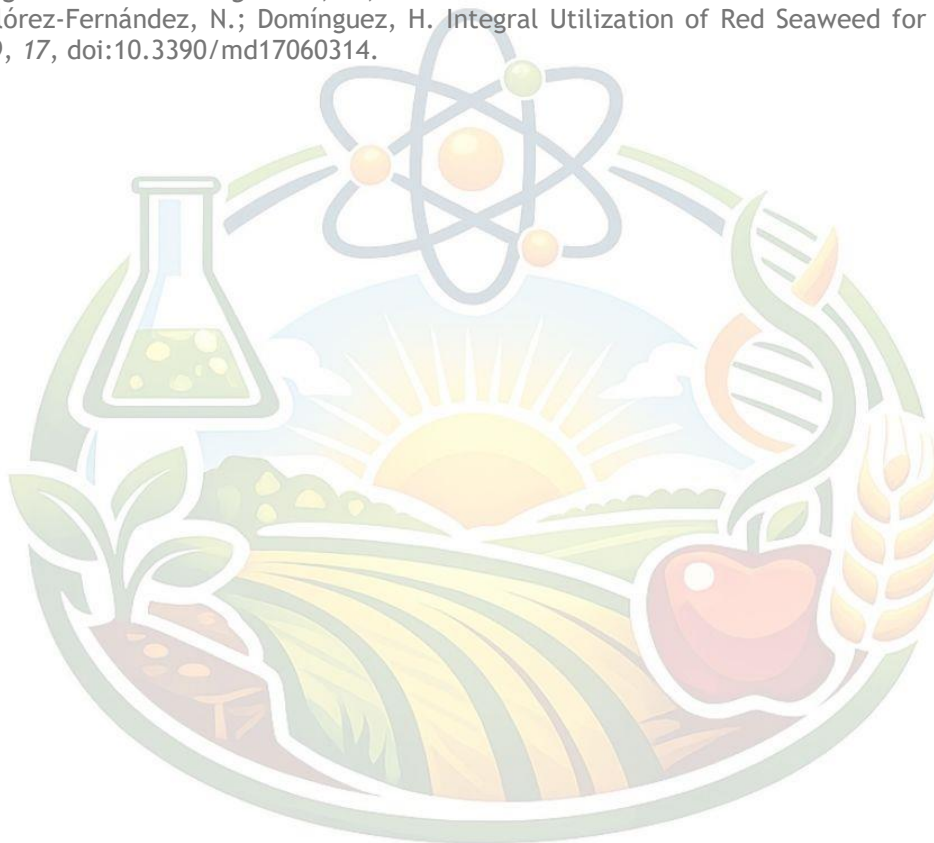
Still, there are obstacles like large-scale cultivation, standardization, and the need for more clinical validation, but marine biotechnology keeps pushing forward and widening the options for seaweed-based products. As studies start bridging the gap between what works in the lab and what can actually be used in clinics, these ocean macroalgae are ready to contribute a lot to safer, more sustainable, and nature-inspired therapeutic solutions.

"The ocean's oldest resources may hold the key to tomorrow's medicines."

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Nano-Enabled Agriculture: Role of Titanium Dioxide Nanoparticles in Improving Crop Tolerance to Salinity Stress

Article ID: 74455

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Introduction

Agricultural productivity is increasingly threatened by environmental stresses, among which soil salinity is one of the major constraints to crop production. Excess salts in soil reduce water availability, disturb nutrient uptake and cause toxic accumulation of ions such as sodium (Na^+) and chloride (Cl^-). Salinity also induces oxidative stress by increasing the production of reactive oxygen species (ROS), ultimately affecting photosynthesis, membrane stability, plant growth and yield.

Conventional approaches such as salt-tolerant varieties, proper irrigation, drainage and soil amendments remain essential for managing salinity. However, emerging technologies such as nanotechnology offer additional possibilities for improving crop resilience. Among various nanomaterials investigated in agriculture, titanium dioxide (TiO_2) nanoparticles have received considerable attention because of their potential effects on photosynthesis, antioxidant defence and stress adaptation.

Salinity Stress and Plant Responses

Salinity affects plants through two interconnected mechanisms. Initially, high salt concentration creates osmotic stress, which restricts water uptake and reduces cell expansion and growth. Subsequently, excessive uptake and accumulation of Na^+ and Cl^- cause ionic stress, disturbing cellular ion homeostasis and nutrient balance.

Salt stress also enhances ROS production. At controlled levels, ROS act as important signalling molecules; however, excessive accumulation can damage membrane lipids, proteins, pigments and nucleic acids. Plants counteract this damage through enzymatic antioxidants such as superoxide dismutase (SOD), catalase (CAT), peroxidase (POD) and ascorbate peroxidase (APX), along with non-enzymatic antioxidants and osmoprotectants such as proline and soluble sugars.

The ability of a crop to maintain water status, ion balance and redox homeostasis largely determines its tolerance to salinity.

Potential Role of TiO_2 Nanoparticles

TiO_2 nanoparticles possess a small particle size and a high surface-area-to-volume ratio, allowing them to interact with plants differently from conventional bulk TiO_2 . Research has shown that TiO_2 nanoparticles may influence several physiological and biochemical processes associated with plant growth and stress tolerance (Figure 1).

Improved photosynthesis: Salinity commonly reduces chlorophyll content and damages the photosynthetic apparatus. TiO_2 -based treatments have been associated with improved chlorophyll retention and photosynthetic performance in several plant species. Maintaining photosynthetic activity enables plants to continue producing carbohydrates required for growth and stress recovery.

Regulation of oxidative stress: One of the important effects associated with TiO_2 nanoparticles is modulation of the antioxidant system. Nanoparticle treatment can stimulate antioxidant enzymes including SOD, CAT, POD and APX, thereby helping plants maintain ROS at controlled levels.

SOD converts superoxide radicals into hydrogen peroxide, while CAT and APX contribute to subsequent detoxification of hydrogen peroxide. This coordinated antioxidant response can reduce oxidative damage to cellular membranes and other biomolecules.

Osmotic adjustment: Plants exposed to salinity often accumulate compatible solutes such as proline and soluble sugars to maintain cellular water balance. Nanoparticle-mediated changes in osmolyte accumulation have been reported in different crops and may contribute to improved cellular hydration and stress adaptation.

Maintenance of ion balance: Maintaining a favourable Na^+/K^+ ratio is an important component of salt tolerance. Excess Na^+ can interfere with potassium-dependent metabolic processes. Emerging research suggests that nanomaterials may influence ion uptake, transport and cellular homeostasis, although the underlying mechanisms remain an active area of investigation.

Molecular regulation: Salinity tolerance involves complex molecular networks containing ion transporters, transcription factors, antioxidant genes, heat-shock proteins and other stress-responsive genes. Nanoparticle treatments may modify the expression of genes involved in these pathways.

This molecular perspective is particularly important because physiological improvements observed after nanoparticle application may ultimately arise from changes in cellular signalling and gene regulation.

Bulk TiO₂ versus Nano TiO₂: An important research question is whether nanoscale TiO₂ provides advantages over conventional bulk TiO₂. Due to their smaller size and greater surface area, nanoparticles can have stronger biological interactions than bulk materials. Several studies have reported greater physiological responses from nano-TiO₂ than from conventional TiO₂.

However, nano-TiO₂ should not be considered universally superior. Its effects depend on particle size, concentration, crystalline structure, application method, crop species, genotype and environmental conditions. Importantly, increasing the concentration does not necessarily increase the beneficial effect. Excessive nanoparticle concentrations may cause phytotoxicity.

Therefore, dose optimization is a prerequisite for responsible agricultural application.

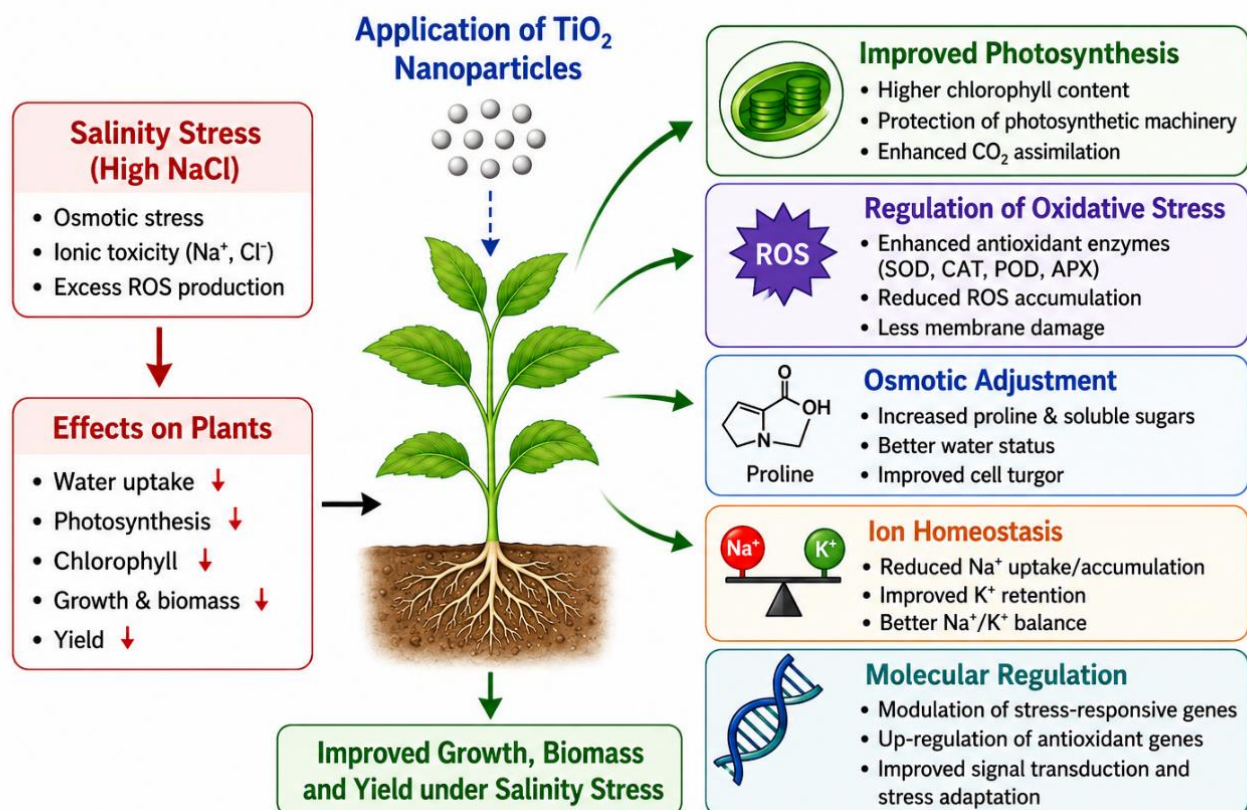


Figure 1. Role of TiO₂ nanoparticles in improving crop tolerance to salinity stress.

Application in Sustainable Agriculture

TiO₂ nanoparticles can potentially be applied through seed treatment, foliar application or root-zone treatment. Seed priming is particularly attractive because it can influence germination and early seedling development, while foliar application provides direct exposure to photosynthetic tissues.

Nevertheless, most nanoparticle studies have been conducted under controlled laboratory or greenhouse conditions. Before recommending nanoparticle-based treatments to farmers, their effectiveness must be validated under field conditions.

Future studies should focus on:

1. Crop- and genotype-specific nanoparticle concentrations;
2. Uptake and translocation mechanisms;
3. Long-term effects on soil health;
4. Interactions with beneficial soil microorganisms;
5. Possible accumulation in edible plant tissues;
6. Field-scale performance; and
7. Environmental and food-safety assessment.

Future Prospects

The future of nano-enabled agriculture lies in precision application rather than indiscriminate use of nanomaterials. The objective should be to identify the appropriate nanoparticle, concentration, application method and developmental stage for a particular crop and stress condition.

Combining nanotechnology with salt-tolerant cultivars, efficient irrigation, soil-management practices and molecular breeding could provide an integrated strategy for improving crop resilience under increasing environmental stress.

For plant scientists, an important research direction is to connect changes in plant growth and biochemical traits with molecular responses. Understanding how TiO₂ nanoparticles influence ROS signalling, antioxidant defence, ion transport, photosynthesis and stress-responsive genes will help in developing more reliable nano-enabled agricultural technologies.

Conclusion

Soil salinity is a complex challenge requiring integrated and scientifically validated solutions. TiO₂ nanoparticles represent a promising research tool for improving plant responses to salinity, particularly through their potential effects on photosynthesis, antioxidant defence, osmotic adjustment, ion balance and molecular regulation.

However, their effects are strongly dose- and crop-dependent, and higher concentrations may produce adverse effects. Therefore, optimization, field validation and environmental safety assessment are essential before large-scale agricultural adoption.

Nano-enabled agriculture should ultimately aim not simply to increase nanoparticle use, but to develop precise, safe and scientifically optimized technologies for climate-resilient crop production.

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The Biochemical Shield of Plants: How Antioxidants and Osmolytes Help Crops Survive Salinity

Article ID: 74456

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Introduction

Plants continuously face environmental challenges such as salinity, drought, heat and extreme temperatures. Among these stresses, soil salinity is particularly damaging because it affects water uptake, nutrient balance, photosynthesis and ultimately crop productivity.

When salt concentration increases around plant roots, plants experience an immediate water deficit followed by ionic stress caused mainly by excessive accumulation of sodium (Na^+) and chloride (Cl^-). Salinity also disturbs cellular metabolism and stimulates the production of reactive oxygen species (ROS).

Plants have evolved an internal biochemical defence system to minimize this damage. This system includes antioxidant enzymes, osmoprotectants, phenolic compounds, flavonoids and other protective metabolites (Figure 1). Together, these compounds form a biochemical shield that helps plants maintain cellular stability under adverse conditions. Recent reviews identify antioxidant defence, compatible solutes and ion homeostasis as major components of plant salinity tolerance.

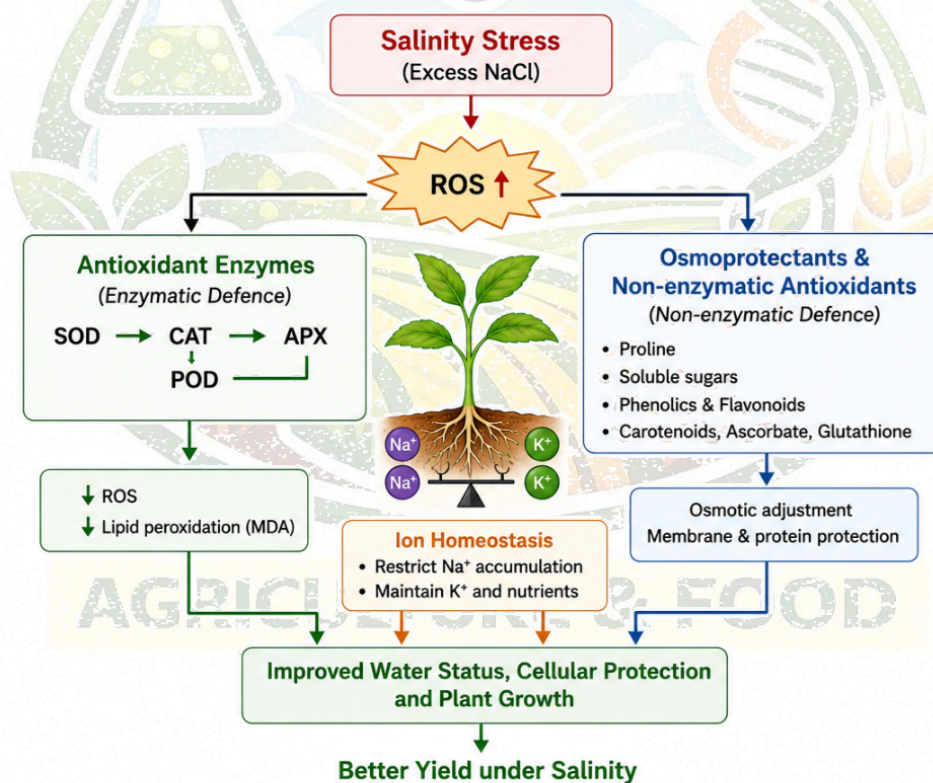


Fig. 1. Biochemical defence mechanisms of plants under salinity stress. ROS: reactive oxygen species; SOD: superoxide dismutase; CAT: catalase; APX: ascorbate peroxidase; POD: peroxidase; MDA: malondialdehyde.

Figure 1. Biochemical defence mechanisms of plants under salinity stress. ROS: reactive oxygen species; SOD: superoxide dismutase; CAT: catalase; APX: ascorbate peroxidase; POD: peroxidase; MDA: malondialdehyde.

What Happens Inside a Salt-Stressed Plant?

Under normal conditions, plants produce small amounts of ROS as part of normal metabolism. These molecules also participate in signalling and cellular regulation.

Under severe salinity, however, ROS production can increase considerably. Important ROS include superoxide radicals (O_2^-), hydrogen peroxide (H_2O_2) and hydroxyl radicals ($OH\cdot$).

When ROS production exceeds the plant's detoxification capacity, oxidative stress develops. Excess ROS can attack membrane lipids, proteins, pigments and nucleic acids.

One important indicator of membrane damage is malondialdehyde (MDA), a product associated with lipid peroxidation. Therefore, increased MDA generally indicates greater oxidative damage, whereas effective stress tolerance is often associated with better control of lipid peroxidation.

Antioxidant Enzymes: The First Line of Defence

Plants possess a sophisticated antioxidant enzyme system that continuously removes or controls excess ROS.

Superoxide dismutase: Superoxide dismutase (SOD) is considered one of the first enzymatic lines of defence. It converts superoxide radicals into hydrogen peroxide and oxygen.

Different forms of SOD occur in plants, including Cu/Zn-SOD and Mn-SOD, which are distributed in different cellular compartments.

Catalase: Catalase (CAT) converts hydrogen peroxide into water and oxygen. It is particularly important when hydrogen peroxide production is high.

Peroxidase: Peroxidases (POD) contribute to hydrogen peroxide removal and participate in several processes associated with cell-wall metabolism and stress responses.

Ascorbate peroxidase: Ascorbate peroxidase (APX) uses ascorbate as an electron donor to detoxify hydrogen peroxide. APX is an important component of the ascorbate-glutathione cycle, which provides a coordinated system for maintaining cellular redox balance.

The activities of SOD, CAT, POD and APX therefore work together rather than independently. A strong antioxidant response allows plants to control ROS while retaining their role as signalling molecules.

Recent research in lentil has demonstrated that improving antioxidant capacity can reduce oxidative injury under salt stress. For example, a 2025 study reported that arginine treatment enhanced antioxidant components including CAT and APX and improved ionic and water balance in salt-stressed lentil plants.

Osmoprotectants: Protecting Cells from Dehydration

Salinity reduces the availability of water to plant roots. To maintain cellular water balance, plants accumulate compatible solutes, also called osmoprotectants.

Important osmoprotectants include:

- a. Proline
- b. Soluble sugars
- c. Raffinose-family oligosaccharides
- d. Sugar alcohols
- e. Certain amino acids and related metabolites

These compounds help maintain cellular osmotic balance without interfering with normal biochemical reactions.

Proline: Proline is one of the most widely studied osmoprotectants. Its accumulation under salinity can help stabilize proteins and membranes, maintain cellular water status and contribute to ROS regulation.

However, increased proline should not automatically be interpreted as proof of greater tolerance. In some situations, proline accumulation represents a stress response, while in tolerant plants it may form part of a more effective protective system. Therefore, proline should ideally be evaluated together with growth, water status, oxidative damage and antioxidant activity.

Soluble sugars: Soluble sugars perform several functions during stress. Besides providing energy, they contribute to osmotic adjustment and can stabilize cellular structures.

Recent research has highlighted the importance of low-molecular-weight carbohydrates in lentil adaptation to abiotic stresses. Raffinose-family oligosaccharides and sugar alcohols are considered potential targets for future stress-tolerance breeding.

Phenolics and Flavonoids: The Non-Enzymatic Defence

Plants also rely on non-enzymatic antioxidants. Phenolic compounds and flavonoids can participate in ROS scavenging and protection against oxidative damage.

Flavonoids are particularly interesting because they can act as antioxidants and also participate in signalling and regulation of plant responses to environmental stress.

The combined action of phenolics, flavonoids, carotenoids, ascorbate and glutathione provides an additional layer of protection alongside antioxidant enzymes.

Thus, plant defence can be visualized as a coordinated system:

Salt stress → ROS production → antioxidant enzymes + protective metabolites → reduced oxidative damage → improved cellular survival

Maintaining Water and Ion Balance

Biochemical defence cannot work independently of physiological processes. A salt-tolerant plant must also maintain adequate water status and ion homeostasis.

Excess Na^+ can interfere with potassium (K^+), calcium (Ca^{2+}) and magnesium (Mg^{2+}) uptake. Maintaining a favourable Na^+/K^+ balance is particularly important because potassium is required for numerous enzymatic and metabolic processes.

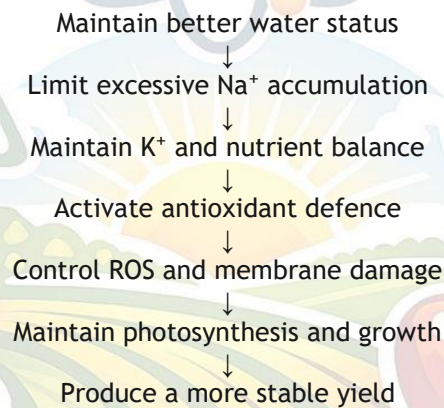
Recent research in lentil has shown that treatments capable of reducing Na^+ accumulation while improving K^+ and other nutrient levels can substantially improve salt-stress responses.

This demonstrates an important principle: salinity tolerance is not controlled by a single biochemical compound or enzyme. It results from the coordinated functioning of water relations, ion regulation, antioxidant defence and metabolism.

What can farmers and Breeders Learn from these Responses?

Understanding biochemical responses provides useful information for crop improvement.

A salt-tolerant genotype may be able to:



These traits can be used together with conventional morphological characteristics to identify promising genotypes.

Biochemical screening can therefore complement field evaluation and molecular approaches. Measurements such as chlorophyll, relative water content, proline, MDA, phenolics, flavonoids, SOD, CAT, POD and APX can provide valuable information about how plants respond to stress.

From Biochemical Screening to Climate-Resilient Crops

Modern crop improvement increasingly combines physiology, biochemistry, molecular biology and genomics. Biochemical traits can help researchers identify physiological mechanisms associated with stress tolerance, while molecular approaches can identify the genes controlling these responses.

In lentil, recent research is expanding beyond simple yield measurements toward understanding the biochemical and genetic mechanisms that determine adaptation to stressful environments. Genomics-based approaches are being explored to identify the genetic basis of physiological traits associated with abiotic stress tolerance.

Such integration will be particularly important as climate change increases the frequency and severity of environmental stresses.

Conclusion

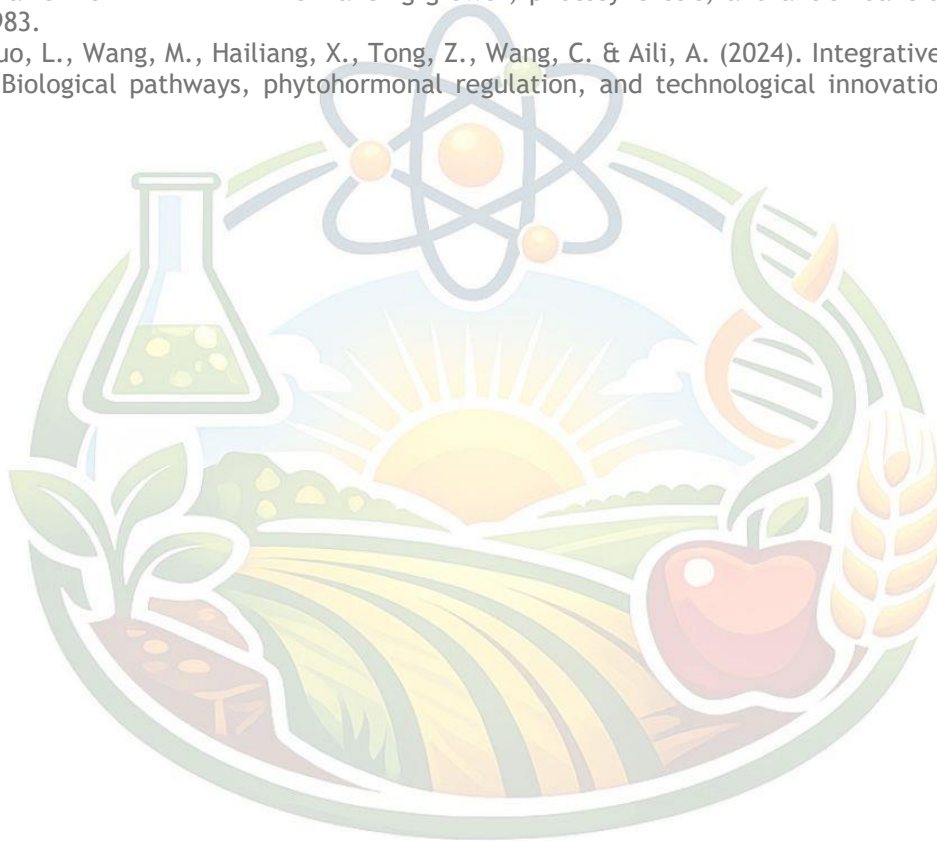
Plants possess a remarkable biochemical defence system that allows them to survive periods of salinity stress. Antioxidant enzymes such as SOD, CAT, POD and APX control excessive ROS, while osmoprotectants such as proline and soluble sugars help maintain cellular water balance. Phenolics and flavonoids provide additional non-enzymatic protection.

However, no single biochemical parameter can fully explain salt tolerance. Successful adaptation results from the coordinated regulation of water relations, ion homeostasis, antioxidant defence, osmotic adjustment and metabolism.

For future agriculture, combining these biochemical indicators with molecular markers, genomics, breeding and innovative crop-management technologies offers a promising pathway toward developing productive and climate-resilient crops for salt-affected environments.

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How Plants Fight Salinity Stress: The Molecular Machinery Behind Salt Tolerance

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Introduction

Salinity is one of the major environmental stresses limiting crop productivity. Excess salts in the soil reduce water availability, disturb nutrient balance and cause toxic accumulation of sodium (Na^+) and chloride (Cl^-). At the cellular level, salinity also increases the production of reactive oxygen species (ROS), which can damage membranes, proteins, pigments and nucleic acids.

Plants, however, are not passive victims of salt stress. They possess a sophisticated molecular signalling network that senses changes in cellular conditions and activates protective mechanisms. These responses involve ion transporters, calcium signalling, antioxidant systems, osmoprotectants and stress-responsive transcription factors.

Understanding these molecular mechanisms is important for developing salt-tolerant crop varieties through conventional breeding, marker-assisted selection, genomics and biotechnology.

How do Plants Sense Salt Stress?

The first step in salt tolerance is stress perception. Salinity rapidly changes the osmotic and ionic environment around plant cells. These changes trigger intracellular signals, including alterations in cytosolic calcium (Ca^{2+}), ROS and phytohormones such as abscisic acid (ABA).

Calcium acts as an important messenger. Salt-induced changes in cytosolic Ca^{2+} are detected by calcium-sensing proteins, which activate downstream signalling proteins and ultimately modify gene expression. Thus, a change in the external environment is converted into a molecular response inside the cell (Figure 1).

One of the best-characterized pathways involved in this process is the SOS (Salt Overly Sensitive) pathway.

SOS Pathway: Controlling Sodium Toxicity

The SOS pathway is a central molecular system for maintaining cellular ion balance under salinity.

The classical pathway involves three major components: SOS3, SOS2 and SOS1. Salt stress induces changes in cytosolic Ca^{2+} , which are sensed by SOS3. The activated SOS3 interacts with SOS2, a protein kinase. This complex activates the plasma-membrane Na^+/H^+ antiporter SOS1, which facilitates Na^+ extrusion from the cell.

In simple terms:

Salt stress $\rightarrow \text{Ca}^{2+}$ signal $\rightarrow \text{SOS3} \rightarrow \text{SOS2} \rightarrow \text{SOS1} \rightarrow \text{Na}^+$ extrusion $\rightarrow$ improved ion homeostasis

Recent research has shown that the SOS pathway is more complex than the original three-component model. Several upstream and downstream regulators can modify the activity, stability and localization of SOS proteins.

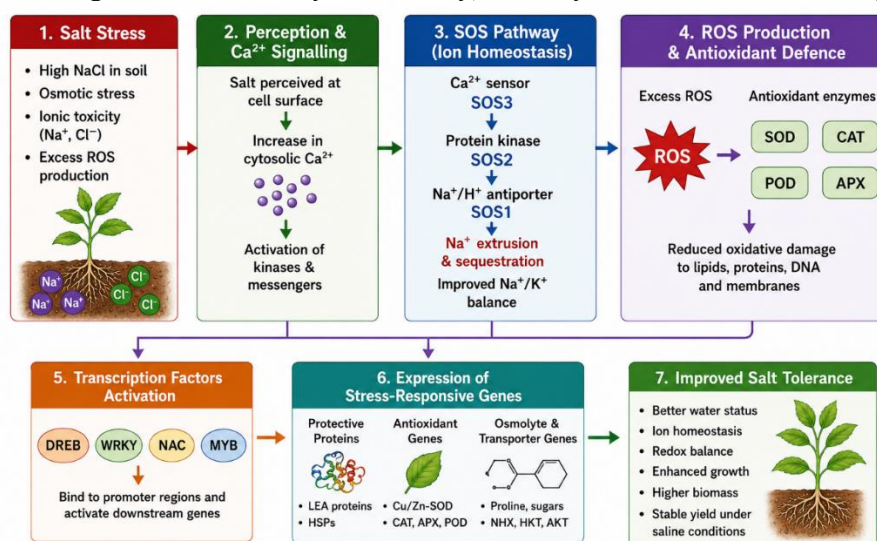


Figure 1. Overview of molecular mechanisms underlying plant tolerance to salinity stress.

Other ion transport systems, including NHX and HKT proteins, also contribute to Na⁺ sequestration, transport and distribution within the plant. Together, these mechanisms help maintain a favourable cellular Na⁺/K⁺ balance.

Reactive Oxygen Species: Damage and Signalling

Salt stress commonly increases ROS production. Important ROS molecules include superoxide radicals, hydrogen peroxide and hydroxyl radicals.

Excess ROS can cause oxidative damage, but ROS are not simply harmful molecules. At controlled concentrations, they also act as signalling molecules that help plants activate defence responses.

Plants maintain ROS homeostasis through antioxidant enzymes such as:

- a. Superoxide dismutase (SOD)
- b. Catalase (CAT)
- c. Peroxidase (POD)
- d. Ascorbate peroxidase (APX)

SOD converts superoxide radicals into hydrogen peroxide, while CAT and APX contribute to its subsequent detoxification. Therefore, salt tolerance depends not on eliminating ROS completely but on maintaining an appropriate redox balance between ROS production and antioxidant capacity.

Transcription factors: turning stress signals into gene responses.

A major molecular component of salt tolerance is the activation of transcription factors (TFs). These proteins bind specific DNA sequences and regulate the expression of multiple downstream genes.

Several transcription-factor families are important in abiotic stress responses, including: DREB, WRKY, NAC, MYB, bZIP and AP2/ERF.

DREB (Dehydration-Responsive Element Binding) transcription factors regulate genes associated with drought, dehydration and salinity responses. They can activate downstream stress-protective genes, including genes encoding LEA proteins and other protective molecules.

The **WRKY family** represents an important group of plant-specific transcription factors. WRKY proteins regulate networks involved in stress signalling, antioxidant defence and hormonal responses. Recent studies have highlighted their important role in salt and saline-alkali stress tolerance.

NAC and MYB transcription factors also participate in regulating stress-responsive genes, including those involved in ROS detoxification, osmotic adjustment and cellular protection.

Because one transcription factor can regulate several downstream genes, these proteins are attractive targets for developing stress-resilient crops.

Protective Genes and Stress Proteins

Molecular responses to salinity extend beyond transcription factors. Plants activate genes encoding proteins that protect cellular structures and maintain metabolic functions.

LEA (Late Embryogenesis Abundant) proteins can protect cellular components during dehydration and osmotic stress. **Heat-shock proteins (HSPs)** act as molecular chaperones and help maintain protein stability under adverse conditions.

Genes encoding antioxidant enzymes such as **Cu/Zn-SOD, Mn-SOD, APX and CAT** also contribute to maintaining cellular redox balance.

Similarly, genes involved in osmolyte biosynthesis can promote the accumulation of compounds such as **proline and soluble sugars**, which help stabilize proteins, membranes and cellular water status.

From Genes to Salt-Tolerant Crops

The molecular complexity of salinity tolerance explains why developing salt-tolerant crops is challenging. Salt tolerance is generally a **multigenic trait**, controlled by interactions among many genes and pathways rather than a single "salt-tolerance gene."

Modern molecular technologies are helping researchers understand these networks more effectively. Techniques such as RT-PCR, qRT-PCR, RNA sequencing, genome-wide association studies and gene editing can identify candidate genes and regulatory pathways associated with stress tolerance.

Transcriptomic studies in lentil, for example, have identified stress-responsive pathways associated with ion regulation, ABA signalling and cellular protection, demonstrating the value of combining molecular data with physiological and biochemical observations.

Such information can support breeding programmes aimed at developing cultivars capable of maintaining productivity under saline conditions.

A Promising Future for Molecular Breeding

The future of salt-tolerant agriculture will increasingly depend on integrating plant physiology, molecular biology, genomics and breeding.

Instead of selecting plants only on the basis of visible growth under salt stress, researchers can identify molecular markers and genes associated with desirable traits such as efficient Na⁺ exclusion, better K⁺ retention, enhanced antioxidant capacity and improved osmotic adjustment.

Gene-editing technologies may further provide opportunities to modify specific components of salt-response pathways. However, molecular modifications must be evaluated carefully because stress-response pathways are interconnected with plant growth and development.

The ultimate goal is therefore not maximum stress response, but a balanced response that protects the plant while maintaining productivity.

Conclusion

Plants respond to salinity through a highly coordinated molecular defence system. The SOS pathway helps regulate Na⁺ homeostasis, calcium signalling connects salt perception with downstream responses, antioxidant genes control oxidative stress, and transcription factors such as DREB and WRKY regulate networks of stress-responsive genes.

Understanding these mechanisms provides a foundation for developing crops with improved salt tolerance. The integration of molecular biology with conventional breeding, genomics and modern biotechnology offers a promising route toward climate-resilient and productive agriculture.

For researchers, the next major challenge is to translate molecular discoveries obtained under controlled laboratory conditions into stable salt tolerance under real field environments.

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Applications of Cold Plasma in Dairy Processing

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Introduction

High-quality protein, fatty acids, carbohydrates (lactose), and a variety of micronutrients, including trace elements, vitamins, and minerals, are all found in milk. Dairy products are regarded as health-promoting foods for the prevention or mitigation of osteoporosis, metabolic syndrome, cardiovascular disease, cognitive decline, and digestive issues in addition to their nutritional value (Coutinho et al., 2018). Effective preservation is crucial since milk's nutrient-rich nature makes it extremely vulnerable to microbial contamination and deterioration. Pasteurization, UHT, and sterilization are examples of conventional thermal treatments that are frequently used to increase microbiological safety and prolong shelf life. However, the sensory, nutritional, and physicochemical qualities of dairy products may be negatively impacted by high heat.

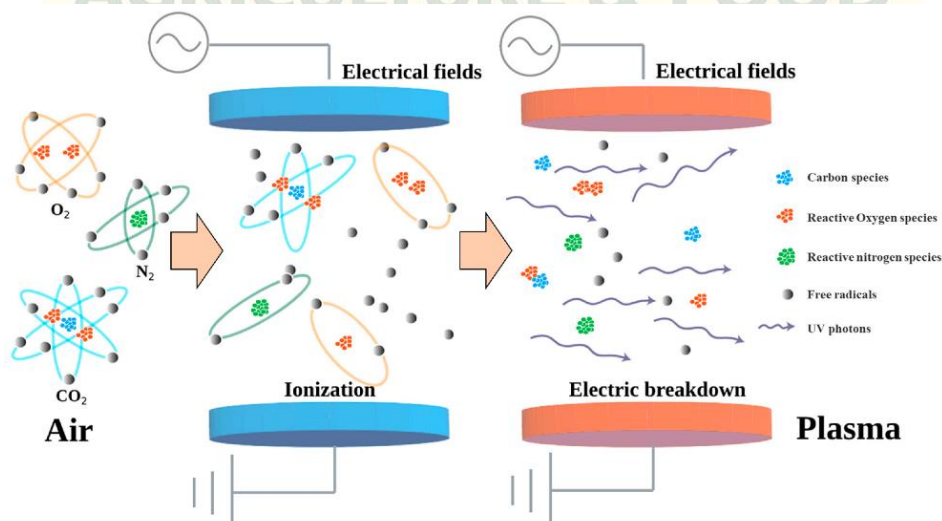
The development of non-thermal food processing technologies has accelerated due to growing consumer demand for fresh, minimally processed, and high-quality foods. Non-thermal processes can meet microbial food safety standards and enhance the physical, nutritional, and sensory qualities of the products, preserving unstable bioactive compounds and modulating enzyme activity. One promising alternative is cold plasma (Coutinho et al., 2018). This article explores the principles of cold plasma technology, its applications in dairy processing, and its potential to transform the dairy industry.

What is Cold Plasma and How Does it Work?

Plasma is the fourth state of matter after solids, liquids and gases. Irving Langmuir coined the term plasma in 1928 and described it as a partially or completely ionized gas. Cold plasma is a non-thermal, partially ionized gas containing reactive species such as electrons, ions, free radicals and excited molecules, generated at near room temperature.

Plasma is created when a gas receives enough energy to cause some of its atoms and molecules to become ionized. Free radicals, neutral atoms, positive and negative ions, and activated molecules make up plasma. Cold plasma is produced by using the temperature of the surrounding air. By exposing a variety of gases to electric fields, including thermal, microwave, radio frequency, direct current, alternating current (higher frequency), and magnetic fields, they can be transformed into plasma. It creates plasma particles that clash with higher kinetic energy, including electrons, free radicals, and ions. In the plasma system, there is no net charge. A number of variables, including supply gas proportion, surrounding phase, power, humidity, and voltage level, affect plasma variations.

In the context of microbial inactivation, electrostatic forces build up at the point of maximum energy when food surface contamination is exposed to reactive species produced by plasma. Cell lysis is the result of much increased radical bombardment activity brought on by the energy flow. Heavy bombardment causes surface damage, which prevents the pathogenic bacteria cell from quickly healing itself and ultimately results in cell death. "Plasma etching" is the term for this. DNA and chemical linkages are denatured by plasma etching, giving the cell an antibacterial action (Harikrishna et al., 2023).



Applications in the Dairy Industry

Cold plasma is among the most promising non-thermal alternatives in modern dairy processing. Being a treatment at or near room temperature, it ensures the destruction of the spoilage microorganisms and the pathogens with minimal effects on the nutritional and sensory properties of milk and dairy products (Misra et al., 2016).

A variety of plasma sources have been directly tested on milk, and a significant log-reduction of the *E. Coli* count in whole, semi-skimmed, and skimmed milk was achieved by a Corona discharge without changing pH and color (Gurol et al., 2012). Treatment of raw and pasteurised milk with argon gas plasma for 2 min reduced *E. Coli* levels up to several log cycles, with the inhibitory effect remaining after 6 months in cold storage (Ponraj et al., 2017). The Dielectric barrier discharge (DBD) plasma application leads to microbial inactivation levels comparable to those obtained with UHT treatment, with no detrimental impact on the nutritional components of the milk matrix (Wu et al., 2021). Sliced cheese is the object of numerous studies, due to its large surface-to-volume ratio that facilitates plasma treatment.

Complete inactivation of *E. Coli*, *L. Monocytogenes*, and *S. Typhimurium* in cheddar and processed cheese slices was reported when treating with DBD plasma, obtaining reductions in several log cycles, as a function of treatment time (Yong et al., 2015a, 2015b). Treatment with Atmospheric pressure plasma has shown reductions up to 8 log cycles in *L. Monocytogenes* count in sliced cheese (Song et al., 2009).

Cold atmospheric plasma was applied to non-fat dry milk powder to inactivate *Cronobacter sakazakii* (especially important in infant formula), with results between 1.17 and 3.27 log cfu/g for treatments carried out with varying time and gas flow rates (Chen et al., 2019).

Packaging sterilization is another emerging application of cold plasma. It is possible to disinfect plastic bottles, lids, pouches and cartons with cold plasma in pre-filling operations, avoiding the use of water or chemical sanitizers, thus leading to no harmful residue and reduced chances of post-processing contamination (Pankaj et al., 2018).

Cold plasma is also highly effective in biofilm removal. Biofilms are an undesirable issue for food processing equipment. Conventional cleaning techniques can be insufficient to remove microbial biofilm. The reactive plasma species can penetrate these protective layers and kill the embedded microorganisms, ensuring a cleaner environment for the food process and reducing contamination risk (Gupta et al., 2019).

In addition to food processing, the use of cold plasma to treat dairy wastewater is also being explored. The reactive oxidizing species produced by the plasma can break down organic compounds in wastewater, reduce microorganisms and chemical oxygen demand (COD), thereby ensuring a safe and environmentally sound disposal or reuse of this water stream (Thirumdas et al., 2018).

Benefits of Cold Plasma Technology

Cold plasma offers several advantages that make it attractive as a next-generation dairy processing technology. Most importantly, it delivers strong microbial inactivation – including bacteria, spores, and biofilms – while operating at near-ambient temperatures (30-60°C), sidestepping the heat-induced damage associated with pasteurisation and UHT treatment (Rathod et al., 2021). Because it avoids high heat, cold plasma better preserves milk's nutritional and sensory qualities, including proteins, vitamins, and flavour compounds, with several studies reporting minimal detectable changes in colour, pH, or taste after treatment (da Cruz et al., 2025).

Sustainability concerns When considered from an environmental perspective, cold plasma technology is referred as a “green” alternative since generally it does not requires water or chemicals sanitisers as opposed to conventional technologies and uses simple gases as process gases, generates no by-product, and requires relative less amount of energy since active species are generated only when the electric power is on and then disappear after power is turned off (Coutinho et al., 2018). Additionally, reduction in chemical use and compatibility with existing packaging systems is a benefit over current thermal treatment technologies (Coutinho et al., 2018).

Challenges and Future Prospects

Although cold plasma offers promising advantages in the food processing sector, it faces several challenges that hinder its wide industrial application. The equipment costs involved are rather expensive, especially when using noble gases like helium and argon, and scaling from lab to high-throughput industrial application is a technical challenge (Coutinho et al., 2018). Precise control of gas chemistry for products with different moisture content (in case of dairy products) is a challenge (da Cruz et al., 2025). A decrease in pH was observed in milk after 10 minutes of plasma treatment (Kim et al., 2015).

Regulatory approval of cold plasma treatment as an official ‘pasteurisation’ treatment method is lacking, as there is no standardized method, similar to the alkaline phosphatase test applied to evaluate the effectiveness of pasteurisation of milk, currently established for this technology (Coutinho et al., 2018). In addition, high fat content in products might lead to undesirable lipid oxidation and development of off-flavours when a prolonged treatment time is used; hence, the impact of treatment on consumers' perception is not sufficiently addressed (da Cruz et al., 2025).

Further development in efficient, cost-effective plasma generators and standardized treatment protocols, as well as additional research in extended storage studies of products treated by plasma, will be crucial for commercial viability of cold plasma as an alternative and/or complement to current thermal processes in dairy applications (Rathod et al., 2021).

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Green Dairy, Clean Future: Strategies for Carbon Neutrality in Food Processing

Article ID: 74459

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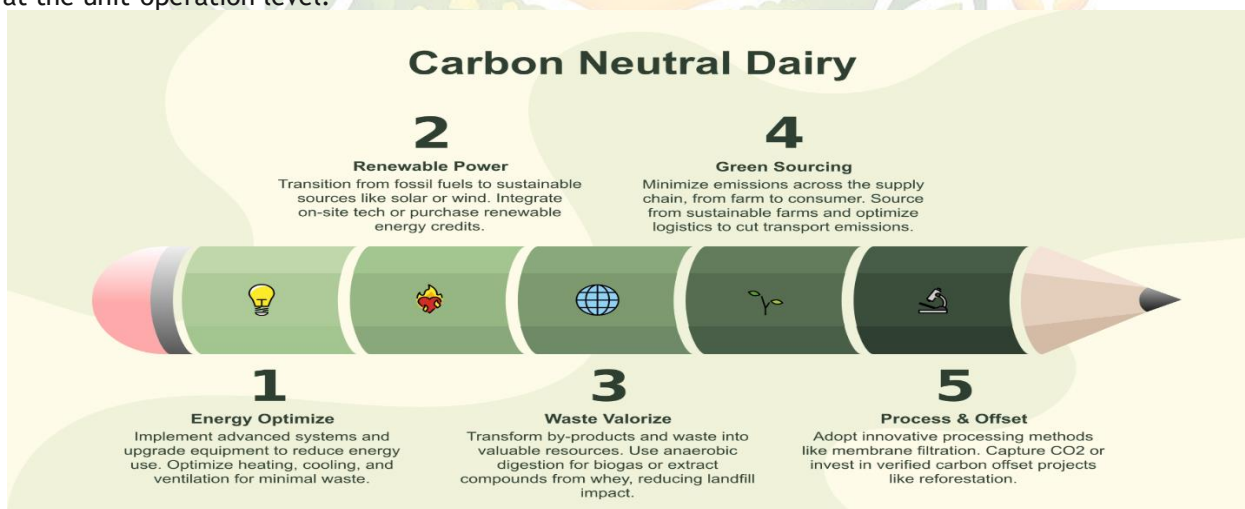
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Introduction

Dairy and food processing activities are inherently unit-operation heavy. Thermal treatment (pasteurisation, sterilisation, evaporation, drying), mechanical separation (centrifugation, membrane filtration) and chilled storage account for the bulk of a plant's energy requirement. Livestock supply chains, including dairy, are estimated by the FAO to be responsible for about 14.5% of anthropogenic GHG emissions globally, with dairy cattle alone accounting for an estimated 8% of overall livestock-sector emissions on a CO₂-equivalent (CO₂e) basis.

Life Cycle Assessment (LCA) studies following ISO 14040/14044 and the IDF (International Dairy Federation) common carbon footprint methodology consistently show the cradle-to-farm-gate carbon footprint of raw milk to be 1.1-1.4 kg CO₂e per kg of Fat-and-Protein-Corrected Milk (FPCM) in intensive systems, rising to 2.5-5 kg CO₂e/kg FPCM in extensive, low-input systems typical of much of South Asia and sub-Saharan Africa, where lower feed digestibility and higher enteric methane yield per unit of milk drive emissions intensity upwards. Processing processes add an additional 0.1-0.3 kg CO₂e/kg of product depending on the process route (liquid milk vs. milk powder vs. cheese), mostly from thermal energy and refrigeration.

This article reviews the process engineering, biochemical and systems level interventions available to move dairy and food processing operations towards net-zero. The article uses the GHG Protocol's Scope 1 (direct), Scope 2 (purchased energy) and Scope 3 (value chain) emissions framework as an organising structure to examine the sector's emissions profile at the unit-operation level.



Carbon Neutrality: Scope and Methodology

Carbon neutrality, as implemented in ISO 14064-1 (organisational GHG quantification) and PAS 2060 (carbon neutrality standard), involves:

1. Measuring a GHG inventory within defined bounds,
2. A reduction plan with verifiable targets, and
3. Offsetting residual emissions with credits that comply with recognised quality standards (e.g. Verified Carbon Standard, Gold Standard).

For a dairy processing plant the inventory would normally include:

a. Scope 1: Direct emissions from combustion of fuel consumed on-site (boiler fuel coal, furnace oil, natural gas, biomass), on-site car fleet and refrigerant leakage (fugitive emissions).

b. Scope 2: Indirect emissions from bought grid electricity consumed in refrigeration, homogenization, separation and packing processes.

c. Scope 3: upstream emissions from milk procurement (enteric fermentation, manure management, feed production) and downstream emissions from distribution, retail refrigeration and packing waste.

At the farm level, enteric methane and feed-related nitrous oxide (N₂O) emissions happen long before the milk arrives at the plant gate, therefore scope 3 is usually the largest source in the inventory for a dairy processor – generally 80-90% of the overall footprint. This has a direct significance for strategy: a processor cannot attain real carbon neutrality by simply improving in-plant efficiency; intervention has to be at the farm level.

Emissions Profile by Unit Operation

Value Chain Stage	Primary GHG(S)	Approx. Share	Key Driver
Enteric fermentation	CH ₄	45-55%	Rumen methanogenesis (feed fiber content, digestibility)
Manure management	CH ₄ , N ₂ O	10-15%	Anaerobic storage conditions, storage duration
Feed cultivation	N ₂ O, CO ₂	10-15%	Synthetic N-fertilizer application, land-use change
On-farm energy	CO ₂	3-5%	Diesel pumps, bulk milk cooler electricity
Processing (thermal)	CO ₂	5-8%	Boiler fuel for pasteurization, evaporation, drying
Processing (refrigeration)	CO ₂ , HFCs	3-5%	Compressor electricity, refrigerant GWP
Packaging	CO ₂	2-4%	Polymer production, multilayer laminates
Distribution / cold chain	CO ₂	3-6%	Reefer transport, retail display cooling

Approximate ranges compiled from IDF Bulletin 479/2016 methodology and representative LCA studies; actual shares vary by region, herd genetics, and product mix.

Enteric Methanogenesis: The Biochemical Basis

Methane is created in the rumen by archaeal methanogens (mostly *Methanobrevibacter* spp.) that decrease CO₂ with H₂ produced in the microbial fermentation of dietary fibre, serving as a metabolic “hydrogen sink.” Methane yield (g CH₄/kg dry matter intake) is affected by:

1. Fiber-to-concentrate ratio: Higher forage/fiber diets boost acetate synthesis (and concomitant H₂ availability), increasing methane yield relative to concentrate-heavy diets that favour propionate fermentation pathways.
2. Feed digestibility: Reduced digestibility leads to increased retention times and more fermentable substrate to the methanogens.
3. Rumen pH and retention duration. Increased passage rates and reduced rumen pH (within physiological limitations) can decrease methanogen activity.

Most of the feed-based mitigating techniques described below are based on this Biochemistry.

Process Engineering Interventions for Carbon Reduction

1. Thermal process: The two most common heat treatments of liquid milk are pasteurisation (HTST: 72 °C/15 s) and UHT sterilisation (135-150 °C/2-4 s), and both depend significantly on regenerative plate heat exchangers in which the incoming raw milk is preheated by the outgoing pasteurized/sterilized product . Properly constructed multi-section plate heat exchangers can achieve regeneration efficiencies of 90 to 95 percent, thus greatly lowering the net thermal energy input per unit product compared to earlier tubular or batch (vat) systems.

For evaporation and spray drying, the most energy-intensive unit operations in milk powder processing, often requiring 900-1,200 kWh thermal + electrical energy per tonne of powder, the following interventions have a noticeable impact:

Multi-effect evaporators (MEE) 5-7 effects, reduce the steam economy ratios of single effect systems, by recycling vapour generated in one effect to the next as the heating medium.

Mechanical Vapour Recompression (MVR): The vapour generated from the evaporator is recompressed and recycled as heating medium by a compressor. This results in a 70-85% reduction in steam consumption compared to traditional multi-effect systems but demands higher electricity consumption, making MVR most carbon-effective when combined with a decarbonised electricity supply.

RO pre-concentration before evaporation can raise the total solids in milk from ~13% to 18-20% before the evaporator, thus reducing the water load (and consequently energy) that the evaporator must remove by 25-35%.

2. Membrane separation: an approach to reduce energy consumption: Ultrafiltration (UF) and microfiltration (MF) at transmembrane pressures generally in the 1-6 bar range permit selective concentration and separation of milk proteins without the phase-change energy penalty of heat evaporation. Adopting UF/MF for goods like paneer, cheese base and

protein concentrates reduces the overall process energy intensity over the traditional thermal routes and also gives better product yield.

3. Design of Refrigeration Systems: Refrigeration (chilling, cold storage, retail display) is a constant source of both direct fugitive emissions (refrigerant leakage) and indirect Scope 2 emissions (compressor energy). Two engineering levers are relevant here:

Refrigerant choice: Using natural refrigerants such as ammonia (R717, GWP = 0), CO₂ (R744, GWP = 1) or propane (R290, GWP ≈ 3) instead of high-GWP HFCs (e.g. R-404A, GWP ≈ 3,900) greatly reduces the climate impact of leakage, which is typically 2-15% of system charge per year in poorly maintained systems.

Large dairy cold storages are increasingly using cascade refrigeration systems with CO₂ (low temperature circuit) and ammonia (high temperature circuit) to combine low GWP with high thermodynamic efficiency.

4. Valorisation of Waste Streams: Design parameters of Anaerobic Digestion: Dairy effluent (wash water, whey permeate) usually has a Chemical Oxygen Demand (COD) in the range of 4,000-80,000 mg/L depending on the process stream (whey alone might have >60,000-70,000 mg/L COD due to the presence of lactose and protein). Anaerobic digestion of this high-COD stream, in UASB (Up flow Anaerobic Sludge Blanket) or CSTR (Continuous Stirred-Tank Reactor) configurations, converts the organic load into biogas typically containing 55-65% CH₄ and 35-45% CO₂, with a methane yield of approximately 0.3-0.35 m³ CH₄/kg COD removed under mesophilic conditions (35-37 °C). The biogas produced after H₂S scrubbing and moisture removal can be directly used as a substitute for fossil boiler fuel or upgraded (via water scrubbing, pressure swing adsorption or membrane separation to >95% CH₄) to bio-CNG/bio-LNG standard for vehicular use. In addition, there is the avoidance of fugitive methane emissions from uncontrolled effluent decomposition (a major liability, as untreated organic effluent left in open lagoons or drains produces methane under anaerobic conditions without energy capture).

Feed Additive Technologies: Mechanisms and Efficacy Data

Additive	Mechanism	Reported CH ₄ Reduction
Asparagopsis taxiformis (seaweed)	Bromoform inhibits cobamide-dependent methyl-transferase step in methanogenesis	Up to 80-98% in vitro; 45-80% in vivo at 0.2-0.5% dry matter inclusion
3-Nitrooxypropanol (3-NOP)	Structural analogue blocks the active site of methyl-coenzyme M reductase	20-30% sustained reduction in lactating dairy cows
Condensed tannins	Direct antimicrobial action on methanogens + reduced fiber digestibility	10-20%
Nitrate supplementation	Competes with CO ₂ as alternative H ₂ sink	10-15%

Efficacy is based on dose and diet, and numerous additives (particularly 3-NOP sold as Bovaer®) have undergone regulatory approval processes (EFSA, FDA) demonstrating efficacy and safety for milk production parameters.

Renewable Thermal and Electrical Energy Integration

The heat demand of dairy processing is mainly between 60 and 150 °C, and thus matches well the output of solar thermal collectors (flat-plate collectors up to ~120 °C; evacuated tube collectors up to ~200 °C). In contrast, higher temperature industrial processes cannot be served practically by solar thermal. Hybrid systems - solar thermal pre-heating feedwater into biomass or grid-electric boilers - can displace 20-40% of yearly thermal fuel demand depending on solar resource and system sizing without the need to replace the entire boiler.

In most Indian industrial tariff categories, rooftop/ground-mounted solar PV under net-metering or open-access power purchase agreements (PPAs) is now cost competitive with grid electricity for electrical demand (compressors, homogenizers, separators, packaging lines), making renewable electricity substitution one of the more economically straightforward Scope 2 reduction levers available to processors.

Case Applications

Documented pilot and commercial-scale interventions relevant to this discussion include:

1. Biogas digesters at village level dairy cooperative societies for 2-10 m³/day gas generation from a herd of 5-20 animals, to meet cooking fuel requirements, reducing dependence on LPG/firewood and generating digestate as a substitute for organic manure.
2. MVR retrofit of milk powder factories, as described in industry technical literature to reduce specific steam usage from about 1.2-1.4 kg steam/kg water evaporated (traditional falling-film evaporator) to < 0.3 kg steam/kg water evaporated after retrofitting.

3. It is reported that biomass briquette boiler conversion, replacing furnace oil/coal with agricultural residue (rice husk, groundnut shell) briquettes, reduces net Scope 1 CO₂e emissions per unit of steam generated by 60-90%, depending on the biomass carbon-neutrality accounting assumptions and the residue transport distance.

4. Retrofits of natural refrigerants (ammonia/CO₂ cascade systems) in cold storage facilities, lowering direct GWP exposure and indirect emissions associated to electricity use due to improved coefficient of performance (COP) at standard dairy storage temperatures.

Technical Limitations and Constraints

1. MVR economics: The energy-for-steam trade-off of MVR makes its net carbon benefit sensitive to the grid emissions factor; the carbon case is weaker in coal-based grids until coupled with renewable electricity purchase.

2. Scalability of feed additive: Seaweed-based additives are limited by supply chain and cultivation scale limits; consistent dosing in smallholder, pasture-based feeding systems (common across much of South Asia) is logistically challenging compared to regulated total mixed ration (TMR) systems.

3. Digestate management: Proper management of land application is needed for anaerobic digestate to avoid simply transferring N₂O emissions downstream if over-applied as fertiliser.

4. Measurement, Reporting, and Verification (MRV): The lack of standardised, low-cost MRV tools prevents the quantification of farm-level emissions across millions of smallholder producers; most current Tier 1/Tier 2 IPCC methodology default emission factors result in significant uncertainty (± 20 -50%) compared to Tier 3 (activity-specific, measured) approaches.

Conclusion

Achieving carbon neutrality in dairy and food processing requires interventions distributed across the value chain, informed by process engineering fundamentals rather than generic sustainability messaging: regenerative thermal design and MVR/RO integration at the evaporator, refrigerant substitution and cascade system design in cold chain infrastructure, biochemically targeted feed additives addressing rumen methanogenesis directly, and anaerobic digestion engineered around the specific COD loading of dairy effluent streams. Because Scope 3 farm-level emissions dominate the sector's total footprint, plant-level efficiency gains while necessary are insufficient alone; durable progress depends on coupling processing-side engineering interventions with farm-level biochemical and management interventions, underpinned by robust MRV frameworks capable of verifying emissions reductions at scale.

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High-Density Cashew: The Smart Way to Boost Productivity

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Introduction

In our nation, cashews are a commercial crop that generates foreign income and are grown extensively in the states of Kerala, Maharashtra, Goa, Karnataka, Tamil Nadu, Andhra Pradesh, Orissa, the North Eastern provinces, and West Bengal. About 11.99 lakh hectares are used for cashew cultivation in our nation; from these, 7.94 lakh raw cashew nuts are produced, yielding a productivity of 674 kg per hectare (Anon., 2024). However, the level of productivity and production is extremely low. Productivity exceeds 2 tons/ha in other nations. We buy raw cashew nuts from other nations and have a processing industry in our nation that can process 15 to 20 tons of raw cashew nuts. To compensate for this, we need to increase production in India. Therefore, in the conventional system, the number of seedlings is low and one has to wait for 3 years for yield. The adoption of the dense planting system plays an important role in increasing production and productivity by planting more plants and obtaining faster yields. This article explains the information about the solid-state drive system in cashew.

High Density Cashew planting is a technique that maximizes productivity per unit area, particularly in the early years, by planting cashew trees closer together than in traditional methods. There are 625 trees per hectare are planted with a 4 m × 4 m spacing for high- density planting. It is necessary to plant appropriate cashew varieties in order to obtain a satisfactory yield from this planting method. The term "HDP" is always linked to training and pruning procedures, which are used to regulate excessive vegetative development and the early framework of the plant. Particularly during the first ten years of plantation ownership, HDP yields more than traditional planting techniques. Not every variety can be used with HDP. Only the pruning-responsive, semi-vigorous, and precocious varieties are suitable for HDP.

Concept of HDP

1. Maximum utilization of natural resources like solar radiation and Land.
2. To increase the productivity and quality of the produce.
3. To avoid congenial microclimate suitable for survival or breeding of pest and disease inoculum by proper pruning operation.

Selection of Site and Land Preparation

Cashews can be cultivated in every soil type, with the exception of black soil and areas that are flooded. Clear the area by getting rid of stubble, old trees, and stumps. If the land is flat, level it with a plow; if it slopes, create terracing across the slope. Two weeks before planting, the pits should be opened and exposed to sunlight to prevent termites, ants, and other insects. Digging a pit that measures 1x1x1 meters in length, width, and depth at a distance of 4x4 meters is advised. Add enough fertile soil to fill the pit two-thirds of the way. 5 kg of well-decomposed compost manure or chicken manure and 200 g of rock phosphate. Earlier they were following 5x5 m spacing, but as per the research experience, 4 m × 4 m is advantageous in the long run as compared to 5 m × 5 m.

Season, Method of Planting and Management

Grafts of particular cashew varieties should ideally be planted right in the center of the pit during the monsoon season, which runs from August to September. Planting can be done year- round if irrigation facilities are available. Life irrigation must begin immediately after planting. Staking is necessary for the graft to grow straight. Long-term moisture retention is possible with green manure mulching. Consequently, fewer irrigations will be required. Irrigation can be applied to trees from January to March using either basin irrigation at fortnightly intervals of 200 liters per tree or drip irrigation at 4-day intervals of 60 to 80 liters per tree. To reduce seedling mortality from waterlogging, suitable drainage should be provided during the rainy season.

Varieties Suitable for HDP

Not every cashew variety is suitable for a high planting density. According to the results of our research, we have identified a few varieties that are suitable for high-density planting systems. They are Bidhan Bonsai Kaju from the AICRP center Nidhan Chandra Krishi Vishwavidyalaya, West Bengal; VRI-3 from Vridachalam, Tamil Nadu; and NRCC selection 2, Nethra Ganga, who was released from the ICAR-Directorate of Cashew Research, Puttur and other varieties. These

types are semi-vigorous and very responsive to pruning, so we can give plants a good framework with heavy pruning, which will result in good cashew yields and flushes.

Training and Pruning

The cashew grafts are allowed to grow without side sprouts in the main stem up to 45-60 cm from the ground level to ensure a stronger trunk in later years. Regular shape pruning should be done to achieve an umbrella-shaped canopy with uniform spread. The growing tip should be pinched or nipped off to promote side branches or primary branches and subsequent secondary branches or laterals. Symmetrically, 3-4 primary branches are allowed in all 4 directions. The flowering and fruiting may start in the first or second year, depending on the precocious bearing nature of cashew varieties. Pruning is a year-wise operation required to be carried out immediately after harvest (May-June). The recommended height of pruning during the 1st and subsequent years is 2 to 2.5 meters from the ground. During the first 6th or 7th year, the crop canopy covers 100 percent of the allotted area. Pruning of branches is done to plants after the 6th or 7th year because, during this period, thick shade is formed due to overlapping of branches and turns to reduce yield. After pruning, 10 % Bordeaux mixture paste swabbing for large cut ends or 1% Bordeaux mixture spray for pruned shoots is recommended (Bhagya *et al.*, 2024). As a preventive measure, pruned trees are to be sprayed with 0.06 % lambda- cyhalothrin twice or thrice in the initial year of pruning. The tender shoots should be protected against attack by spraying with lambda cyhalothrin 0.06 % or thiamethoxam 0.02 %.

Fertilizer and Manuring in HDP

Recommended fertilizer dosage for HDP is 160 g N: 80 g P₂O₅: 80 g K₂O/plant/year for 5th year and above plantation. 10-15 kg well decomposed FYM (Bhagya *et al.*, 2025).

Year of Planting	Urea	Rock Phosphate	Muriate of Potash
I year	70 g	80 g	30 g
II year	140 g	160 g	60 g
III year	210 g	240 g	90 g
IV year	280 g	320 g	120 g
V year and onwards	350 g	400 g	150 g

Fertilizers need to apply 50 cm, 75 cm and 100 cm away from trunk by opening circular trenches of 25 cm width and 15 cm depth during 1st, 2nd and 3rd year onwards, respectively and after application of fertilizer, it should thoroughly mixed with soil. Fertilizer should be applied during August-September month and we should avoid during heavy rain period to avoid the loss of fertilizer by leaching.

Plant Protection Measures

1. Pests: Though the cashew is infested with many pests, two major pests are bothering in cashew plantation they are Tea Mosquito Bug (TMB) and Cashew Stem and Root Borer (CSRB) (Aswathy *et al.*, 2025).

a. Tea Mosquito Bug (TMB): In general, TMB incidence commences during October to November coinciding with the emergence of new flushes after the monsoon. The population reaches a maximum during December to January when the plants are in full bloom and its activity is seen until harvest. The pest infests tender leaves, shoots, panicles, immature nuts as well as immature apples.

Symptoms: Initially water-soaked lesions appear at the feeding sites which turn scabby black in 2-3 days. Later, the lesion coalesces and ultimately results in drying of shoots and leaves. In the panicle it results in blossom blight where the flowers and stalks completely dried up. Upon severe damage most of the flushes and panicles dry up and the tree develops a scorched appearance.

Control measures: Spraying of Lambda cyhalothrin (0.6 ml/liter), Thiamethoxam (0.2 g/liter) and Acetamiprid (0.5 g/lit) whenever the incidence occurs at 5-10 % damage.

b. Cashew stem and Root Borer (CSRB): In general, the pest incidence observed from December to May month.

Symptoms: At the base of the CSRB infested tree, gum and fibrous material are exuded in small quantities in the initial stage of attack. During later stage of attack, the infested tree canopies show a sickly appearance and the green leaves turn yellowish and start dropping prematurely. In the severe stages of attack, the twigs dry off and the bark on the trunk starts splitting. At this stage, large quantity of chewed fibers and gum (commonly known as frass) are seen as big lumps at the base of the CSRB infested tree.

Control Measure

Cultural method:

- Phyto sanitation of the cashew plantations helps to reduce the past population.
- The young plants should be trained to have branching at height of 0.6 m from the ground.
- Once the larva enters into the wood for pupation, it is difficult to locate. Hence, it has to be killed by inserting a gear wire/any bending metal wire.

Chemical method:

- The pest stages have to be carefully removed by chiseling of the tunnels in the infested portion.
- The chiseled portion should be swabbed thoroughly with Fipronil 2 ml/lit and subsequently the tree base should also be drenched.

Disease Management

Diseases are not much bothered in cashew plantations and some recent emerging and important two diseases have been discussed here; they are Anthracnose and Gummosis.

1. Anthracnose:

Symptom: Initially elongated dark brown to black water-soaked lesions on shoots later it will dry up and leaves which become crinkled, dry up and fall off. Small dark spots are formed on main stalk and lateral branches of the panicle, the flowers eventually wither and drop down and floral branches show drying symptom. Immature fruit turn black and fall prematurely. On mature fruit black irregular or roundish spots develop those are often sunken and gradually start rotting. The disease is more severe when rainfall coincidence with flowering season. Small black spots appear on nuts and apples and it becomes mummified.

Management:

- The anthracnose disease can be effectively managed by spraying plants and seedlings with the help of protective and curative fungicide.
- The affected plant parts should be pruned and burnt to prevent the spread of the disease.
- Spraying with 1% Bordeaux mixture or Mancozeb 0.25% or Copper oxy chloride 0.3 %.
- As infection of the fungus is usually preceded by infestation of tea mosquito bug, combined application of insecticide and fungicide is effective and more economical.

2. Gummosis:

Symptom: Initially the symptom will exhibit as gum oozing from small cracks of the infested parts and reddish-brown liquid from the main stem and branches which later turns black in color giving tree bleeding appearance. The most diagnostic symptom is gum exudation followed by leaf yellowing and leaf drop. Longitudinal cracks also appear on the affected region from which gum exudes. The inner tissues of the affected portions turn reddish fluid and the affected branches dry gradually.

Management:

- Monitor the cashew plantations regularly and keep clean, prune the unproductive, dry and disease/insect infected branches.
- Chiseling out the affected plant portion and applying Bordeaux paste (10 %).

Harvesting and Yield

Harvesting fruits will be done by collecting of fallen fruits in the cashew plantation. In normal density planting cashew yield starts from 3rd year onwards and we can expect 0.5 kg /plant but in the high-density planting system we can expect yield from 1st or 2nd year itself with less than 1 kg. But in the 3rd year we can expect 2-3 kg yield. So, by doing this we can get more than 1 ton's cashew nut yield per hectare. Till 10th year HDP can be maintained with pruning and protective spray and 11th year onwards diagonal thinning need to be carried out for proper growth of canopy and 11th year onwards HDP will become normal density system and then it can be maintained as per the normal density cultivation practices. As per the earlier report from our directorate, it has been proved that 3 kg nuts /plant at 3rd year of planting even it is 2 kg also can bring 1.25 tones/hectare under HDP. This yield is superior over our national average yield of 674 kg/ha.

Conclusion

High Density Planting is advantageous with effective utilization of natural resources with 4- fold increase in yield till 6th year and 2-3-fold increase in yield up to 12th year under high density planting with 625 plants per hectare and 2-3-fold profit (Naik *et al.*, 2011) can be obtained till 12th year as compared to normal density planting (156 plants/ha).

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Fig. 1 Field view of High-Density Planting in Cashew



Fig 2. Flowering and fruiting of one year old cashew plantation under high density planting



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Microgreens: Tiny Yet Powerful Superfoods

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Microgreens are young vegetable greens harvested just a few weeks after germination. Unlike sprouts, which are consumed along with their roots, microgreens are cultivated in soil and harvested by cutting the stems.

This method makes them safer to consume, as it reduces the risk of microbial contamination.

These miniature greens are highly valued for their rich flavors, vibrant appearance, and delicate texture. Beyond their visual appeal, they are nutritionally dense and can significantly enhance the quality of meals. Studies indicate that microgreens often contain higher concentrations of vitamins, minerals, and antioxidants compared to their fully grown counterparts.

Microgreens can be grown easily in small home setups or on a commercial scale. Whether cultivated in soil trays or hydroponic systems, they provide a continuous supply of fresh produce. Despite their short shelf life, their rapid growth and ease of cultivation make them a practical and rewarding crop.

Nutritional and Health Benefits

Microgreens are often referred to as “superfoods” because they are packed with essential nutrients such as vitamins C, E, and K, along with minerals like iron and magnesium. Their high antioxidant content helps neutralize harmful free radicals, thereby lowering the risk of chronic diseases such as heart disease, diabetes, and cancer.

Certain microgreens, such as broccoli, contain compounds like sulforaphane, which are being researched for their anti-inflammatory and anti-cancer properties.

Uses and Applications

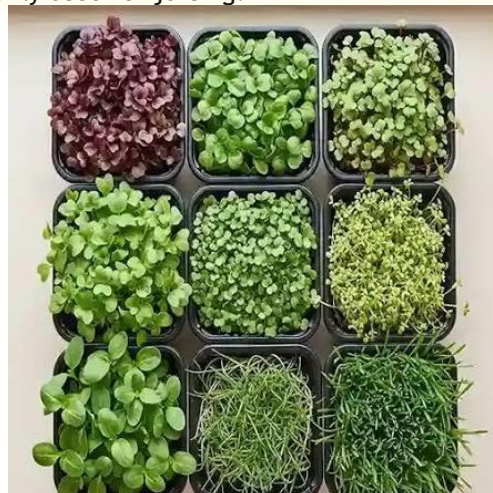
In the culinary world, microgreens are widely used to enhance flavor, texture, and nutrition. They can be added to salads, sandwiches, soups, smoothies, and even used as garnishes for various dishes. Their intense flavors—ranging from spicy to sweet—can elevate any meal.

On a larger scale, microgreens play an important role in urban agriculture and vertical farming systems. Their fast growth and minimal space requirements allow year-round production with a smaller environmental footprint. They are also increasingly used in health products, nutraceuticals, and specialty food items.

Crops Suitable for Microgreens

A wide variety of crops can be grown as microgreens, including:

1. **Brassicaceae** (e.g., broccoli, radish, mustard): Fast-growing with a peppery taste
2. **Amaranthaceae** (e.g., beetroot, spinach): Known for vibrant colors and mild sweetness
3. **Apiaceae** (e.g., coriander, dill): Aromatic but slower growing
4. **Asteraceae** (e.g., lettuce): Mild and suitable for salads
5. **Lamiaceae** (e.g., basil, mint): Strong and aromatic
6. **Poaceae** (e.g., wheatgrass): Commonly used for juicing.



Advantages

1. High nutritional value
2. Quick growth cycle (1-3 weeks)
3. Requires minimal space
4. Enhances flavor, color, and texture of food.

Disadvantages

1. Very short shelf life
2. Cannot regrow after harvest
3. Requires regular care and monitoring
4. Risk of contamination if hygiene is poor

Production Methods

Microgreens can be produced using two main methods:

1. Soil-Based Method: This traditional approach involves growing microgreens in trays filled with a sterile medium such as potting mix or coco coir. Seeds are spread evenly, lightly watered, and initially kept in darkness for germination. Once sprouted, they are exposed to light and maintained with proper moisture and airflow.

Pros: Low cost, natural flavor, beginner-friendly.

Cons: Messy, risk of pests, requires regular watering

2. Hydroponic Method: This soilless method uses grow mats and nutrient solutions. It is widely used in commercial production due to its efficiency and cleanliness.

Pros: Clean, faster growth, fewer soil-related issues.

Cons: Higher setup cost, requires technical knowledge, energy usage

Harvesting

Microgreens are typically harvested within 1-3 weeks when the first true leaves appear. They are cut just above the growing medium using a clean knife or scissors. Since they do not regrow after cutting, fresh seeds must be sown for each cycle. Proper storage in cool conditions helps maintain freshness, although they are best consumed quickly.

Pests and Diseases

Although generally hardy, microgreens can be affected by:

1. **Fungal diseases** like damping-off due to excess moisture
2. **Mold growth** under high humidity and poor ventilation
3. **Insect pests** such as fungus gnats and spider mites.



Maintaining proper hygiene, airflow, and moisture levels helps prevent these issues.

Integrated Livestock and Agroforestry Systems: Enhancing Productivity and Sustainability

Article ID: 74462

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Agriculture is facing ever-growing pressure to yield more, in addition to protecting the environment and maintaining livelihoods for millions of rural families. In India alone, small and marginal farmers constitute approximately 86% of the agricultural population, who work in most cases on broken, sloping, or degraded land. Traditional monocropping or split farming of livestock has failed to ensure round-the-year income and sustained productivity. Climate change, land degradation, and socio-economic vulnerabilities add to the problems.

Integrated Livestock and Agroforestry Systems (ILAFS) offer a synergistic and holistic method of agricultural improvement through the integration of tree cultivation, animal husbandry, and pasture improvement within the same unit of land. ILAFS simulate nature, where more than one biological element exists and interacts, leading to increased efficiency in the utilization of resources, ecological stability, and livelihood protection. ILAFS facilitate sustainable intensification of agriculture, diversify sources of income, and enhance climate and market risk resilience. Their significance is particularly acute in hill country, tribal areas, and dryland environments where mainstream agriculture is confronted with numerous constraints.

They have high potential to conserve natural resources while sustaining productivity. Trees increase soil organic content, minimize soil erosion, manage water regimes, and offer shade and protection to animals, enhancing animal well-being and productivity. Livestock reciprocate by advancing system productivity through the transformation of low-quality biomass into high-value commodities such as milk, meat, manure, and draught power. The manure enhances the structure and fertility of the soil, completing nutrient cycles within the farm. Multipurpose shrubs and fodder trees assist in over-coming seasonal fodder deficits, a limiting factor in most rainfed situations.

Integrated systems also address food and nutritional security. Through supporting live-stock production, families receive animal proteins and milk products. Agroforestry elements such as fruit trees, medicinal plants, and legumes add to household nutrition and provide cash inflows during off-peak agricultural seasons. Further, these systems present the ability to engage gender, as women are usually engaged in livestock management and processing of agroforestry products.

Climate-wise, ILAFS are being considered an integral nature-based solution in increasing measure. They increase carbon capture, manage microclimates, and provide adaptive capacity to biotic and abiotic stress. Farmers are able to manage droughts, floods, and market volatility better as a result of the diversity and resilience that is inherent in these systems. With the integration of trees, forage, and livestock, ILAFS is a diversified strategy of production that reduces overall risk and enhances long-term resilience.

The shift toward integrated systems requires not just technical measures but institutional support, capacity development, and facilitatory policies as well. Encouragingly, a number of national missions, including the National Agroforestry Policy (2014) and livestock development schemes, are starting to identify and facilitate integrated means. But implementation gaps, awareness, research, and market integration still remain. Thus, encouraging ILAFS demands concerted action by researchers, extension personnel, policymakers, and agricultural communities to achieve its maximum potential for productivity improvement, restoration of the environment, and rural livelihood security.

Understanding the System: Components and Interactions

ILAFS are rooted in the ecological concept of complementary interaction between elements. Deep-rooted trees tap nutrients and water from lower layers of soil, and grasses and crops utilize the top soil horizon. Live stock make use of both layers of biomass, transforming unusable biomass into animal products and cycling nutrients back in the form of manure.

The systems can be broadly classified into:

1. Silvi-pastoral systems: Merging trees with pasture and live-stock.
2. Agri-silvi-pastoral systems: Integration of crops, trees, and animals on the same land.
3. Horti-pastoral systems: Fruit trees accompanied by forage and livestock.
4. Homestead or backyard systems: Multi-strata systems composed of vegetables, fruits, poultry, and small ruminants.

Physical arrangement and spatial structure are important. Trees are usually planted at field boundaries, contours, or in alley systems to reduce competition and enhance mutual benefits. The fodder grasses are sown in strips or under tree cover, whereas the livestock are either rotationally grazed or stall-fed. These configurations improve ecological services

like soil stabilization, microclimate moderation, and conservation of biodiversity. In addition, the inclusion of various biological components provides for the cycling of nutrients, optimization of utilization of solar radiation, and the control of pests and diseases through biodiversity. Trees also act as windbreaks, and grasses act to prevent erosion and hold ground cover. Livestock help recycle nutrients by dropping manure, which may be composted and reapplied to land. Knowledge of the interactions between the components of the system allows farmers to create efficient, ecologically based, and climatically and economically resilient agroforestry systems.



Advantages of Integration: Productivity, Resilience, and Livelihood Security

The integrated system of integrating livestock with agroforestry systems has several advantages that are both economic and ecological. Farmers gain a twelve-month income through diversification of crops—milk, meat, eggs, fodder, fruits, timber, and fuelwood. Integration enhances land-use effectiveness, with several outputs from one unit of land, particularly useful where land is scarce. Live- stock are sustained throughout the year on farm fodder, lessening reliance on off-farm feed inputs. Additionally, the inclusion of trees enhances soil fertility by litter fall, nitrogen fixation, and increased microbial activity.

Trees also hold hillsides in place and stop soil loss, particularly important in sloping areas. The system enhances adaptation to climatic shocks like floods and droughts through provision of substitute sources of fodder and income. Recycling of nutrients through manure and addition of biomass minimizes fertilizer use and enhances long-term soil health. From a social perspective, ILAFS create job opportunities for family members, particularly youth and women, in taking care of livestock, managing fodder, and marketing products. On the whole, these systems enhance livelihood security while being ecologically sustainable.

Management Practices

Nutrient Cycling, Grazing, and Biomass Management Proper management practices are critical for harvesting the maximum benefits of ILAFS. Rotational or controlled grazing facilitates maximum utilization and regeneration of the pasture. Stall feeding and manure composting promote recycling of nutrients. Tree lopping must be timed to anticipate livestock feed requirements without over-pruning. Branches, leaves, and crop residues resulting from pruning can be composted to enhance soil organic matter or used as mulch. The inclusion of legumes in pastures increases nitrogen availability. Water harvesting methods like contour bunding, trenches, and farm ponds should be incorporated in the design. Pest and disease control should emphasize biological methods through mixed species, biological controls, and habitat management. Regular soil fertility and fodder monitoring optimizes inputs and outputs. Training of farmers in silviculture, animal husbandry, and book keeping is also crucial. Systematically well-managed, ILAFS can become self-renewing in nutrient cycles and biomass yields in the long run.

Challenges and Constraints

In spite of their potential, ILAFS also have a number of constraints in implementation. Farmers might be unaware, lack technical expertise, or not have initial funds to invest in trees or livestock. Insecurity of land tenure, particularly in forest fringe or tribal areas, constrains long- term investment. Pastoral rights and crop-livestock user conflicts are also prevalent in community lands. Extension systems tend to have limited knowledge on integrated systems, dealing with crop or animal individually. Limited access to quality planting material, veterinary services, and market linkages for diversified products also slows down adoption.

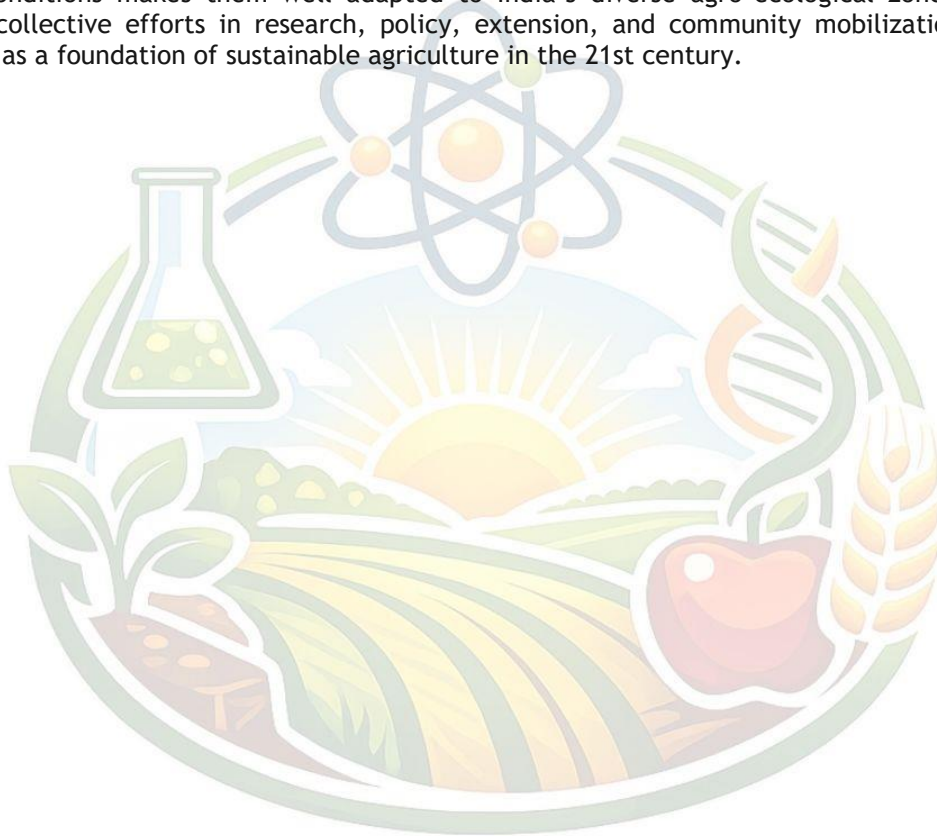
Labor requirements for fodder harvesting or stall feeding may also be considerable without mechanization. Erratic rainfall and degraded soil in hilly and rainfed areas can delay establishment of the system. Overcoming these obstacles calls for concerted actions by government organizations, research centers, NGOs, and farmer associations.

Climate Resilience and Environmental Services

ILAFS play a major role in adaptation and mitigation of climate change. Forests capture carbon, control local microclimates, and act as windbreaks. Grass cover and organic mulch diminish temperature fluctuations and retain soil moisture. Methane emissions are lowered and soil carbon is improved through manure management. These systems provide habitat for biodiversity and pollinators as well. By minimising the reliance on external inputs and maximising ecological balance, ILAFS enhance farm resilience against extreme climate events like droughts, floods, and temperature variations. Scaling up ILAFS through mainstreaming in national and state climate action plans can accelerate environmental and socio-economic co-benefits.

Conclusion

Integrated Livestock and Agroforestry Systems represent a win-win approach to increase productivity, sustainability, and rural livelihoods. By replicating ecological processes and optimizing land, labor, and biomass, such systems provide diversified and secure sources of income for smallholder farmers. Their capacity to retain soil, recycle nutrients, and respond to local conditions makes them well adapted to India's diverse agro-ecological zones. Though there are challenges ahead, collective efforts in research, policy, extension, and community mobilization can unlock ILAFS' enormous potential as a foundation of sustainable agriculture in the 21st century.

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Field Guide to Seed Identification of Major Carp, Exotic Carp, and Catfish Species

Article ID: 74463

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Characteristics	Catla	Mrigal	Rohu
Body shape	Wider body depth	Slender body	Moderate
Mouth	• Uprturned mouth • Circular mouth gap/ opening • Lower lip folded but not fringed • Lower lip and upper lip terminate at the same point	• Mouth inferior • D-shaped / rectangle mouth gap • Lower lip neither folded nor fringed • Extending upper lip which covers the lower lip	• Terminal mouth • Square mouth gap • Lower lip fringed and folded • Extending upper lip which covers the lower lip
Eye	A red spot on the lower part of eye ball	No such red spot	No such red spot
Fin colour	All fins are darkish in colour	Pectoral, pelvic and anal fins are orange in colour	Pelvic fins are red in colour and other fins are darkish in colour
Lateral line	Curved	Clearly visible and almost straight	Slightly curved
Head size/ shape	Larger head	Isosceles head	Equilateral head
Scale size/shape	Larger scale	Exposed portion of scale is rectangular shaped	Exposed portion of scale is diamond shaped
Body colour	Dorsal side blackish in colour while ventral region silvery	Silvery	Slight golden appearance with darker dorsal side
Images			

Exotic Carps

Grass Carp (*Ctenopharyngodon idella*)

- No barbels.
- Snout very short.
- Mouth terminal with thin lips.
- Tip of caudal and anal fins are rounded.



Common Carp (*Cyprinus carpio*)

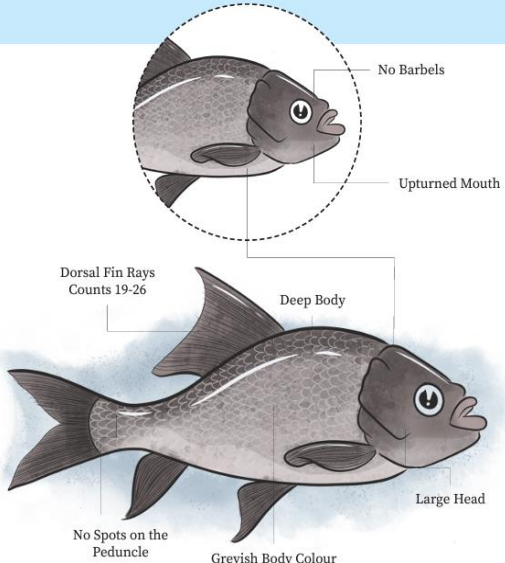
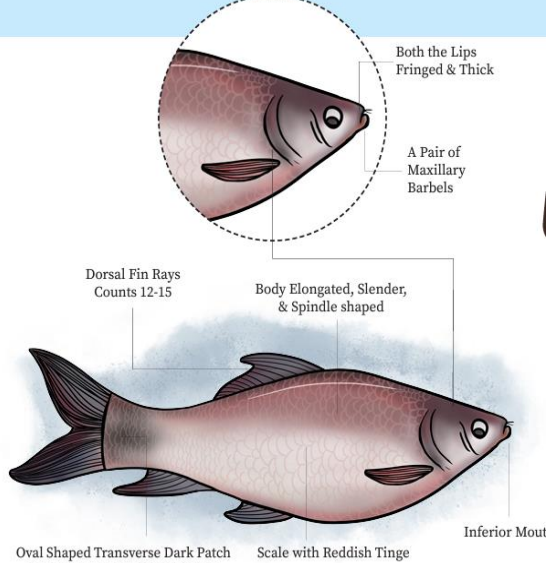
- 2 pairs of barbels.
- Scales large and thick.
- Large protruding mouth.
- Bulging belly compared to other carps.

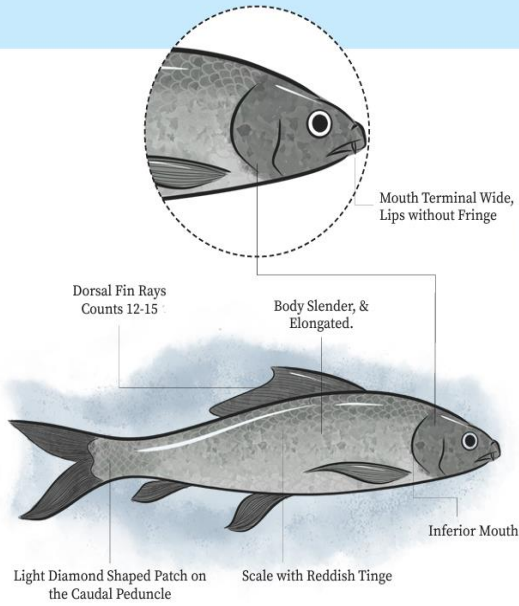


Silver carp (*Hypophthalmichthys molitrix*)

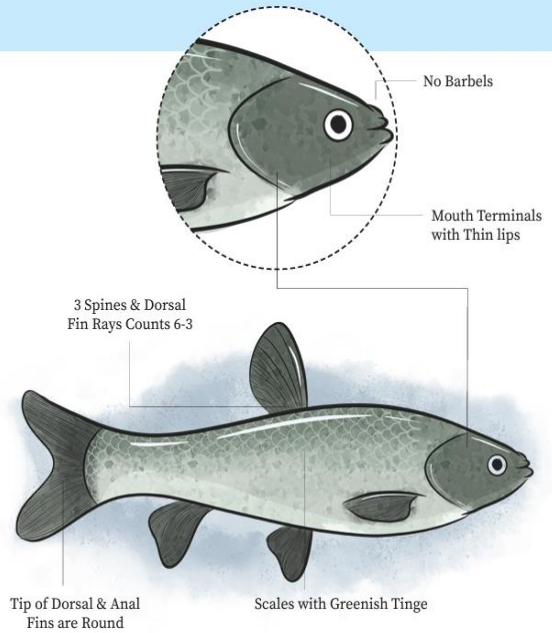
- Body olivaceous to silvery.
- Barbels absent. Scales small in size.
- Edge of last simple dorsal ray not serrated.
- Keeled belly. Keels extend from isthmus to anus.



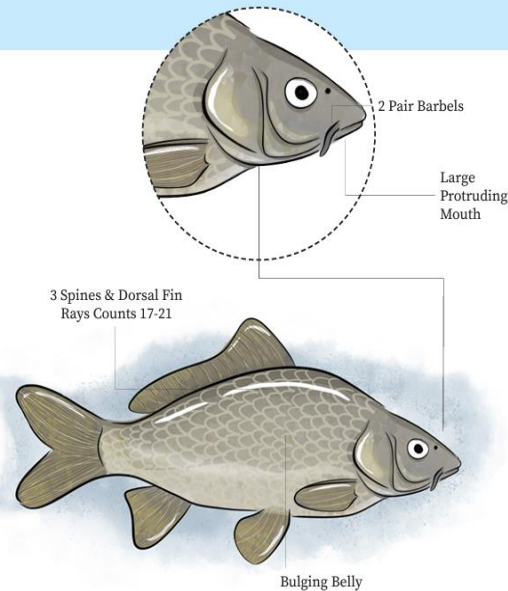
 Catla (<i>Catla catla</i>)	 Rohu (<i>Labeo rohita</i>)



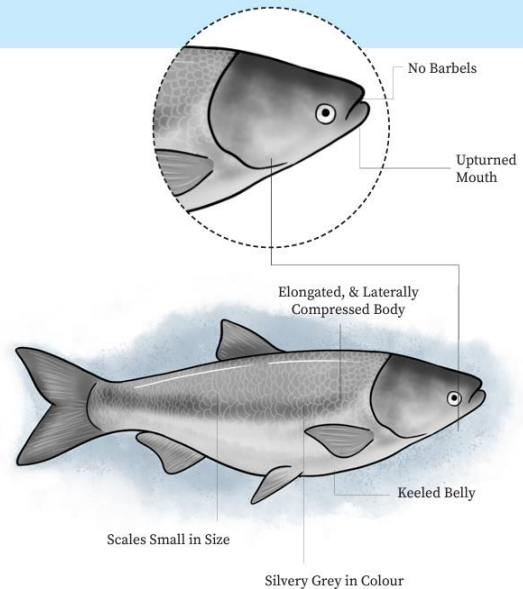
Mrigal (*Cirrhinus mrigala*)



Grass Carp (*Ctenopharyngodon idella*)



Common Carp (*Cyprinus carpio*)



Silver Carp (*Hypophthalmichthys molitrix*)

Catfish Seeds

Clarius batrachus (Magur)

- Occipital process more or less triangular.
- Upper jaw a little projecting.
- Body compressed posteriorly.



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Pangasianodon hypophthalmus

- a. Fins dark grey or black.
- b. 6 branched dorsal-fin rays.
- c. Gill rakers normally developed.
- d. A black stripe along lateral line and a second long black stripe below lateral line, large adults uniformly grey.
- e. Dark stripe on the middle of anal fin; dark stripe in each caudal lobe.



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Tilapia Breeding: The Secret Behind Successful Fish Farming

Article ID: 74464

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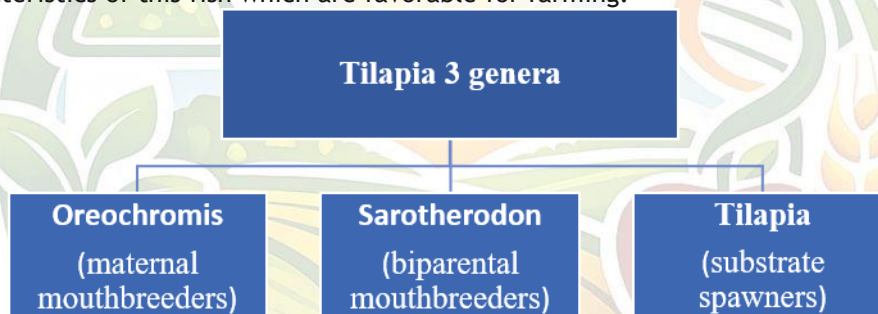
Abstract

Tilapia is one of the most widely cultured freshwater fish species due to its rapid growth, adaptability and high reproductive capacity. Successful seed production depends on efficient breeding technologies and hatchery management. Modern techniques such as broodstock conditioning, artificial egg incubation, hormonal sex reversal and hybridization have improved fry quality and monosex production. These advancements enhance growth performance, feed efficiency and farm profitability while reducing problems associated with uncontrolled reproduction. Continued genetic improvement and sustainable breeding practices will play a vital role in supporting global tilapia aquaculture and food security (El-Sayed, 2020; FAO, 2024).

Keywords: Tilapia breeding, Hatchery technology, Broodstock management, Mouthbrooding, Artificial incubation, Monosex tilapia, Hormonal sex reversal, Hybridization, Sustainable aquaculture.

Introduction

Among the farmed species of fishes in inland waters, contribution of tilapia, a cichlid fish, is perhaps next only to that of carps and other cyprinids. About 80 species of tilapia have been described out of which about 10 species are reported to be used for culture. Though originally a native of Africa, it is distributed all over the world at present because of certain distinct characteristics of this fish which are favorable for farming.



Importance of Species

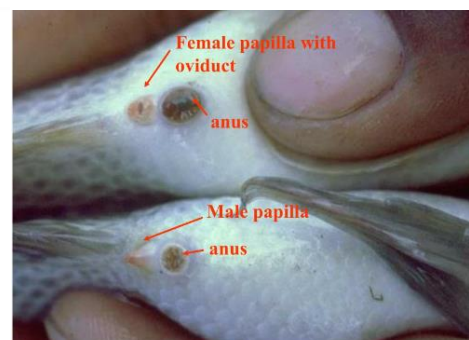
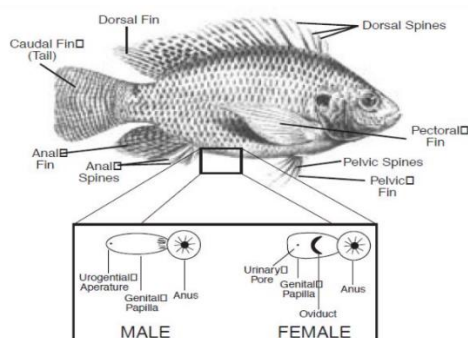
It is an easy growing fish. Capacity to adapt to different climatic conditions, salinities, food and ecosystems, sexual maturation under certain adverse conditions. Highly resistant to diseases. Reproduces prolifically under natural conditions. Exhibits good growth rate and feed conversion efficiency.

Breeding of Nile Tilapia (*Oreochromis niloticus*)

Species Biology: It is an omnivorous fish feeding mainly on phytoplankton such as green algae, blue green algae and diatoms and also on detritus. Temperature below 12°C is found lethal. It can tolerate salinity up to 29 ppt. The males exhibit a growth rate 2.5 times more than female.

It grows more than 600 g within 6 months.

Sexual dimorphism:



Male have pointed urinogenital papilla whereas female have thick genital papilla with oviduct.

Sexual maturity:

- It attains 1st sexual maturity on reaching 10-17 cm length i.e. 4-5 months old in farm condition.
- In wild, it matures on attaining 20-39 cm.



Courtship and mating: The males engage themselves in active display in a breeding territory which is referred to as "lek" (Macintosh and Little, 1995) where nests are prepared by males by scooping out depressions at pond bottom.

The mature female visits a "lek" when there shall be immediate courtship and mating resulting in spawning, spermiation and fertilization.



Spawning and Fecundity: A mature fish spawn 6-12 times in a year. The no. of eggs / batch is reported to vary from a few hundreds to 2000. Larger females - more eggs per batch - larger in size. Smaller females - less no. of eggs - smaller in size. Though the number of eggs in a batch is less, the smaller fishes (less aged) spawn more frequently as a result, smaller brood fish yields more eggs/fry collectively.

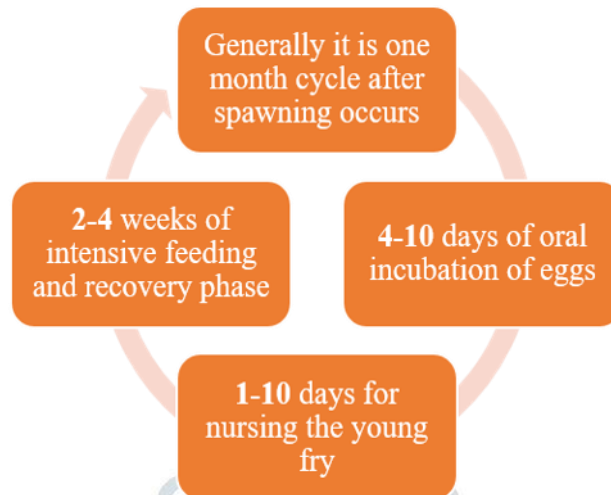
Parental care: Soon after the eggs are laid and fertilized the same are picked up by the female in its mouth for incubation. Soon after taking the eggs in its mouth the female leaves the breeding territory, "lek" or nesting area. Incubation period - 4 to 10 days depending on temperature. Yolk sac absorption - 4 to 6 days.

After they are called swimup fry and they start feeding.

The mother continues to shelter the larvae for another 1 to 4 days. Larvae take 10 to 12 days to become fully independent.



Reproductive cycle:



Environmental Factors Affecting Reproduction

Three major factors are found to affect the reproduction of tilapia- Temperature, Light & Salinity. Optimum temperature required is 27 °C, but generally it breed in temperature between 20-23 °C. Some scientists have reported that bright sunlight stimulates the breeding in tilapia. Salinity above 20 ppt shown to decreased fecundity. For optimum fecundity isotonic concentration reported to be ideal.

Constraints in Natural Condition

Tilapia breeds prolifically in confined waters, and fry are released by the mother into the pond continuously, collection of the naturally produced fry was not sustainable because of the following reasons. Cannibalism among the fry. Asynchronous spawning habit, Overcrowding, stunted growth and decline in the reproductive efficiency. Because of these limitations, for large scale production of fry under controlled conditions, advanced techniques for brood stock management became necessary.

These techniques included:

1. Conditioning brood fish before spawning and
2. Replacement of spawned females with conditioned brood fish.

Broodfish Conditioning

Two major aspects in conditioning:

1. Stocking the fish at optimum stocking density.
2. Feeding the fish on good quality feed to meet actual nutritional requirement.
3. For green water system, 25 - 30 % CP, whereas 30 - 40 % required for clear waters.

Collection of Eggs from Mouth

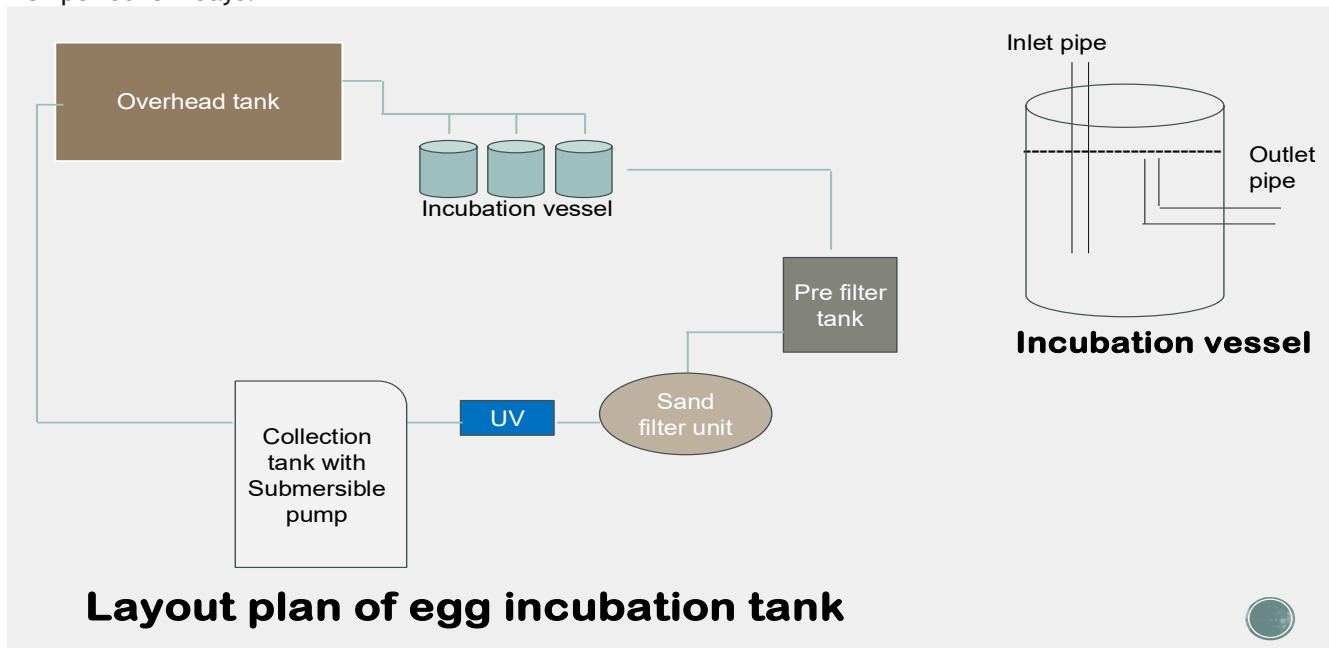
Water level lowered by draining out the water to a depth of 20-30 cm. So, we can easily collect and examine the mouth of females. Females are forced to spit out eggs and it collected into basin. Eggs are put under artificial incubation.

Spawned females are replaced with ready to spawn (mature) females once in every 5-10 days.



Incubation of Eggs

Round bottom incubator of 20 ltr which can hold 80000 eggs for incubation are good as this avoid damage to egg chorion. Incubation period varies on temperature, 6 days at 20 °C-3 days at 34.5°C Optimum incubation temperature is 28-29 °C at which period is 4 days.



Larval Care

Larvae are reared in trays for 20 days after hatching. Aluminium or plastic tray of size (40 x 30 x 10) cm with holes on lateral sides are used. Holes are drilled in a way that 3 cm water depth are maintained. Swim up fry start feeding 4-8 times a day for another 10 days. With 64 such trays, 0.5 million fries can be produced with stocking of 10000 fry per tray (80% survival). Maintain good quality water and optimum flow rate of water are necessary.

Production of Monosex Tilapia

There are two techniques used for production of monosex tilapia

1. Hormonal sex reversal
2. Hybridization

Hormonal sex reversal: Androgens - genotypic female into functional males. Hormones administered orally mixed with feed. Oral administration done between 10th - 20th day of hatching when gonad is in undifferentiated stage. 17 α methyl testosterone [17 α MT] is used mostly with dose not standardized. Generally, 1.5 mg/gm body weight is necessary to achieve 100% sex reversal, but it can't be more than 8 mg/gm body weight.

Hybridization: Hickling was the first to produce all male offsprings by crossing *O. mossambicus* with *O. urolepis hornorum*. In hybridization if both parents are homogametic, all male offspring shall be obtained. Strong chromosomal sex determination mechanism does not exist in tilapia. Autosomal genes play major role in sex determination.

Red Tilapia - Hybridization

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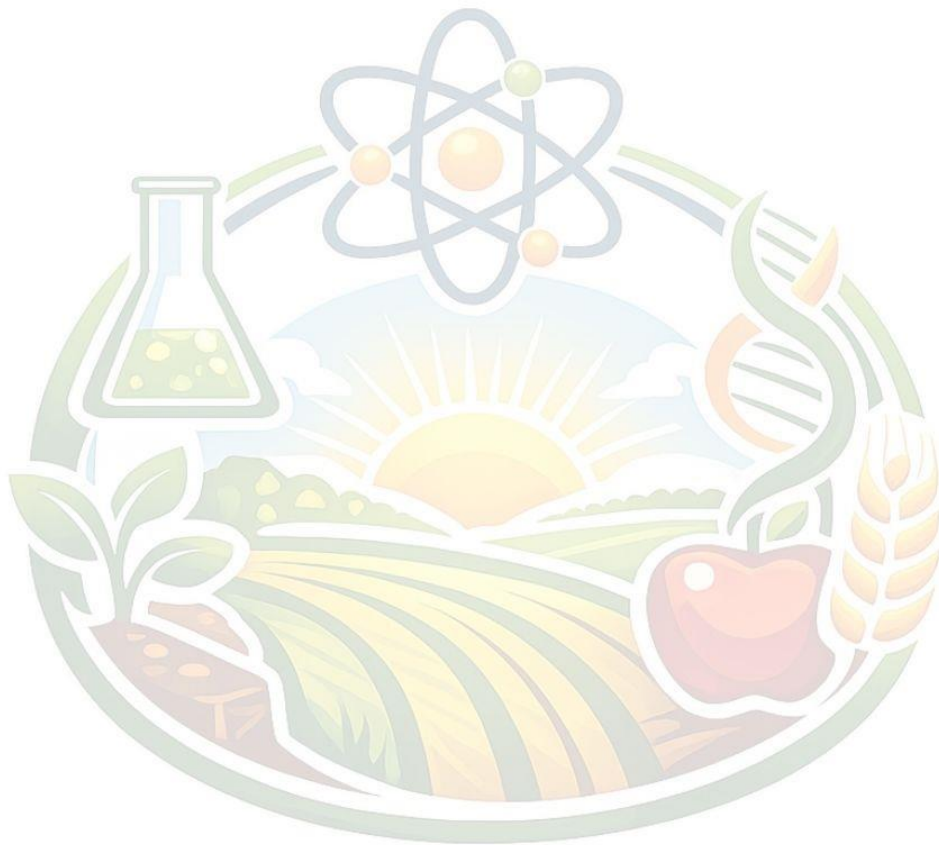
Red tilapia is produced using hybridization by Taiwan fisheries research institute. Produced by crossing a mutant variety of *O. mossambicus* (having red body colour and red eyes) with *O. niloticus*, red stain exhibits fast growth rate i.e. 500-600 g in 5 months and 1200 gm in 18 months.

Conclusion

Tilapia breeding technology has greatly improved the production of healthy, high-quality seed for sustainable aquaculture. Modern hatchery practices, including broodstock management, artificial egg incubation, hormonal sex reversal, and hybridization, have enhanced fry survival and monosex production. These technologies improve growth performance, feed efficiency, and farm profitability while reducing uncontrolled reproduction. Continued genetic improvement and sustainable breeding strategies will further enhance productivity, disease resistance, and environmental adaptability. Overall, modern breeding technologies are essential for the long-term growth and global sustainability of tilapia aquaculture (El-Sayed, 2020; FAO, 2024; Thomas, 2003).

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Pangenomics and its Applications in Crop Breeding

Article ID: 74465

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Abstract

The development of next-generation sequencing technologies has greatly advanced plant genetics and crop breeding by enabling detailed investigation of genetic diversity within crop species. Conventional breeding programs often depend on a single reference genome, but a single genome cannot represent the complete genetic diversity present in a species. Pangenomics overcomes this limitation by combining genomic information from multiple individuals to represent the total genetic repertoire of a species. A pangenome generally consists of a core genome containing genes shared among individuals and an accessory genome containing genes found in only some genotypes. Pangenomic analysis can identify presence-absence variations, copy number variations, structural variations, and novel genes that may be missed in single-reference genome studies. These genetic resources are particularly valuable for discovering genes associated with yield, disease resistance, abiotic stress tolerance, nutritional quality, and environmental adaptation. Integration of pangenomics with genomic selection, marker-assisted selection, genome editing, and artificial intelligence is providing new opportunities for precision crop breeding. This chapter summarizes the concept, components, construction, applications, advantages, challenges, and future prospects of pangenomics in crop improvement.

Keywords: Pangenome, Crop Breeding, Genetic Diversity, Structural Variation, Gene Discovery, Precision Breeding, Climate Resilience.

Introduction

Agriculture is facing major challenges due to population growth, climate change, depletion of natural resources, soil degradation, and increasing incidences of pests and diseases. At the same time, crop production must increase to meet the growing demand for food, feed, and industrial raw materials. Modern crop breeding therefore aims to develop varieties with high yield, improved nutritional quality, resistance to diseases and insects, and greater tolerance to environmental stresses such as drought, heat, salinity, and flooding.

Conventional breeding has made significant contributions to crop improvement, and molecular breeding has further accelerated the identification and utilization of useful genetic variation. The availability of reference genomes for major crops provided an important foundation for gene discovery, genome-wide association studies, and marker development. However, a single reference genome represents only one genotype and cannot capture the complete genetic diversity of a species. Genes or genomic regions absent from the reference genome may therefore remain undetected. Pangenomics has emerged as an important approach for overcoming this limitation. It involves the analysis and integration of genomic sequences from multiple individuals to construct a broader representation of the genetic content of a species. Pangenomics captures both conserved and variable genomic regions and therefore provides a more complete understanding of crop diversity. This information can be directly utilized for the discovery of novel genes and alleles and for improving the efficiency and precision of breeding programs.

Concept and Components of Pangenomics

The term pangenome refers to the complete collection of genes and genomic sequences found within a group of individuals belonging to the same species. In plants, the pangenome is generally divided into the **core genome** and the **accessory genome**. The core genome contains genes that are conserved and present in most or all individuals. These genes are usually involved in essential biological processes such as cell division, photosynthesis, respiration, DNA replication, protein synthesis, and primary metabolism.

The accessory genome contains genes that are present in some individuals but absent from others. These genes often contribute to environmental adaptation, disease resistance, stress responses, and specialized metabolic pathways. Some sequences may occur only in particular genotypes and can be described as genotype-specific or unique genes. Such genes may provide valuable sources of novel traits for crop breeding.

Therefore, the pangenome can be broadly represented as:

Pangenome = Core Genome + Accessory Genome + Genotype-Specific Sequences

The distinction between core and variable genomic components is particularly important in crop improvement. While core genes are essential for basic biological functions, accessory and unique genes may provide much of the variation responsible for adaptation and agronomic performance.

Genetic Variation Revealed by Pangenomics

A major advantage of pangenomics is its ability to identify several types of genetic variation simultaneously. One important type is **presence-absence variation (PAV)**, in which a gene or genomic region is present in one genotype but absent in another. Disease-resistance genes and genes involved in environmental adaptation frequently show this type of variation. PAVs may be difficult to identify using conventional SNP-based approaches, particularly when the sequence is completely absent from the reference genome.

Copy number variation (CNV) refers to differences in the number of copies of a gene or genomic region among individuals. Changes in gene copy number can influence gene expression and biological function and may affect yield, disease resistance, stress tolerance, and metabolic traits.

Structural variations (SVs) include insertions, deletions, inversions, duplications, and translocations. These variants can alter gene structure, gene dosage, regulatory regions, and chromosome organization and may have significant effects on important agronomic characteristics. Long-read sequencing technologies have greatly improved the detection of structural variations in crop genomes.

Single nucleotide polymorphisms (SNPs) remain one of the most widely used forms of variation in breeding. SNPs are extensively used in marker-assisted selection, genome-wide association studies, genomic selection, and genetic mapping. Pangenomics complements SNP-based approaches by allowing breeders to investigate larger and more complex genomic variants.

Construction of Crop Pangenomes

Construction of a crop pangenome begins with the selection of genetically diverse germplasm. The selected materials may include elite cultivars, breeding lines, landraces, traditional varieties, and wild relatives. Including diverse germplasm is important because the ability of a pangenome to capture genetic diversity depends strongly on the individuals used in its construction. The selected genotypes are subjected to whole-genome sequencing using technologies such as Illumina, PacBio, and Oxford Nanopore. Illumina sequencing produces highly accurate short reads, whereas PacBio and Oxford Nanopore technologies generate long reads that are particularly useful for producing high-quality genome assemblies and identifying structural variations. After sequencing, genome assembly is performed to reconstruct the chromosomes and genomic regions of each genotype. High-quality genome assemblies are essential because incomplete assemblies may lead to missing genes or inaccurate estimates of genetic variation. Comparative genomic analysis is then used to identify conserved genes, accessory genes, unique sequences, PAVs, CNVs, and structural variations. The resulting information is integrated to form the pangenome. Pangenomes may be represented as multiple genome assemblies or through graph-based approaches. Graph pangenomes allow alternative genomic sequences and structural variants to be represented simultaneously and can reduce the bias associated with using a single linear reference genome.

Applications in Crop Breeding

1. Novel Gene Discovery: Pangenomics provides an effective approach for discovering genes that are absent from conventional reference genomes. Valuable genes may be present in landraces, wild relatives, or geographically adapted varieties but absent from elite cultivars. By comparing diverse genomes, breeders can identify these genes and investigate their potential contribution to agronomic traits. Novel genes discovered through pangenomic analysis can become targets for marker-assisted selection, genomic selection, gene introgression, or genome editing. Thus, pangenomics expands the genetic resource base available to crop breeders.

2. Disease Resistance: Disease resistance is one of the most promising applications of pangenomics. Resistance genes frequently show considerable genetic variation and may occur as presence-absence or copy number variants. Pangenomic analysis enables breeders to identify resistance genes across diverse germplasm and develop markers for their utilization.

In rice, pangenomic resources can assist in identifying genes associated with blast resistance. In wheat, they can contribute to the discovery of genes involved in resistance to rust diseases. Similar approaches can be applied to maize and other crops for identifying resistance to fungal, bacterial, viral, and other pathogens. The identification of diverse resistance genes also facilitates gene pyramiding and the development of varieties with more durable resistance.

3. Abiotic Stress Tolerance: Climate change has increased the importance of developing crops tolerant to drought, heat, salinity, and flooding. Pangenomics can identify genetic variants associated with adaptation to these stresses. Genes involved in water-use efficiency, osmotic regulation, root development, ion transport, and stress signaling may differ among genotypes. Stress-adapted landraces and wild relatives are particularly valuable sources of genetic variation. Pangenomics enables breeders to identify favorable alleles in these materials and transfer them into elite breeding populations through conventional crossing, marker-assisted selection, genomic selection, or genome editing.

4. Yield Improvement: Yield is a complex quantitative trait controlled by many genes and strongly influenced by the environment. Pangenomic studies can improve the identification of genetic variants associated with grain size, seed weight, plant architecture, biomass, reproductive development, and harvest index. Combining pangenomic information

with genome-wide association studies and genomic prediction can help breeders identify useful variants and improve selection accuracy. This can contribute to faster genetic gain and more efficient development of high-yielding varieties.

5. Nutritional Quality: Pangenomics also has considerable potential for improving nutritional quality. Genetic variation controlling protein composition, iron and zinc accumulation, vitamins, antioxidants, and other nutritional characteristics can be identified across diverse germplasm. Such information can support biofortification programs aimed at developing crops with improved micronutrient content.

6. Hybrid Breeding: Successful hybrid breeding requires the identification of genetically diverse and complementary parents. Pangenomic information provides a more comprehensive measure of genetic diversity by considering SNPs as well as structural and gene presence-absence variations. Such information can assist in parent selection, heterosis studies, and prediction of hybrid performance.

Crop-Specific Applications

Pangenomics has important applications in several major crops. In **rice**, pangenomic studies have expanded knowledge beyond the commonly used Nipponbare reference genome and have identified genetic variation associated with yield, blast resistance, submergence tolerance, and environmental adaptation.

In **wheat**, the large and complex polyploid genome makes pangenomic approaches particularly valuable. Multiple genome assemblies have revealed extensive structural variation among wheat genotypes. These resources can support the discovery of genes associated with rust resistance, heat tolerance, grain quality, and other important traits.

In **maize**, the considerable genetic diversity and large accessory genome provide opportunities for studying heterosis, stress adaptation, disease resistance, and yield components. Pangenomic comparisons can identify genomic regions contributing to adaptation across different environments.

In **soybean**, pangenomics can contribute to studies of nitrogen fixation, disease resistance, seed composition, oil and protein quality, and environmental adaptation. Similarly, pangenomic resources in **Brassica species** can support breeding for improved oil quality, disease resistance, flowering behavior, and abiotic stress tolerance.

Integration with Modern Breeding Technologies

Pangenomics can be integrated with several modern breeding approaches. In **genomic selection**, pangenome-derived markers can provide additional information about genetic variation and may improve prediction of breeding values. This can increase selection efficiency and shorten breeding cycles.

In **marker-assisted selection**, pangenomic analysis can identify markers linked to useful genes and genomic variants. Such markers can be used to track resistance genes, stress-tolerance alleles, and other favorable traits in breeding populations.

Genome editing provides another important opportunity. Pangenomic analysis can identify candidate genes and alleles associated with desirable traits. After functional validation, these genes can potentially be modified using CRISPR-Cas and other genome-editing technologies. Thus, pangenomics can serve as a discovery platform for precision breeding.

The integration of **artificial intelligence and machine learning** with pangenomic datasets is also promising. AI-based methods can help predict gene functions, identify trait-associated genomic regions, prioritize candidate genes, and support breeding decisions. Combining genomic, phenotypic, and environmental data may further improve the ability to predict crop performance.

Advantages and Challenges

Pangenomics provides a more comprehensive assessment of genetic diversity than a single-reference genome. It facilitates the discovery of novel genes and alleles and helps identify structural variants and presence-absence variations that may be missed by conventional approaches. It also supports the utilization of landraces and wild relatives and contributes to precision breeding and climate-resilient crop improvement. However, several challenges remain. Generation of high-quality genome assemblies can require substantial financial and technical resources, particularly when large numbers of genotypes are analyzed using long-read sequencing. Pangenomic analysis also requires considerable computational power, advanced bioinformatics tools, and large data-storage capacity.

Another challenge is the complexity of interpreting pangenomic data. Accurate genome assembly and annotation are essential, while repetitive regions, rare variants, and complex structural variations can be difficult to characterize. Furthermore, a pangenome constructed from a limited number of genotypes may not adequately represent the complete diversity of a species. Therefore, careful germplasm selection and standardized analytical approaches are essential.

Future Prospects

The future of pangenomics will be strongly influenced by advances in long-read sequencing, graph-based genome representation, artificial intelligence, and multi-omics technologies. Graph pangenomes are expected to become

increasingly important because they can represent alternative genomic sequences and structural variations more accurately than a single linear reference genome.

The integration of pangenomics with transcriptomics, proteomics, metabolomics, epigenomics, and phenomics will provide a more complete understanding of how genetic variation influences crop phenotypes. AI-assisted analysis may further improve the identification of candidate genes and prediction of important traits.

Pangenomics will also be highly relevant to climate-smart agriculture. Genomic comparisons of crops adapted to different environments can identify alleles associated with drought, heat, salinity, and flooding tolerance. These adaptive variants can then be incorporated into breeding programs to develop varieties capable of maintaining productivity under changing climatic conditions.

Conclusion

Pangenomics has transformed crop genomics by moving beyond the limitations of single-reference genome approaches. By integrating genomic information from multiple individuals, it provides a comprehensive representation of the genetic diversity present within a crop species. It enables the identification of core, accessory, and unique genes as well as PAVs, CNVs, structural variations, and other forms of genetic diversity.

For crop breeding, pangenomics offers important opportunities for discovering novel genes associated with disease resistance, abiotic stress tolerance, yield, nutritional quality, and environmental adaptation. Its integration with genomic selection, marker-assisted selection, genome editing, genome-wide association studies, and artificial intelligence can accelerate the development of improved crop varieties.

As sequencing technologies become more affordable and computational methods continue to advance, pangenomics is expected to become an important component of modern breeding programs. It will contribute to the development of high-yielding, disease-resistant, climate-resilient, and nutritionally enhanced crops and will enable breeders to make more effective use of the genetic diversity available within crop species.

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The Hidden Cost of "Net Zero": How Carbon Accounting Can Mislead

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Introduction

In recent years, "net zero" has become the most repeated pledge in climate and corporate sustainability policies. The announcement made at the COP26 summit indicated that India will become a net-zero country by 2070, twenty years after the target of 2050 set by the US, UK, EU and ten years behind China who will become net-zero by 2060. India has 17% of the world's population and yet it emits only 5% of the total greenhouse gases, which is why it shouldn't be following the schedule of countries who became industrialized many decades ago. The argument of common but differentiated responsibility of nations (CBDR) is very much true and justified in this situation, but this same argument indicates the real issue with the concept of "net-zero" as an international agenda as everyone gets to define the term according to their own schedule.

More than 140 countries and biggest multinational corporations already committed to net-zero targets, accounting for the significant share of global GDP. Concerning India, it is now working on the development of the Domestic Carbon Credit Trading Scheme (CCTS), which will be helping to reach the goals. The idea is clear do not produce more CO₂ than you absorb. In fact, "net zero" became one of the most controversial and easily manipulated figures in modern economics.

Carbon accounting is defined as the way of quantifying and monitoring greenhouse gas emissions and removals resulting from an action, organization, product, farm, project, or nation. It has become standard practice for companies and nations to make pledges toward "net zero" in relation to climate action. However, underneath the polished graphs and reports, there lies a much more complicated reality: the carbon accounting methods that quantify "net zero" and challenges in accounting without leakages.

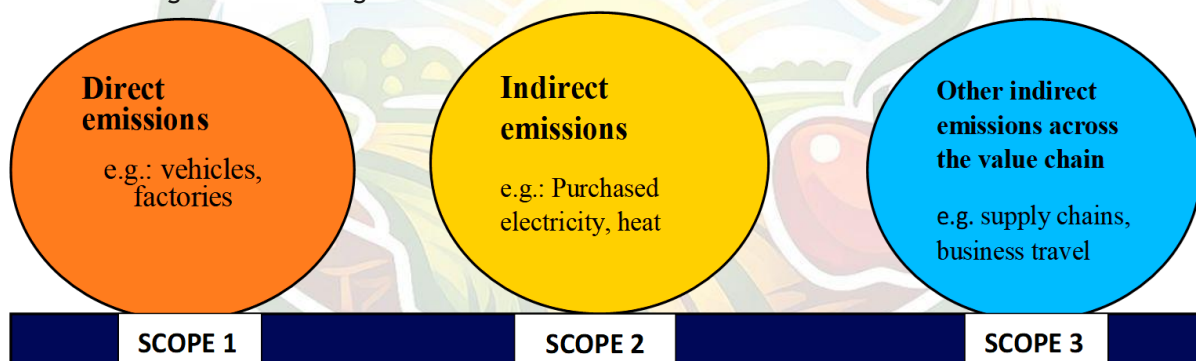


Fig 1: Framework of categorization of organizational emissions

Importance of Carbon Accounting

1. Misleading carbon accounting isn't just a reporting issue, it has economic and ecological consequences.
2. Investors allocate capital based on these numbers.
3. Policymakers set targets and regulations by assuming the data is accurate.
4. If the accounting is wrong, capital gets misallocated.
5. Gap between perceived and actual progress keeps widening.
6. Climate risk goes under pricing.

Challenges in Carbon Accounting

1. **Multiple methodologies:** Companies choose frameworks like the GHG Protocol, ISO standards or the Science-Based Targets initiative and no single universal methodology exists.
2. **The scope 3 blind spot:** Scope 3 emissions are largest indirect contributor to emissions but difficult to account, this is where leakages happens.
3. **Hidden carbon debt:** Emissions embedded in building, transporting, installing renewable energy systems are often neglected and eventually retiring wind turbines, solar panels, and batteries.

4. The offset illusion: Carbon offsets and credits allow companies to claim reductions they haven't actually made themselves by paying for emissions reductions elsewhere for reforestation, renewable energy projects or carbon capture. This shows net zero in papers of organization but not in reality.

5. Question of additionality: Countries or companies classify the natural, unmanaged forests as "managed land" in their inventories and count them as natural carbon absorption.

Challenges in Carbon Accounting in Agriculture Sector and Solutions

Corporate targets frequently focus on energy and industry while less focus on farming or agricultural emissions. Livestock methane emissions, land-use claims like counting unmanaged forests as "managed" carbon sinks or crediting farming practices and systems, soil carbon sequestration credits etc. can be exploitable but problem in using estimated data rather than measured ones, less studies on carbon credits generation and linking to organizations, MRV (monitoring, reporting and verification) issues, dynamic nature of agriculture and management practices, long term measurements costs time, money and energy, dilemma over duration of practices that actually helps in sequestration etc.

To resolve these issues, farm level primary data management, independent MRV (measurement, reporting, verification) systems instead of one-time certifications, apply reversal buffers for soil/land credits, standardize on one methane metric, use of accredited registries and third-party audits, and tie each credit to a specific traceable claim so invalidate credits don't undermine total net-zero progress.

Conclusion

Net zero is a useful destination, but the road there is currently mapped with inconsistent, challengeable metrics. Too fulfil the gap between reported progress and real emissions reductions will require standardized accounting rules, better verification of offsets, diversification of targeted sectors under accounting of carbon credits and honesty about timelines of decarbonization.

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From Soil to Smartphones: Integrating AI, Plant-Based Nutrition and Precision Agriculture for Gen Z Health

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Abstract

Historically, soil has been considered the basis of life, supporting the bacteria, plants, animals, and nutrients necessary for human survival. Even though soilless production is made possible by contemporary cultivation technologies like hydroponics and aeroponics, soil-nourished plants are still essential sources of naturally enriched nutrients that are necessary for human health. In order to create individualized health systems for Generation Z (Gen Z), this study investigates the integration of artificial intelligence (AI), horticulture, and plant-based nutrition. By using image-based analysis to determine food composition, identify vitamin shortages, and produce personalized diet recommendations, the study investigates how AI-enabled smartphones serve as portable nutrition laboratories. AI applications in agriculture, such as satellite imaging, IoT sensors, machine learning, and predictive analytics, improve decisions about crop yield prediction, irrigation control, soil health, and pest and disease detection. Rich in dietary fiber, vitamins, minerals, antioxidants, and phytochemicals, plant-based meals have a major role in preventing chronic illnesses and enhancing general health. Furthermore, precision nutrition based on genetic, metabolic, and lifestyle parameters is made possible by AI-driven diet-gene interaction study. As smartphones link agricultural output with individual wellness, the study demonstrates a paradigm shift away from experience-based agriculture and toward data-driven food and health systems. Climate-smart nutrition and resilient food systems that promote human and global health can be achieved through the integration of AI, sustainable horticulture, and digital health technology.

Keywords: AI, Gen Z, Smartphone, Plant based foods, Health

Introduction

Soil is the mother and origin of all creatures in the world. It serves as the foundation for nutrients, microbes, plants, and animals. Earlier, it was believed that without soil there would be no food, no oxygen, and no life. However, with advancements in science, cultivation is now possible without soil through technologies such as hydroponics and aeroponics. Yet, these systems cannot fully replace soil-nourished plants and their naturally enriched nutrients that provide essential health benefits to humans. Plants and plant-based foods play a crucial role in the development and maintenance of the human body. Gen Z refers to the youth of the nation, for whom smartphones have become a basic necessity. By using AI and smartphones, it is possible to determine the nutritional requirements of the human body through image-based analysis. AI can assess nutrient deficiencies by identifying visible symptoms and based on this analysis, can also generate an appropriate diet chart for individuals.

Horticulture and agriculture have traditionally relied on experience-based decision-making. In most farming systems, individuals are responsible for deciding the application of fertilizers, insecticides, pesticides, and herbicides. Determining when, where, and how much to apply these inputs has long been considered a critical decision based on the knowledge and experience of agricultural experts. However, with the advancement of artificial intelligence (AI), decision-making processes are becoming more data-driven and precise. AI now supports agricultural management through technologies such as IoT sensors, satellite imaging, predictive analytics, and modern machine learning techniques. These technologies help monitor soil moisture stress, nutrient availability, disease incidence, pest outbreaks, and physiological disorders in crops. Sensors, including camera-based systems, assist in detecting these parameters, and farmers can easily access and analyze the results through smartphones.

Fruits and vegetables play a crucial role in maintaining overall human health and body functioning. Plant-based foods provide essential dietary fiber, phytochemicals, antioxidants, vitamins, minerals, proteins, carbohydrates, and other bioactive compounds. These functional foods help prevent chronic diseases such as obesity, cardiovascular disorders, diabetes, and allergic responses, thereby contributing to improved health and well-being.

With the integration of AI and smartphones, Generation Z (Gen Z) users can assess food quality and obtain personalized diet recommendations based on individual body requirements. AI-based research demonstrates that diet-gene interactions can be computationally analyzed to design individualized dietary strategies. Disease detection in crops has also become easier through smartphones by capturing images of visible symptoms. Crop yield prediction can now be achieved by analyzing interactions among weather data, soil conditions, and crop growth parameters. Nutrient

deficiencies can be identified accurately, and suitable fertilizer recommendations can be provided to correct deficiency symptoms. Automated irrigation systems further enhance efficiency by allowing computers or smartphones to regulate irrigation based on real-time soil moisture conditions. Additionally, AI contributes to quality enhancement of plant foods through value addition, nutrient retention monitoring, postharvest prediction, and automated food sorting.

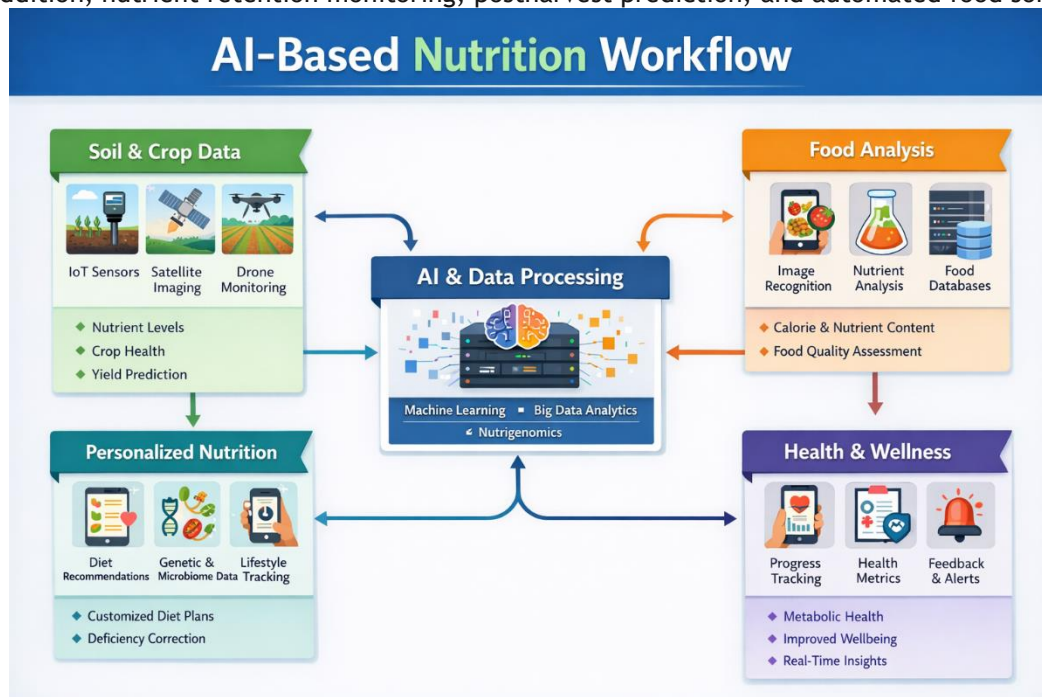


Fig 1. AI- Based Nutrition model, Image Source: AI

Smartphones are increasingly functioning as portable nutrition laboratories. AI-powered systems can identify foods through camera images, estimate calorie and nutrient content, track individual eating behavior, and generate personalized diet plans. AI models provide nutrient recommendations tailored to individuals, enabling precision nutrition based on genetics, metabolism, microbiome composition, and lifestyle patterns.

Gen Z represents the primary users and consumers of AI and digital technologies. Therefore, it is essential to promote the responsible and sustainable use of AI, as excessive dependence on technology may lead to potential risks. Gen Z is driving the digital revolution and shaping modern wellness culture through digital platforms. This generation demonstrates unique characteristics such as technological dependence, preference for personalization, environmental consciousness, and a strong focus on preventive healthcare. AI-based nutrition applications provide instant feedback, gamified health tracking, and data-driven lifestyle optimization. AI-driven plant-based diet adoption is supported through recipe recommendation systems, nutrient optimization algorithms, sustainability scoring tools, and personalized meal planning.

Plant-based foods are rich in micronutrients and phytonutrients essential for human health. Fruits and vegetables provide vitamin C, folate, potassium, magnesium, and dietary fiber. Berries, citrus fruits, leafy vegetables and nuts and seeds are major sources of vitamins, minerals and carbohydrates, which reduce oxidative stress, slow aging process and also improve immune response. Below is the table which tells the nutrients and its deficiency symptoms.

Table 1. Macronutrients functions and its sources:

Nutrient	Role	Healthy Plant Sources
Carbohydrates	Energy supply	Rice, wheat, millets, fruits
Protein	Body building	Lentils, soybean, chickpea, quinoa
Healthy Fats	Brain & hormone health	Nuts, seeds, avocado, flaxseed
Dietary Fiber	Gut health	Fruits, vegetables, oats, legumes

Table 2. Minerals function its deficiency along with its sources:

Mineral	Function	Deficiency Symptoms	Plant-Based Sources
Iron (Fe)	Hemoglobin formation	Anemia, fatigue	Spinach, lentils, jaggery, beans
Calcium (Ca)	Bone and teeth health	Weak bones	Sesame seeds, ragi, broccoli
Magnesium (Mg)	Muscle & nerve function	Muscle cramps	Nuts, seeds, whole grains
Potassium (K)	Blood pressure control	Weakness	Banana, coconut water, potato
Zinc (Zn)	Immunity, wound healing	Poor immunity	Pumpkin seeds, legumes
Iodine (I)	Thyroid function	Goiter	Iodized salt, sea vegetables

Phosphorus (P)	Energy metabolism	Bone pain	Nuts, legumes
Selenium (Se)	Antioxidant defense	Weak immunity	Sunflower seeds, whole grains

Table 2. Major vitamins functions its deficiency along with its source:

Vitamin	Main Function in Body	Deficiency Symptoms	Major Plant-Based Sources
Vitamin A (Retinol/B-carotene)	Vision, immunity, skin health	Night blindness	Carrot, spinach, pumpkin, mango, sweet potato
Vitamin B1 (Thiamine)	Energy metabolism	Fatigue, nerve weakness	Whole grains, legumes, sunflower seeds
Vitamin B2 (Riboflavin)	Cell growth, metabolism	Mouth cracks, skin disorders	Almonds, mushrooms, green vegetables
Vitamin B3 (Niacin)	Nervous system function	Pellagra, skin inflammation	Peanuts, whole grains, legumes
Vitamin B6	Brain development, protein metabolism	Anemia, depression	Banana, chickpea, potato
Vitamin B9 (Folate)	DNA synthesis, pregnancy health	Megaloblastic anemia	Spinach, broccoli, lentils
Vitamin B12	Nerve function, RBC formation	Anemia, weakness	Fortified cereals, nutritional yeast*
Vitamin C	Immunity, antioxidant	Scurvy, weak immunity	Citrus fruits, guava, amla, capsicum
Vitamin D	Calcium absorption	Bone weakness	Sunlight exposure, fortified foods
Vitamin E	Antioxidant protection	Muscle weakness	Nuts, seeds, vegetable oils
Vitamin K	Blood clotting	Excess bleeding	Leafy greens, cabbage, broccoli

Future developments may include digital twins for nutrition prediction, real-time metabolic monitoring, AI-guided functional food design, and climate-smart dietary recommendations. Horticulture and agriculture scientists can further utilize AI for research purposes, including the development of nutrient-dense crop varieties, functional foods, bio fortification strategies, and enhanced farm-to-consumer digital integration.

Conclusion

A model change in food systems can be seen in the move from soil to smartphones. Plant-based diets, agricultural productivity, and personal well-being are all integrated into a single ecosystem thanks to artificial intelligence.

Food is now data-driven wellbeing for Gen Z, not just a source of nourishment. Smartphones are smart interfaces that convert agricultural results into tailored health advice. Through the integration of digital health technology, AI-powered nutrition science, and precision agriculture, society advances toward sustainable food systems that support human and planetary health. The future of nutrition depends on how well we link food to human biology as well as what we farm.

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Beyond Human Hands: The Robotic Revolution in Food Packaging

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Summary of Article

Robot palletizing is becoming an important part of modern packaging operations, particularly in the food and beverage industry, where high production speeds, product variety, hygiene and worker safety are one of these major concerns. Traditional palletizing depends heavily on repetitive manual lifting and stacking, which can reduce productivity and place considerable physical strain on workers. The introduction of robotic palletizers has changed this line to line operation by providing faster, more consistent and reliable pallet formation. Modern systems can handle different packaging formats and are integrated with conveyors, case packers, wrapping systems, sensors and vision technologies. Recent developments in artificial intelligence, machine learning and digital twin technology are further expanding their capabilities and reducing the need for frequent manual adjustments. However, the initial investment, technical expertise, maintenance and employee upskilling can improve adoption. Robotic palletizing therefore represents more than simple automation, it is becoming a strategic component of sustainable packaging operations. This development method is expected to create some of these new opportunities for engineers and researchers working across food technology, packaging, robotics and automation.

Keywords: Artificial Intelligence; Machine learning; Robotic palletizing; pallet handling.

Introduction: From Manual Stacking to Intelligent End-of-Line Operations

Traditionally, one of the most physically strenuous and injury-prone operations in a food and beverage manufacturing plant is palletizing, which involves repeatedly lifting, twisting and stacking heavy cartons at the end of high speed lines. With growing product lines and distribution channels, manual palletizing was proving to be a limiting factor in throughput, consistency, and worker safety. A robotic palletizing solution has become a viable, cost-effective and increasingly popular solution to end of line packaging, moving it from a labour intensive process to a highly engineered and data driven process.

In the food and beverage industry, this is especially noteworthy as poor pallet quality, traceability and hygiene impact downstream logistics, cold chain integrity and, ultimately, product safety and brand reputation. Today's robotic palletizing solutions are no longer simply a muscle replacement phenomenon, but are essential parts of smart and connected factories.

Technology Landscape in Food and Beverage Palletizing

In the food and beverage sector, robotic palletizers can come in three types - articulated arm, gantry and collaborative robots (cobots) and each have a particular throughput, payload capacity and footprint. High-speed carton/case handling usually employs articulated arms and gantry systems are utilized for large size patterns and heavy loads. For small and medium enterprises (SMEs) seeking compact and re deployable options, emerging cobot palletizers with built-in safety sensors and reduced payloads prove to be an appealing option.

These systems are becoming more interconnected with the conveyors on the upstream side, case packer machines, automatic stretch wrappers and warehouse management systems. Vision systems and high-grade sensors can provide robots with accurate position, orientation and package integrity information, and end of arm tooling can accommodate a wide variety of packaging formats, including corrugated cartons, shrink wrapped bundle, trays, sacks and crates, without harming package integrity or risking food safety. The latest advancements in artificial intelligence and machine learning allow for pattern agnostic palletizing, which minimizes the need for manual reprogramming by robots to adjust to new case dimensions or mixed stock keeping unit (SKU) pallets. (Bd et al., n.d.)

For instance, in the Indian bakery and dairy segments, the large processors like Amul, Britannia, ITC, Parle, Nestlé India and Aavin have introduced or experimented with robotic palletizing to handle the high line speeds, multi SKU production and cold chain applications. The same type of deployments are being observed in around the world in the food packaging sector such as beverages, confectionery and ready to eat segments where reliability and hygienic design are clearly important purchase criteria.

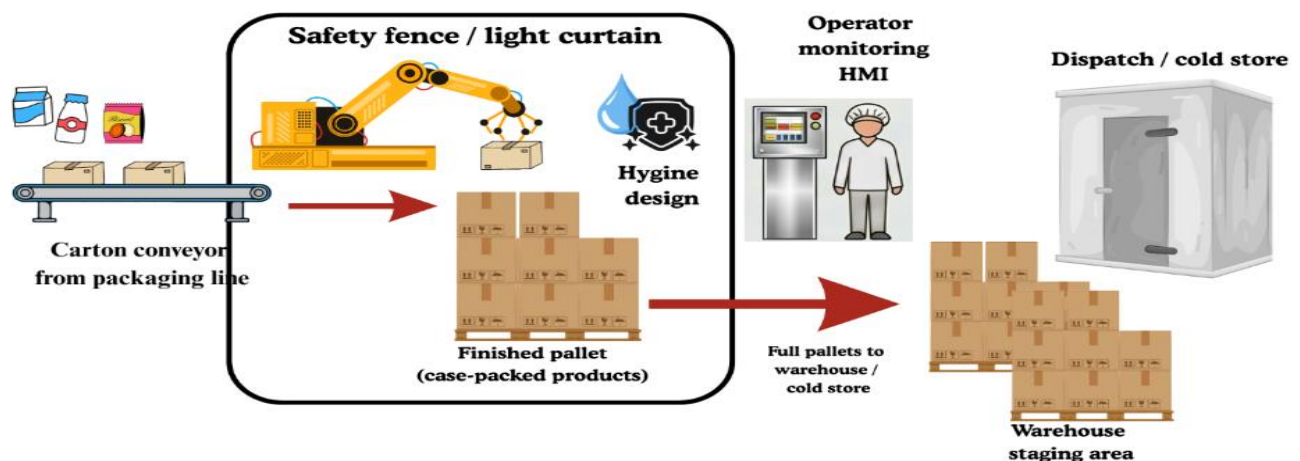
Operational and Hygienic Benefits for Manufacturers

Throughput, consistency and ergonomics are the key operating benefits of robotic palletizing for food and drinks applications. Robots carry out a high number of operations per cycle, without fatigue, and can work around the clock in

long shifts, to meet peak seasonal demands and e-commerce motivated order variability. The repeatability of pallets is down to the millimetre, which enhances load stability, truck fill efficiency and safety while transporting and handling in the warehouse. Ergonomic and safety advantages are as important. Robotic palletizers minimize (musculoskeletal disorders) MSDs, back injuries and lost time accidents by eliminating repetitive heavy lifts and awkward positioning of the operator and can help free up operator time for supervision, quality monitoring, and system optimisation. This is consistent with the results of several recent industrial case studies that have shown savings in manual handling injuries after the installation of palletizers. (Aroub, 2019)

Robotic palletizing technology is well suited to handle the additional design constraints imposed by food safety and hygiene requirements. New variations of palletizers for wet or chilled conditions include enclosed drives, washdown compatible structures, food grade lubricants and very little horizontal dust accumulating surfaces. Robots can be used in low temperature cold rooms, high humidity location to do reliable work and feeding to the stronger cold chain management of dairy, meat, frozen food, and Beverage companies. (Sied, 2025).

ROBOTIC PALLETIZING CELL IN A HYGIENIC FOOD PACKAGING LINE



Economics, Adoption Barriers, and Workforce Implications

Even though technically they will have their merits, the decision to adopt these technologies in a food and beverage plant will depend on economics, integration difficulty and workforce implications. While the total cost of ownership of robotic palletizers may be competitive with manual operation, taking into account factors such as labour availability, worker absence, rework, and injury-related costs, upfront hardware investment can be significant for small and medium-sized enterprises (SMEs). Common issues that processors often encounter are the lack of knowledge about future product mix, limited knowledge of technical support and spares, and lack of in-house skills to program and maintain robotic cells. To overcome these, integrators are increasingly providing “palletizing cells” that are modular and pre-engineered for easier deployment and outcome based contracts and remote monitoring services to reduce risks. (Sied, 2025). The effects on jobs are more complex than those of job displacement. Experience in food and warehouse applications shows that robotic palletizers tend to eliminate manual, low-skill stacking jobs and bring new roles to the market, such as technicians, controls engineers, and data analysts who are required to set recipes, optimise pallet patterns, and interpret performance dashboards. Upskilling and cross training programs play an important role in successful implementations, especially in regions where there is a shortage of labour and where youth unemployment exists.

Future Directions: AI, Digital Twins, and Connected Intralogistics

The fourth generation of robots for palletizing is closely connected to the other Industry 4.0 projects and applications in warehouses and intralogistics. Increasingly, full and empty pallets are being moved by autonomous mobile robots (AMRs) or automated guided vehicles (AGVs) to and from palletizing cells to achieve a fully automated dock to dock flow. On the software side, manufacturers can simulate palletizer layouts, stress test various pallet patterns, and optimise line balancing before physical changes are made (“Intelligent Robotic Palletizer System,” n.d.). Anomaly detection within drives or grippers, performed based on vibration, temperature, and current draw signatures can be used to schedule interventions before unplanned downtime occurs, using condition monitoring and predictive maintenance. Furthermore, sustainability and traceability goals are also met with data rich palletizing systems. With better stacking, as a result of vehicle utilisation, transport emissions are decreased, with integration of traceability systems securing the association of each pallet with batch, allergen and temperature history data throughout the supply chain. In today's world, where food brands strive to prove their environmental impact as well as supply chain visibility, robotic palletizers are no longer just a side automation solution, but a key asset.

Implications for the Next Generation of Food Engineers

Robotic palletizing is an applied field where several disciplines converge, which is why it is an exciting field of study for students and early career professionals in Food Technology, Packaging, Mechanical Engineering, Mechatronics, and Data Science. Understanding of product and packaging characteristics, hygiene and cleaning regimes, safety standards, control systems and AI enabled perception algorithms is required to design, commission and optimize these systems. Practical testbeds for concepts in the Industry 4.0 can be realised in the academic curriculum and industry - academy partnerships with the hardware in the loop simulations, the digital twin and the performance analytics. This is especially true for the emerging economies, in which food and beverage sector is undergoing a significant transformation and the demand for engineers who are able to integrate processing and packaging with intralogistics is high.

Conclusion

From niche solutions in high throughput plants to standard elements of food and beverage packaging operations, Robotic palletizers have come a long way. These systems, which integrate mature robotics with elements of sensing, AI and connected warehousing, offer increased throughput, greater uniformity / quality of pallets, better ergonomics and greater utilisation of transport and storage capacity. Adoption is picking up in dairies, bakeries, and beverage plants in other regions, as well as large, global multi-nationals, as modular solutions and service based models reduce entry barriers. The most interesting prospects for the future are the close integration of palletizers with upstream processing, packaging and downstream intralogistics, which is achieved using data driven control and digital twins. For manufacturers, it is a chance to look at palletizing as a “necessary end of line task” and instead consider it as a strategic point in the smart, resilient and sustainable food supply chain. Robotic palletizing is a fascinating and interdisciplinary area for future researchers and engineers, and further advancements in the fields of mechanics, controls, artificial intelligence, and human - robot interaction will continue to influence the future of food and drinks production.

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Beyond Taste: Leveraging Colour as a Strategic Advantage in Food Tech

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Summary of Article

Long before the first bite or sip, colour begins to influence how we perceive food. The colour of a food or a beverage can create expectations about its flavour, texture, quality and even its nutritional value, which sometimes influence our perception even before the first bite or sip. In the highly competitive food industry, food colours play a role beyond just visual aesthetics, they act as a tool for attracting consumers, communicating product identity and influencing purchasing decisions. This article explores the psychology behind food colours and ways in which it visually influences flavour perception and consumer behaviour. In addition, it discusses the rise in the use of natural food colorants and the technical difficulties involved with the stability of these natural colorants during processing and storage. In different food groups such as beverages, confectionery, dairy products, and processed foods, colour is becoming an important means of creating differentiation and meeting changing customer needs. By linking sensory science, consumer psychology and food innovation, this article explores how colour can act as a “silent salesperson” and give food products a competitive edge.

Keywords: Colour psychology; Consumer perception; Competitive advantage; Food colour.

The Silent Salesperson: How Colour Shapes Taste and Drives the Food Market

Have you ever gone to the supermarket to get milk and come home with a new snack that you didn't realise you wanted? You aren't alone, and it's not an accident. With all the competition in the food and beverage industry today, customers make their buying decisions in seconds. Our brains have already judged the quality, freshness and flavour of a product before we read a label on it, and long before we taste it. How? Utilising the most potent, yet unspoken instrument of the food industry: Colour.

Colour is not an afterthought but is the first psychophysical stimulus that establishes our expectations of the senses. It's the silent salesman on the shelf. Colour is usually the first characteristic consumer notice when they see any product. Bright colours tend to be associated with freshness and energy, while natural colour tones can indicate health and authenticity. Colour is a very powerful signal because often people's buying decisions are instantaneous. It helps the products stand out on crowded shelves, strengthening the brand identity and creates emotional connections with consumers (Spence and Velasco, 2018). Colour is no longer merely a decorative in Modern food and beverage markets, but is now a strategic tool that can impact buying decisions and offer a significant competitive edge to a brand.

Psychology of Food Colour

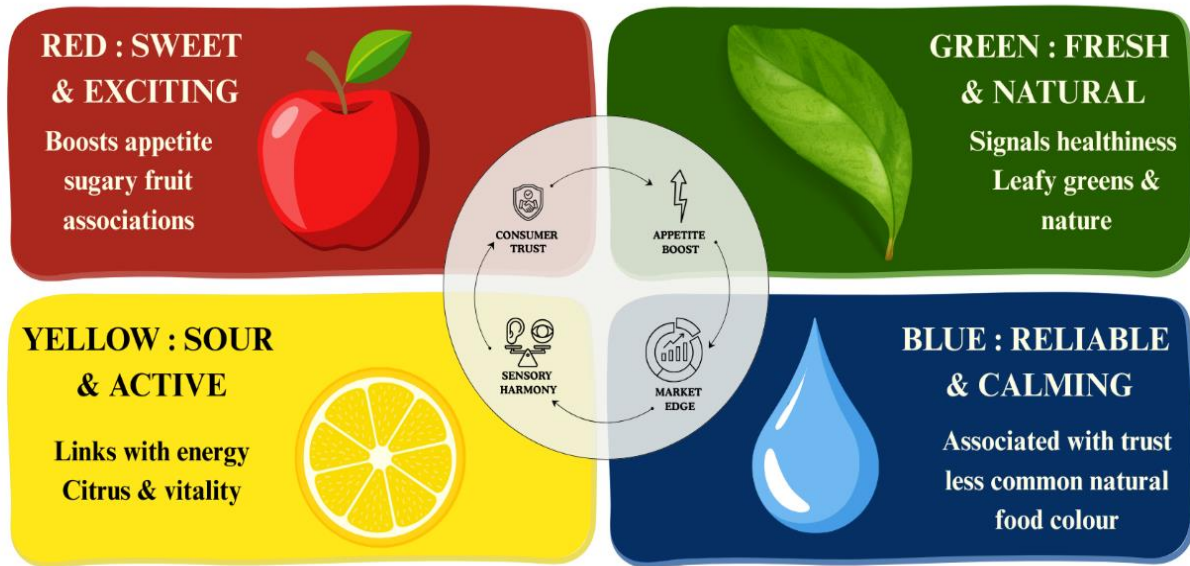
One of the strongest connections between the sense of sight and the sense of taste is found in food colour psychology. Specific colours are precursors of flavour with affective expectations. Red often represents a sweetness and energy; green, an acidity and sourness.

These connections are so profound that they can even affect the person's taste perception. It has been found that the colour yellow alone can decrease sourness detection (Won and Westland, 2017). So, colour is a stimulus, and it also plays an active role in the consumer experience of tasting flavour.

1. Red colouring is highly linked to sweetness, energy, stimulation and appetising properties.
2. Green hues typically signal acidity and sourness.
3. Yellow can physically alter taste thresholds, specifically by reducing the detection limit for sourness.
4. Blue tones project reliability, hygiene, high quality, and healthfulness.
5. Orange vibrancy stimulates psychological excitement and dynamism

There's also a lot of colour politics. To a consumer in North America, cherry is a bright-red fluid; to a consumer elsewhere, watermelon or rose would be as bright red. Mastering these particular colours isn't only about looking, it's about visual promise that matches the sensory reality in each and every target market (Won and Westland, 2017).

UNDERSTANDING FOOD COLOUR : A SIMPLE PERCEPTION MAP



Packaging Colour as a Silent Salesperson

Packaging is the first way consumers interact with a product, making it a primary communication tool that helps uncover the attributes of the actual product through visual information. When colours are integrated into packaging design, they evoke instant responses and promote crucial product differentiation. When consumers are making decisions on the spur of the moment, in seconds, packaging colour serves as a silent salesperson, influencing the perception and capturing the attention of the consumer (Spence 2015). Bright, natural colours are often linked to freshness, quality and flavour consumers like (Spence 2018).

1. White packaging symbolizes purity and cleanliness, and the quality of raw materials.
2. Black packaging exudes luxury, sophistication and exclusivity.
3. Transparent packaging (with little applied colour) gives a visual assurance of the product within and reassures consumers.

These visual cues instil positive expectations of the product, making them more attractive and likely to be purchased. Colours are also used strategically to prompt early sales and to reinforce brand recognition and long-term consumer loyalty.

Natural Colour Challenge

Food colourants are made from natural and synthetic sources to fulfil aesthetic requirements. Artificial colour is chemically synthesised with great stability and predictability of use, while natural pigments come from various biological sources (botanical, algal and animal sources), and there is a growing trend towards their use in favour of artificially synthesized pigments, due to their perceived health benefits and reliability. However, one of the processing challenges of natural colorants is the high variation in their natural colour, which is often susceptible to degradation under light, heat and other processing stresses (Silva et al., 2022).

Colour Strategies Across Food and Beverage Categories

For a food and beverage brand, colour is a convenient instrument that can help them achieve visibility and market share. For instance, in the dairy category, creamy yellows in dairy butter and cheese represent the richness and quality of the product, and white packaging indicates cleanliness and purity of the raw materials. In bakery and confectionery products, the colour is associated with the perfect texture of the surface of breads or pastries, while the bright colour of candies is associated with indulgence, fun and innovation. The colours of fresh and packaged products should be intense colours, to convey maturity and freshness without letting the consumer think that these products have been overprocessed. Fruit drinks must accurately represent the colour of the fruit they are made from, while bright saturated colours are a

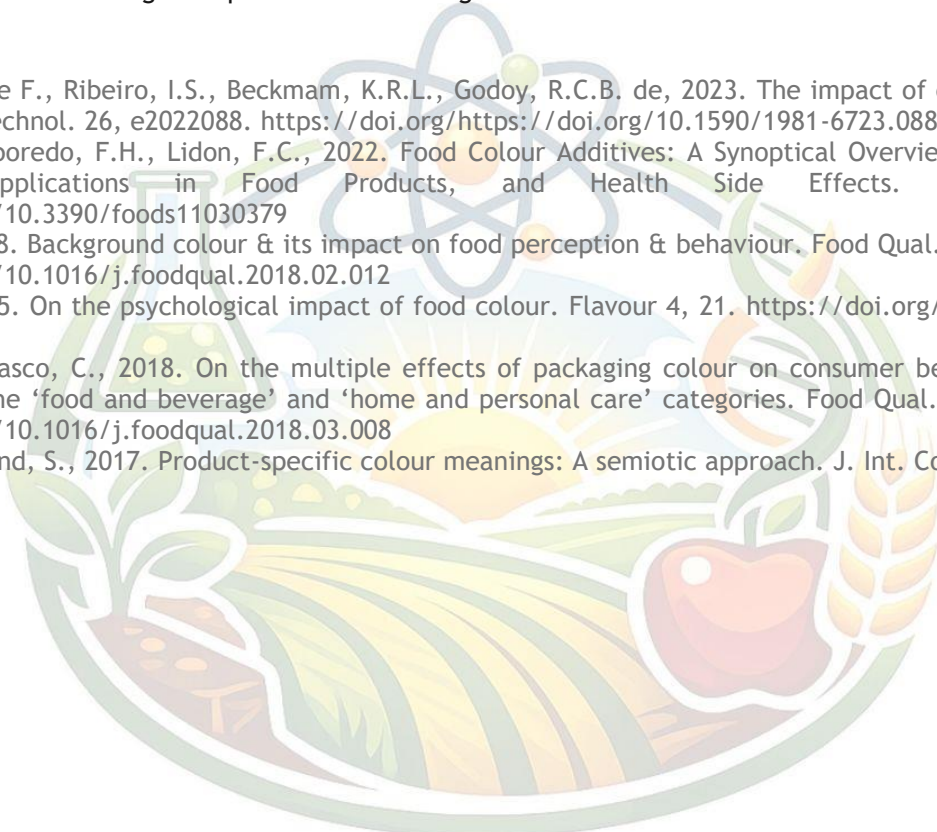
reflection of the high performance, stimulation and intensity of the soft drinks and energy drinks. Functional products and health-oriented foods frequently use vibrant colours such as, green and dark purple to indicate Naturalness, antioxidant content, and well-being (Muniz et 2023).

Conclusion

Colour can be considered a strong competitive tool in the food and beverage industry, affecting sensory perceptions, consumer behaviour and buying decisions. Through product appearance and packaging, it helps to convey characteristics such as taste, freshness, value, and quality, thereby contributing to effective marketing brand building. Colour also shapes expectations and emotions, increasing product attractiveness and competitiveness in crowded retail environments. It draws attention to products on busy shelves and makes them visible among numerous competing options. At the same time, colour helps establish visual connections between products and brands, reinforcing identity and loyalty among consumers. Suitability of colourant and colour stability management become even more important in the trend towards more natural “clean label” products. Therefore, colour management is a major part of product acceptance, positioning and food and beverage companies' sustainable growth.

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Biofertilizers: Harnessing the Power of Beneficial Microbes for Better Crops

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Introduction

The rapidly growing global population, coupled with declining per-capita agricultural land availability, is placing unprecedented pressure on agricultural systems to increase food production. However, growth in agricultural productivity is staggered at on place, while the intensive use of external inputs such as fertilizers, herbicides, pesticides, and irrigation water continues to increase. Fertilizers are one of major input to maintain the productivity but conventional fertilizers are low nutrient use efficiency which resulting substantial nutrient loss like volatilization, leaching, surface runoff and other pathways which leads to increase in cost of crop production with adverse environmental effects also. This imbalance highlights the need for more efficient and sustainable agricultural production systems that can produce more food from limited land and resources while minimizing environmental impacts. Within this context, biofertilizers have emerged as a promising and sustainable alternative to reduce dependence on chemical fertilizers without compromising productivity. Biofertilizers are microbial consortia that fix atmospheric nitrogen, mineralize nutrients locked in unavailable forms, or mobilize already-available nutrients to where they are needed. Unlike chemical fertilizers, the term "biofertilizer" is, in many ways, a misnomer it carries no nutrient reserve of its own. In ancient times farmers use biological nitrogen fixation unknowingly by using **rotating legumes** and manure "tea", commercial journey of biofertilizer is started in 1895 by launch of "Nitragin" as a seed inoculant and has since grown into today's advanced, multi-strain products that clearly boost nitrogen, phosphorus, and potassium availability across major crops. Biofertilizers are broadly categorized on the basis of the microbial group and the functional role they perform. These include nitrogen-fixing microbes such as *Rhizobium*, *Bradyrhizobium*, and *Frankia*; phosphate-solubilizing biofertilizers, comprising bacteria such as *Bacillus* and *Pseudomonas*; and potassium-solubilizing biofertilizers, among others. Collectively, these organisms promote plant growth through a combination of direct mechanisms like including nitrogen fixation, phosphorus solubilization, potassium solubilization, siderophore production, and phytohormone synthesis and indirect mechanisms like such as hydrolytic enzyme production, induction of systemic resistance, and bioremediation of heavy metals. India's biofertilizer market was worth USD 159.41 million in 2025 and is expected to grow to USD 443.79 million by 2034, expanding at a strong annual growth rate of 11.04% between 2026 and 2034 (IMARC Group, 2025). This sustained market expansion reflects the growing recognition of biofertilizers as a viable pillar of sustainable agriculture. Against this backdrop, the present chapter examines the classification and functional diversity of biofertilizers, their mechanisms of action, current formulation and application technologies, their market and policy landscape, and the challenges and future prospects shaping their role in sustainable agricultural systems.

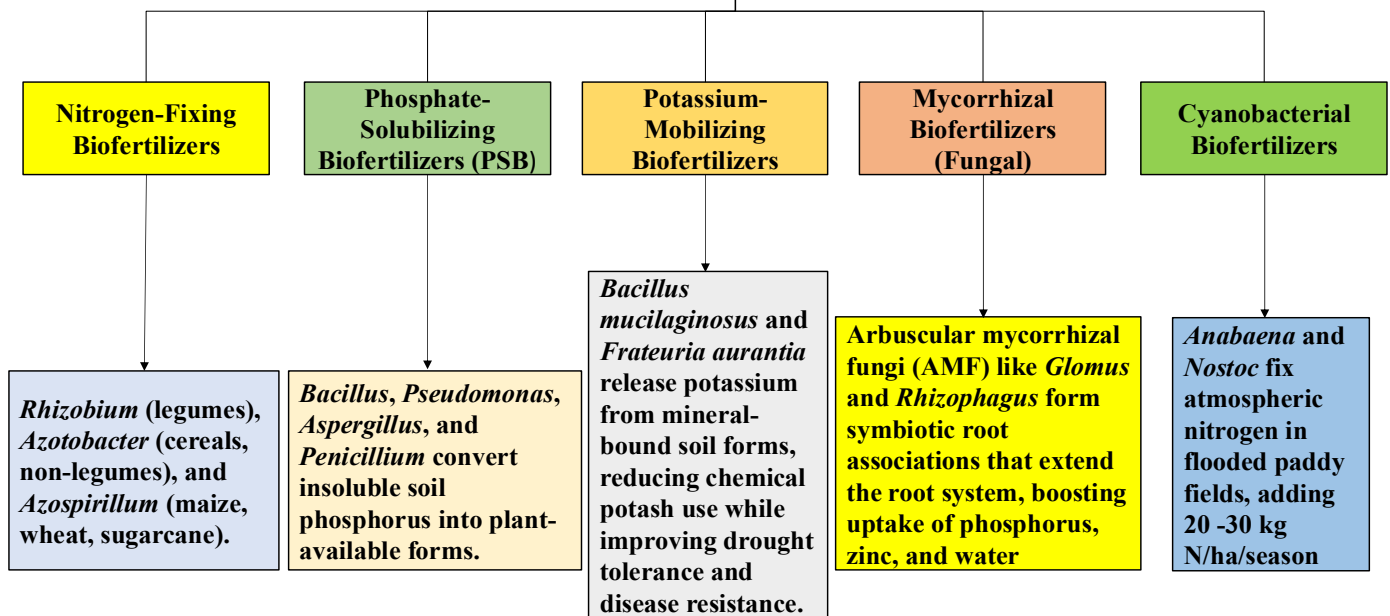
Current Status

India's move toward sustainable farming is being strongly supported by government policy. The most notable is the National Mission on Natural Farming (NMNF), approved in 2024, which plans to set up 10,000 Bio-Input Resource Centres and bring chemical-free farming to about one crore farmers. Alongside this, schemes like the Paramparagat Krishi Vikas Yojana (PKVY) and the Mission Organic Value Chain Development for North Eastern Region (MOVCDNER) offer direct financial help between ₹15,000 and ₹32,500 per hectare for organic inputs such as biofertilizers, along with farmer training through the National Centre of Organic and Natural Farming (NCOF). At the same time, technology is advancing too: in 2024, CSIR-National Botanical Research Institute partnered with a local entrepreneur in Odisha to set up a liquid biofertilizer production unit using better microbial strains, reaching over 25,000 farmers in the region (PIB, 2024). Liquid biofertilizers are becoming more popular in general because they last longer, keep microbes alive better, and work well with drip irrigation and modern fertigation systems used in horticulture. Looking at the overall market, nitrogen-fixing biofertilizers lead by type (55% share), cereals and grains are the top crop segment (40%), *Rhizobium* is the most-used microorganism (28%), seed treatment is the main method of application (52%), and South India leads by region (34%), thanks to its strong farmer cooperatives and early adoption of organic farming (IMARC Group, 2025).

Types of Biofertilizer

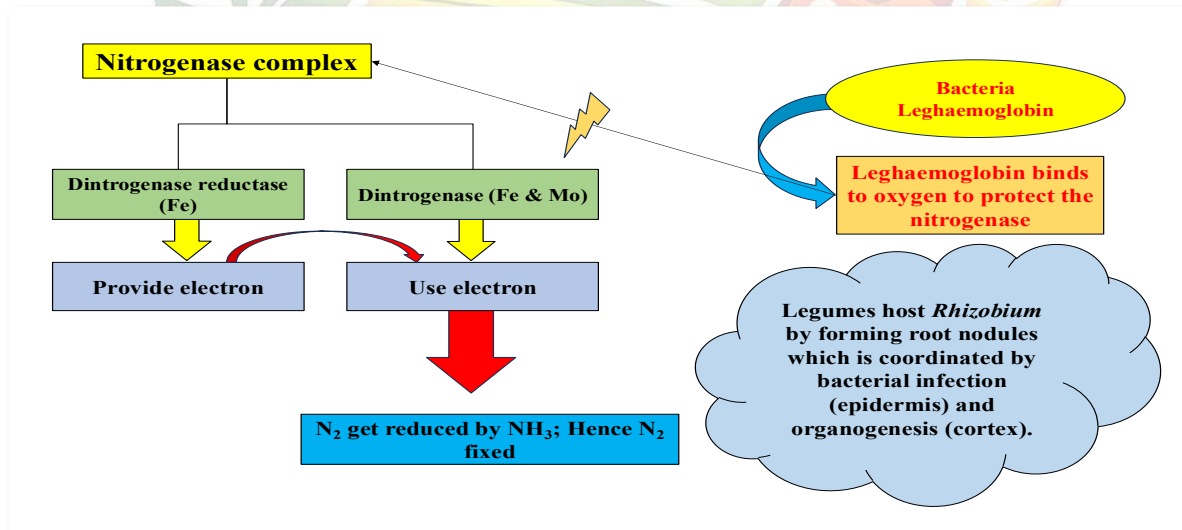
Biofertilizers can be grouped either by the microorganisms they contain or by the specific nutrient function they perform for plants. Each category contributes differently to soil health and crop growth, and together they form the main classes used by farmers and agronomists in sustainable nutrient management.

Biofertilizer



Mechanism of Action

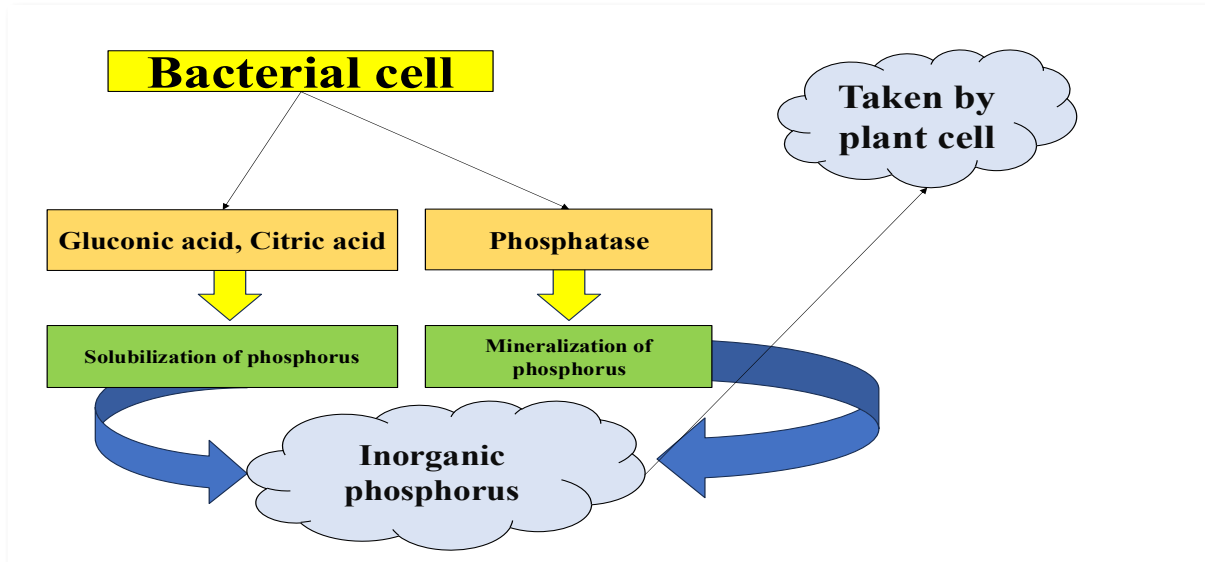
Biofertilizers exert their beneficial effects on plants through a combination of direct and indirect mechanisms, ranging from nutrient mobilization to the production of growth-promoting and protective compounds.



1. Nitrogen fixation: The process of biological nitrogen fixation by *Rhizobium* unfolds through a coordinated sequence of molecular and physiological events, beginning with root colonization and culminating in the conversion of atmospheric nitrogen into a plant-usable form. Infection raises plant ethylene, which naturally limits further nodulation. Some rhizobia counter this with **rhizobitoxine**, suppressing ethylene to allow more nodules to form (Stewart et al., 2012). *Azospirillum* is a Gram-negative, aerobic, nitrogen-fixing bacterium belonging to the family Spirillaceae. Unlike *Rhizobium*, it does not form root nodules but instead establishes an associative symbiosis with the plant root system. It shows a particular affinity for crops using the C4 (Hatch-Slack) photosynthetic pathway, making it especially suited to maize, sugarcane, sorghum, and pearl millet. Beyond nitrogen fixation, *Azospirillum* produces plant growth-promoting substances including indole-3-acetic acid (IAA), gibberellins, and cytokinin that stimulate root development and enhance the uptake of nitrogen, phosphorus, and potassium. Inoculation with *Azospirillum* has been shown to significantly

improve root architecture and root exudation, further reinforcing nutrient acquisition and plant growth (Trabelsi *et al.*, 2013). *Azotobacter* is a free-living, aerobic nitrogen fixer, with *A. chroococcum* the most common species in neutral-to-alkaline arable soils. Beyond fixing 15-93 kg N/ha, it produces Vitamin B complex, phytohormones (gibberellins, NAA), and in the case of *A. indicum* antifungal antibiotics that protect seedlings from root infections. It is commonly associated with rice, maize, sugarcane, bajra, vegetables, and plantation crops.

2. Phosphate Solubilization: Phosphorus solubilization by microorganisms occurs through several distinct biochemical processes, each converting insoluble, fixed forms of soil phosphorus into forms readily available for plant uptake (Daniel *et al.*, 2022).



Collectively, these nitrogen-fixing and phosphate-solubilizing mechanisms illustrate how biofertilizers work in tandem with the plant's own physiology mobilizing essential nutrients while simultaneously promoting root growth and offering protection against pathogens thereby laying the biological foundation for the sustainable nutrient management strategies discussed in the sections that follow.

Benefit of Biofertilizer

Continuous, indiscriminate use of chemical fertilizers has contributed to environmental contamination and long-term declines in soil fertility, leaving crops more disease-prone. This challenge is compounded by rising global food demand the world's population is projected to reach roughly 10 billion by 2050, with growing incomes driving a shift toward more resource-intensive, animal-based diets. Meeting this demand sustainably requires re-evaluating current reliance on chemical fertilizers and pesticides. Biofertilizers offer a safer, cost-effective, and eco-friendly alternative that helps preserve ecosystem balance while improving soil fertility over time. Studies report yield increases of 10-40% with biofertilizer use, driven by improved nitrogen fixation and enhanced protein, amino acid, and vitamin content in crops. Beyond nutrient supply, biofertilizers contribute organic matter, growth-promoting hormones, and micronutrients, while helping offset the negative effects of chemical fertilizer overuse underscoring the broader role soil microorganisms play in sustaining long-term soil health and crop productivity.

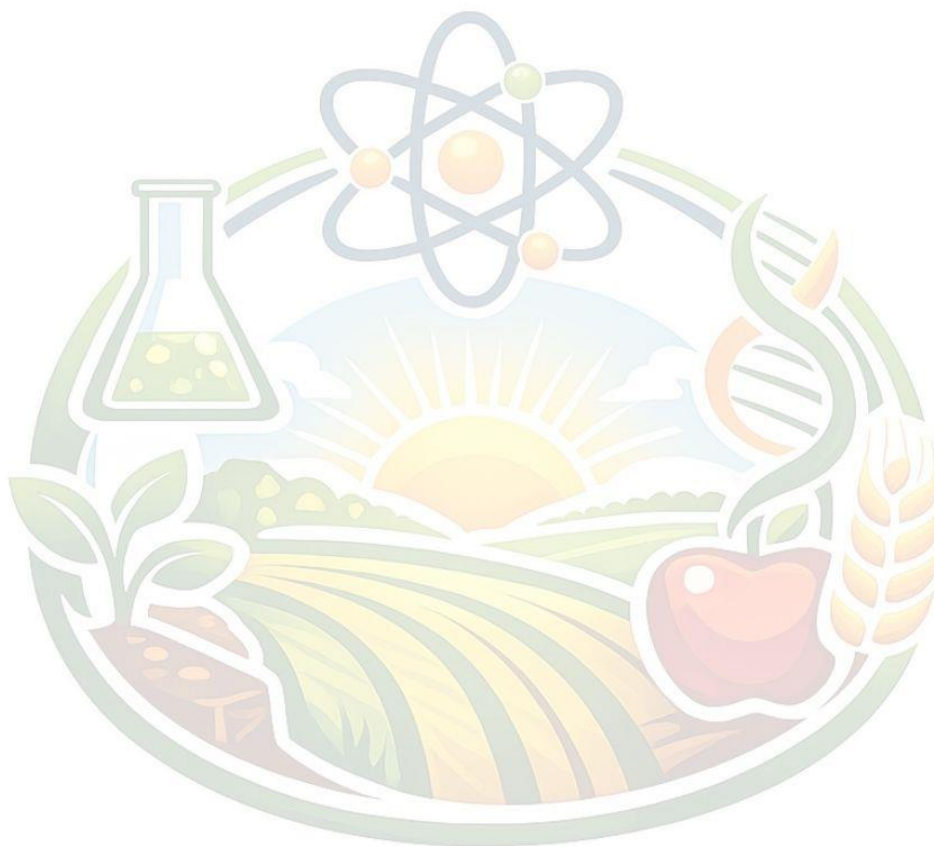
Conclusion and Future Prospectus

Given rising food demand, shrinking arable land, and the environmental costs of chemical fertilizers, biofertilizers stand out as a sustainable path forward improving nutrient availability, root growth, and soil health while boosting yields by 10-40%. Their effectiveness, however, is closely tied to soil organic carbon (SOC): microbial activity follows a U-shaped relationship with SOC, declining sharply below roughly 1.5% SOC and improving steadily above it. This means biofertilizer performance depends on baseline soil health, and soils with low SOC may need organic amendments (compost, FYM, residues) alongside microbial inoculation for best results. Future efforts should focus on SOC-calibrated, site-specific biofertilizer recommendations, better multi-strain and liquid formulations, integration with precision farming, and continued policy support positioning biofertilizers as a core, not peripheral, tool for sustainable and resilient agriculture.

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Oyster Mushroom Production Technology

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Abstract

Oyster mushroom (*Pleurotus* spp.) is an edible mushroom of economic importance popularly called “dhingri” in India. It is known for its high nutritional quality and ability to convert various agricultural and forest wastes into protein-rich food. Oyster mushroom cultivation in India started in the 1960s and has gradually developed into a commercial enterprise. *Pleurotus* can be cultivated on a variety of lignocellulosic substrates such as paddy, wheat and ragi straw, sugarcane bagasse, saw dust, corn cobs and other agro-industrial wastes. Successful production requires spawn prep, substrate prep, spawning and crop management. Correct temperature, humidity and ventilation are necessary for mycelial growth and fruiting. The crop is vulnerable to insect pests, competing fungi and bacterial diseases that require proper environmental management and timely protective measures. Oyster mushrooms can produce more than 500 kg of fresh mushrooms per ton of dry wheat or straw during a 45-60 day cropping period. Good harvesting, storage, packaging and transportation practices are important to retain quality and improve shelf life. Therefore, oyster mushroom cultivation has great potential for efficient utilization of agricultural wastes, nutritional security, income generation and sustainable mushroom production especially in areas with suitable agro-climatic conditions.

Introduction

Known as “dhingri” in India, the oyster mushroom (*Pleurotus* sp.), a member of the Class Basidiomycetes and Family Agaricaceae, grows naturally in temperate and tropical forests on dead and decaying wooden logs or occasionally on dying trunks of deciduous or coniferous woods. It can also grow on decomposing organic matter. Depending on the species, the fruit bodies have a distinctive shell or spatula shape and can be white, cream, gray, yellow, pink, or light brown. It is one of the best fungi for creating food that is high in protein from a variety of agricultural or forest wastes without the need for composting.

Origin

In 1917, Flack began experimentally cultivating a species of oyster mushroom (*Pleurotus ostreatus*) on wood logs and tree stumps in Germany. Block, Tsao, and Hau mastered growing technique in the United States. In India, oyster mushroom cultivation began in the early 1960s. In the middle of the 1970s, commercial cultivation started.

Botanical Description

A fleshy shell or spatula-shaped cap (pileus), a short or long lateral or central stalk (stipe), and lengthy ridges and furrows beneath the pileus (gills or lamellae) are the three separate elements of oyster mushrooms. The spores are carried by the gills, which extend from the cap's margin to the stalk. The smooth, cylindrical spores germinate quickly—between 48 and 96 hours—on any type of mycological medium. *Pleurotus* mycelium is entirely white.

Production

The third most popular type of cultivated mushroom is oyster mushrooms. Nearly 85% of the approximately one million tons of oysters produced worldwide come from China, the world's top producer. Korea, Japan, Italy, Taiwan, Thailand, and the Philippines are among the other nations that produce oyster mushrooms. Due to poor local demand, India now produces just about 1500 tons of this crop. Large export demand orders that can only be fulfilled by establishing a connection between producers, cooperatives, and exporters are another barrier.

Production Technology

Agro-climatic Requirements: For six to eight months out of the year, oyster mushrooms may thrive in temperatures between 20 and 30°C and humidity levels between 55 and 70%. By supplying the additional humidity needed for its growth, it can even be grown in the summer. The ideal growing season is from March/April to September/October in hilly locations over 900 meters (m.s.l.) and from September/October to March/April in lower regions.

Growing and Potential Belts: Orissa, Karnataka, Maharashtra, Andhra Pradesh, Madhya Pradesh, West Bengal, and the majority of the hill states in the northeast are the main Indian states that produce this mushroom.

Varieties Cultivated: *Pleurotus* has the greatest number of commercially grown species that are suitable for year-round cultivation out of all the farmed mushrooms. With the exception of *P. olearius* and *P. nidiformis*, which are toxic, all oyster mushroom species are edible. *P. flabellus*, *P. sajor cajo*, *P. sapidus*, *P. membranaceus*, *P. citrinopileatus*, *P. eous*, etc. are among the species that are commercially grown worldwide in the summer, whereas *P. ostreatus*, *P. florida*, *P. cornucopiae*, *P. fossulatus*, *P. eryngii*, etc. are produced in the winter.

Cultivation Technology: The procedure for oyster mushroom cultivation can be divided into following four steps:

- a. Preparation or procurement of spawn
- b. Substrate preparation
- c. Spawning of substrate
- d. Crop management

Spawn Preparation

A pure culture of *Pleurotus* sp. is needed for inoculation on sterilized substrate. It takes 10-15 days for mycelial growth on cereal grains. It has been reported that jowar and bajra grains are superior to wheat grains.

Substrate Preparation

Oyster mushrooms can be grown on a variety of agricultural wastes that contain cellulose and lignin, which increases the production of cellulose enzymes and increases output. These include used citronella leaves, sugarcane bagasse, sawdust, jute and cotton waste, dehulled corncobs, peanut shells, dried grasses, sunflower stalks, used tea leaf waste, discarded waste paper, synthetic button mushroom compost, and straw from paddy, wheat, and ragi. Additionally, industrial wastes such as paper mill sludges, coffee byproducts, tobacco waste, apple pomace, etc. can be used to develop it.

The popular methods of substrate preparation are:

- a. Steam Pasteurization;
- b. Hot Water Treatment;
- c. Sterile Technique (Till method)
- d. Fermentation or Composting
- e. Chemical Sterilization.

Spawning of Substrate

The optimum grain spawn for spawning is freshly made (20-30 days old). Mycelium aggregation causes old spawn (3-6 months) kept at room temperature (20-30°C) to create a very thick mat-like structure, and occasionally immature pinheads and fruit bodies begin to develop inside the spawn bottle itself. Spawning should take place in a chamber that has been pre-fumigated with 2% formaldehyde for 48 hours.

Crop Management

1. Incubation: Spawned bags, trays or boxes are arranged in a dark cropping room on raised platforms or shelves for mycelium colonization of the substrate. Although mycelium can grow from 10 to 33°C, but the optimum temperature for spawn running lies between 22 to 26°C.

2. Fruiting: The fungus is prepared for fruiting once the mycelium has completely invaded the substrate. While bags with patchy mycelial growth may be left for a few more days to finish mycelial growth, contaminated bags containing molds may be thrown away. All species need high humidity (70-85%) during fruiting, even if they require varied temperature regimes. Depending on the humidity in the air, the cropping room needs to be sprayed with water often. Fruit bodies grown at 65-70% relative humidity are small with high dry matter, but those produced under humid conditions (85-90%) are larger with less dry matter. During cropping, the CO₂ content should not exceed 600 parts per million, or 0.6%. Fruiting requires adequate airflow.

Crop Protection Measures

1. The crop is vulnerable to attacks by mites, springtails, and flies (sciarid, cecid). Insect-specific pesticides must be sprayed on time.

2. Fungal infections might affect the crop. The substrate utilized for culture has been observed to contain a number of competing molds, including *Aspergillus* sp., *Cladosporium* sp., *Fusarium* sp., and *Rhizopus* sp. Benomyl or Bavistin spraying is a suggested preventative strategy.

3. Additionally, the crop is susceptible to diseases like bacterial rot, brown spot, and yellow blotch. The following control actions are required:

4. Appropriate humidity and temperature control during the growing season.

5. Applying chlorinated water with 100-150 parts per million of easily accessible chlorine on a regular basis every three to five days.

6. Using streptocycline and oxytetracycline.

Harvesting and Yield

The best shape for plucking can be determined by looking at the size and shape of the fruit body. To avoid leaving the stubs on the beds (straw), the fruit bodies should be collected by twisting them before the spores are discharged. If you select every mushroom from a cube at once, the subsequent flush will occur all at once. More than 500 kg of fresh mushrooms can be harvested for every ton of dry wheat or straw if the crop is cultivated in 45-60 days.

Post Harvest Management

Storage:

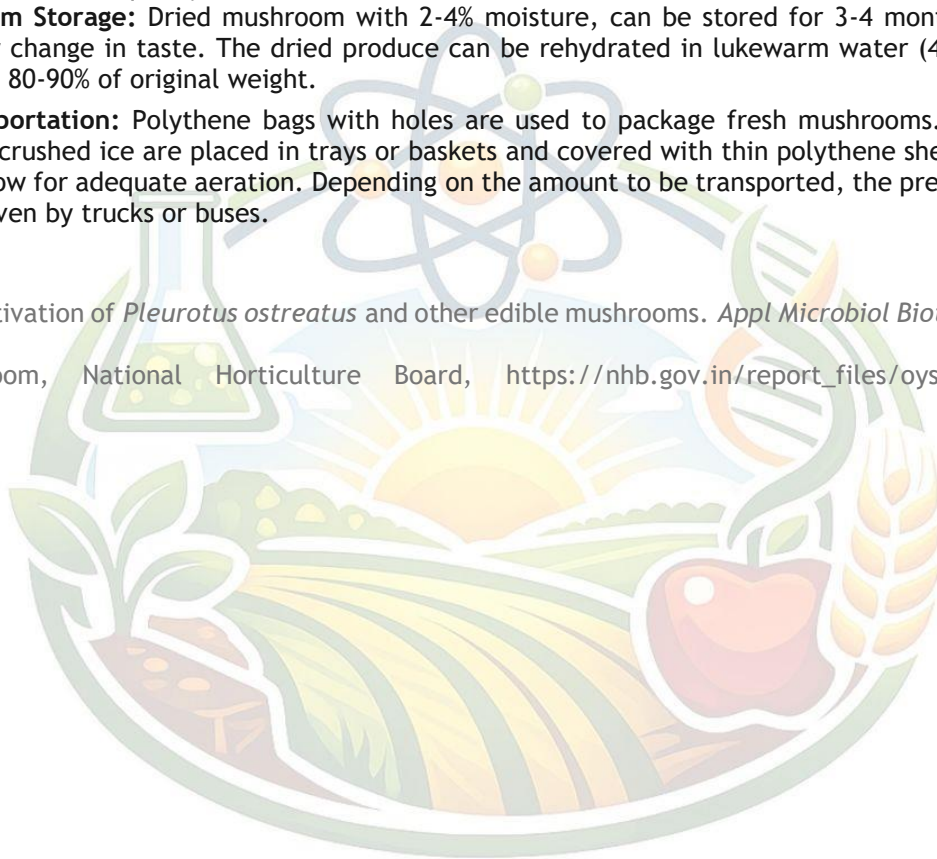
a. Short-term Storage: Fresh mushrooms are packed in perforated polythene bags which are directly sent to the local market situated nearby. Freshly harvested mushrooms can be stored at low temperature ($0-5^{\circ}\text{C}$) for 1-2 weeks without loss in quality in case it is to be sent to the distant markets.

b. Long-term Storage: Dried mushroom with 2-4% moisture, can be stored for 3-4 months in sealed pouches without any change in taste. The dried produce can be rehydrated in lukewarm water ($40-50^{\circ}\text{C}$) within 20-30 mins. giving 80-90% of original weight.

Packing and Transportation: Polythene bags with holes are used to package fresh mushrooms. Paper-wrapped poly pouches filled with crushed ice are placed in trays or baskets and covered with thin polythene sheets that have enough holes in them to allow for adequate aeration. Depending on the amount to be transported, the pre-packed pouches (250 or 500 g) can be driven by trucks or buses.

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A Paradigm Shift in Vegetable Production through Robotics, Automation and Smart Technologies

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Abstract

Vegetable production faces increasing challenges from labour shortages, rising input costs, climate variability and the need for sustainable resource use. Precision agriculture, integrated with robotics, artificial intelligence (AI), the Internet of Things (IoT) and advanced sensing, offers an effective approach to address these constraints. Agricultural robots equipped with cameras, LiDAR, Global Navigation Satellite System (GNSS) and AI can perform crop monitoring, weeding, spraying and harvesting with high precision. IoT-enabled sensors facilitate real-time monitoring of soil, crop and environmental conditions, supporting efficient irrigation, fertigation and crop protection. These technologies have particular potential in high-value vegetables such as tomato, cucumber, capsicum and lettuce. However, high investment costs, inadequate infrastructure, limited technical skills and variable field conditions remain major barriers. Integrating intelligent automation with human expertise can improve productivity, resource-use efficiency and sustainability in vegetable production.

Introduction

Vegetable crops are essential for food and nutritional security but require intensive management, including nursery raising, transplanting, weeding, plant protection, harvesting and grading. Increasing labour costs and seasonal labour shortages have made these operations increasingly difficult. Inefficient use of water, fertilizers and plant-protection products further increases production costs and environmental pressure. Precision agriculture shifts crop management from uniform practices towards site-specific, data-driven decisions. Automation and robotics extend this approach by enabling machines to perform repetitive and precise operations with minimal human intervention. Integration of AI and computer vision allows robots to recognize individual plants, weeds, fruits and stress symptoms, making these technologies particularly valuable for intensively managed vegetable crops.

Concept of Precision Vegetable Production

- 1. Autonomous field robots:** Autonomous robots use GNSS, cameras, LiDAR and other sensors for navigation, crop monitoring, weeding, spraying and harvesting. They can repeatedly operate between crop rows and collect plant-level information more efficiently than conventional manual scouting.
- 2. Robotic transplanting and seeding:** Automated transplanting systems improve seedling placement, spacing and depth while reducing labour requirements. Nursery automation can also support seed filling, sowing, tray handling, watering and seedling selection, particularly in commercial vegetable nurseries.
- 3. Automated weeding:** AI-based vision systems can distinguish crops from weeds and guide mechanical blades, hoes or targeted sprayers. This approach can reduce manual labour and unnecessary herbicide application. However, variable illumination, leaf overlap and similarities between crops and weeds remain important challenges.
- 4. Precision spraying:** Smart spraying systems combine sensors, machine vision and variable-rate technology to apply plant-protection products only where required. Targeted application can reduce chemical consumption, spray drift and production costs while maintaining effective crop protection.
- 5. Robotic harvesting:** Harvesting is one of the most complex robotic applications because machines must identify mature produce, locate it accurately, detach it without damage and transfer it safely. Tomato, cucumber, capsicum and other high-value crops are important targets for robotic harvesting research. Successful systems require integration of computer vision, robotic manipulators, end-effectors and motion planning.

Smart Technologies Supporting Vegetable Production

- 1. Artificial intelligence and machine learning:** AI enables automated crop recognition, weed and disease detection, yield estimation, fruit maturity assessment and autonomous decision-making. Machine-learning and deep-learning models can analyse large datasets and identify crop patterns that are difficult to detect manually.

2. Computer vision: Computer vision acts as the perception system of agricultural robots. RGB, depth, thermal and multispectral cameras can support plant identification, crop counting, weed detection, disease diagnosis, fruit localization, maturity assessment and quality grading. Reliable performance, however, requires diverse datasets representing different cultivars, environments and growth stages.

3. Internet of Things (IoT): IoT connects sensors, machinery and digital platforms for continuous monitoring and automated control. Soil-moisture sensors, weather stations and greenhouse sensors can support precision irrigation, fertigation, ventilation and climate management.

4. Sensors and remote sensing: Ground-based sensors provide information on soil moisture, temperature, salinity and crop status. Satellite imagery, multispectral sensors and proximal sensing provide spatial information on crop vigour, water status and stress, supporting timely management decisions.

5. UAVs/Drones: UAVs equipped with RGB, multispectral or thermal cameras enable rapid, non-destructive monitoring of large vegetable fields. They can identify areas affected by water stress, nutrient deficiency, disease or poor crop establishment and guide detailed ground-level interventions.

6. GPS/GNSS and autonomous navigation: GNSS provides accurate positioning for autonomous machinery, while Real-Time Kinematic (RTK) systems can improve positioning accuracy. Machine vision can complement GNSS by detecting crop rows and correcting navigation errors, enabling precise movement between closely spaced vegetable rows.

Applications in Major Vegetable Crops

Robotics and smart technologies have applications across a wide range of vegetables. In tomato, capsicum and cucumber, computer vision can support crop monitoring, fruit detection, maturity assessment and robotic harvesting. In lettuce, cabbage and broccoli, autonomous systems can assist with crop monitoring and weed management. Onion, carrot and other root crops offer opportunities for automated planting, crop monitoring and harvesting, although underground sensing remains challenging. Protected cultivation is particularly suitable for automation because environmental conditions can be controlled more effectively. Automated irrigation, fertigation, climate regulation, crop monitoring and harvesting can therefore be integrated into greenhouse management systems.

Benefits for Productivity, Labour and Resource-Use Efficiency

Precision automation offers several potential benefits:

1. Reduced dependence on manual labour and drudgery
2. Improved water, fertilizer and pesticide-use efficiency
3. Timely detection of weeds, pests, diseases and crop stress
4. Improved crop productivity and product quality
5. Reduced environmental losses and unnecessary inputs
6. More precise and timely farm operations
7. Improved working conditions.

Robotic harvesting may additionally improve harvesting selectivity by identifying and collecting produce at the appropriate maturity stage.

Constraints and Challenges

Despite rapid technological progress, adoption remains constrained by:

1. High initial investment and maintenance costs
2. Complex and variable agricultural environments
3. Limited datasets for reliable AI development
4. Poor rural connectivity and digital infrastructure
5. Shortage of technical expertise
6. Limited access for small and fragmented farms
7. Uncertainty regarding economic returns
8. Concerns related to data ownership and cybersecurity

Field conditions such as changing light, dust, plant variability, uneven terrain and unpredictable obstacles can significantly affect robotic performance. Therefore, technologies developed under controlled conditions require extensive validation under commercial production environments.

Future Prospects

Future vegetable production is expected to increasingly integrate robotics, AI, IoT, UAVs and advanced sensing into unified management systems. Multi-robot systems combining aerial monitoring with ground-level intervention could improve the efficiency of large-scale crop monitoring and targeted management. Development of affordable, modular and multifunctional robots will be particularly important for small and medium-sized farms. Advances in sensor fusion, edge computing, machine vision, battery technology and wireless connectivity are expected to improve robotic

performance and autonomy. Future research should emphasize real-field validation, standardized datasets, interoperability, cybersecurity, farmer training and economic feasibility. The focus should shift from technologically complex prototypes towards reliable, affordable and farmer-oriented systems.

Conclusion

Robotics, AI, IoT and smart sensing are transforming vegetable production from conventional labour-intensive management towards precise, data-driven production. These technologies can improve crop monitoring, weeding, spraying, irrigation, transplanting and harvesting while enhancing resource-use efficiency and reducing production losses. Nevertheless, high costs, infrastructure limitations, technical complexity and field variability remain important barriers. The future of precision vegetable production will depend on developing affordable, reliable and farmer-friendly technologies that combine intelligent automation with human expertise to achieve productive, profitable and sustainable vegetable farming.

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Biological Control of Diamondback Moth and Cabbage Butterfly in Cabbage

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Introduction

Cabbage (*Brassica oleracea* var *capitata* L.) is a popular leafy green vegetable. Insect pests pose a substantial impediment to increased crucifer productivity (Venkateswarlu *et al.*, 2011; Lal *et al.*, 2020). Cabbage, a cool-season crop from the Brassicaceae family, is widely cultivated for its thick, tasty head. Cabbage originated in Europe and is well adaptable to temperate and subtropical climates. It was imported to Taiwan during the Dutch colonial era. It became a popular crop in Taiwan after its early introduction to China in the fourteenth century. Cabbage is highly valued in organic farming due to its adaptability and little pest pressure when properly maintained. Crop rotation, composting and natural pest management are examples of sustainable agricultural practices that promote cultivation and soil health, making cabbage a promising component of environmentally friendly farming systems (Hou & Chang, 2025). One of the most critical difficulties humanity faces in the twenty-first century is lowering atmospheric concentrations of greenhouse gasses in order to avert climate change and feed the world's rapidly growing population (Myers *et al.*, 2017).

Conventional reliance on chemical insecticides has led to serious challenges, including resistance development, environmental contamination and disruption of natural enemy populations. As a result, the focus has shifted toward biological control strategies, which harness natural enemies and microbial agents to suppress pest populations in an eco-friendly manner. The diamondback moth and cabbage butterfly remain persistent threats to cabbage production worldwide, but biological control offers a sustainable and environmentally sound solution. Parasitoids, predators and microbial agents have demonstrated significant potential in reducing pest populations while preserving ecological balance. Integrating these bioagents into pest management programs not only minimizes reliance on chemical insecticides but also enhances long-term crop resilience. Future research should focus on improving field efficacy, farmer adoption and compatibility with integrated pest management strategies to ensure that biological control becomes a cornerstone of sustainable cabbage cultivation.

Diamondback Moth

Damaging symptoms: The diamondback moth (*Plutella xylostella*) is a major pest of cruciferous crops like cabbage. Its larvae cause damage by burrowing tunnels into cabbage heads, thus diminishing market value. Early infestations are sometimes noticeable as little yellow mines on the leaves caused by immature caterpillars. Plants cultivated on ridges in crucifer fields are typically the first to show indications of injury, making them especially vulnerable. A few fourth-stage larvae can leave a cabbage unsellable and when *P. xylostella* populations are considerable, crop losses can surpass 90% (Gautam *et al.*, 2018). Leaf mines, transparent feeding patches, holes, skeletonized leaves and head boring are the hallmark symptoms of diamondback moth damage in cabbage.

Table 1: Biological control of Diamondback Moth in Cabbage:

Types of biocontrol agent	Name of biocontrol agent	Order/Family Bioagents	of References
Predeator	<i>Chrysoperla carnea</i> Stephens	Neuroptera: Chrysopidae	Reddy <i>et al.</i> , 2004
Parasitoid	<i>Cotesia plutellae</i> Kurdjumov	Hymenoptera: Braconidae	Talekar & Shelton, 1985
Pathogen	Nuclear Polyhedrosis Virus (NPV)	Lefavirales: Baculoviridae	Talekar & Shelton, 1985
Parasitoid	<i>Trichogramma</i> spp. <i>Trichogramma toidea</i> spp.	Hymenoptera: Trichogrammatidae	Talekar & Shelton, 1993
Parasitoid	<i>Diadegma semiclausum</i> Hellen	Hymenoptera: Ichneumonidae	Hardy, 1938

Cabbage Butterfly

Damaging symptoms: The cabbage butterfly (*Pieris brassicae*) is a devastating pest of cruciferous plants. In its early instar stages, the caterpillars scratch the leaf surface, whereas later instars feed more vigorously, consuming the lamina along the edges or making big holes. This eating activity results in skeletonized leaves with only the veins intact. In

extreme infestations, caterpillars have been seen burrowing into cabbage heads, rendering the food unmarketable (Riyaz & Sivasankaran, 2022).

Table 2: Biological control of Cabbage butterfly in Cabbage:

Types of biocontrol agent	Name of biocontrol agent	Order/Family Bioagents	of References
Entomopathogenic bacteria	<i>Bacillus thuringiensis</i> var. <i>kurstaki</i>	Bacillales: Bacillaceae	Kashyap, 2022
Entomopathogenic bacteria	<i>Bacillus thuringiensis</i> subsp. <i>Galleriae</i> , <i>Bacillus thuringiensis</i> subsp. <i>dendrolimus</i> sotto, <i>Bacillus thuringiensis</i> subsp. <i>Kurstaki</i>	Bacillales: Bacillaceae	Shternshis <i>et al.</i> , 2000; Kashyap, 2022
Entomopathogenic biocontrol	<i>Streptomyces</i> sp.	Actinomycetales: Streptomycetaceae	Shternshise <i>et al.</i> , 2002
Entomopathogenic fungus	<i>Metarhizium anisopliae</i>	Hypocreales: Clavicipitaceae	Lacey <i>et al.</i> , 2015

Conclusion

Biological control of the diamondback moth and cabbage butterfly offers a sustainable alternative to chemical insecticides in cabbage cultivation. Natural enemies such as parasitoids, predators and microbial agents effectively reduce pest populations while maintaining ecological balance. These strategies not only prevent resistance development but also minimize environmental contamination and safeguard beneficial biodiversity. Integrating bioagents into IPM programs enhances crop resilience and supports climate-smart agriculture. Strengthening farmer adoption and improving field efficacy will ensure biological control becomes a cornerstone of sustainable cabbage production.

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Importance of Birds in Insect Pests Management

Article ID: 74474

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Introduction

India is bestowed with rich and diverse avian fauna. Birds are an important component of the natural balance. Several species of birds pollinate plants and disperse seeds while many others are insectivorous and predatory, which destroy insect and rodent pests of crops. On the other hand, some species of birds are pest of agricultural crops causing significant loss in yield. There are about 8600 species of birds, representing 27 orders in the world, out of these about 1200 species observed in India. As yet no information is available to show as to how many of these are pests and in which situation per crops per region. However, various workers have studied over 100 birds species and their role as predatory or beneficial has been established. Only 25 out of 1200 species observed associated with agriculture in India.

Predators are one of the most important extrinsic factors acting on animal populations and are a strong selective force in the evolution of form and function. Birds are dangerous predators with the ability to pounce on unsuspecting animals. They attack insects, reptiles, turtles, and worms. Eagles, hawks, owls, kites, and buzzards are some birds of prey. They are grouped under the term birds of prey. The American vulture (Andean condor), Vultur gryphus, is the heaviest and largest bird of prey in the world. Integrated pest management uses all available techniques to reduce the occurrence of pests before they cause economic damage and to provide economic benefits to farmers. One of these techniques is biological control, which is a major concern for farmers and an important ecosystem service provided by a variety of organisms and is expected to be a sustainable solution for the agro-ecosystem. Birds aid farmers by reducing invertebrate crop pests, yet they are seldom used in Integrated Pest Management (IPM) practices. The use of avian groups to control insects and other pests in the agroecosystem also causes damage to other valuable plants that have higher economic value. Recent studies have shown that insectivorous birds, which feed mainly on insect populations, play an important role in various agroecologies.

Insectivorous birds are observed in agricultural ecosystems and reduce pest infestations in many agricultural and horticultural crops such as apples, broccoli, cacao, coffee, corn, kale, grapes, and oil palms. For example, it is reported that birds reduce pest infestations and increase yield by 66 percent in Dutch apple orchards. Similarly, researchers in Borneo reported that pest control by birds prevented 9 to 26 percent of fruit losses in oil palm plantations. Birds are among the important and efficient arthropod predators in agroecosystems, with 50 percent feeding primarily on insects and 75 percent occasionally feeding on invertebrates. Studies of predation on insect pests by birds in natural and agricultural areas have found that invertebrate reductions by birds range from 20 to 70 percent. This predation by birds not only reduces the number and incidence of herbivores but also significantly reduces foliar damage and plant mortality and can result in up to a 60 percent increase in crop yield or fruit production.

Role of Birds in Agriculture as Beneficial

Birds playing an important beneficial role in agriculture like insect-pest control, rodent control, pollination and insect pathogen dispersal

Insect Pest Control: Several species of insectivorous birds like Black drongo, Bank Myna etc. have been found to feed on insect-pest of crops.

Rodent Control: Birds like owl play an important role for control of rodent pest in India.

Weed-Seed Control: Some birds' species mostly feed on weed-seed in agriculture. To minimize the weed from the field.

Pathogen Dispersal: Birds like India Myna, Cattle Egret and House sparrow were capable of dispersing *Bacillus papillae* var. *Holotrichae* causing milky disease of white grub.

Pollination: Along with bees, birds such as purple sunbirds and purple rumped sunbirds are important pollinating agents.

Neutral Birds Species Associated with Agricultural Crops

Some bird species of avian community viz. House sparrow, streaked weaver bird, Indian Myna may be or may not be harmful or beneficial to agricultural crops.

Harmful Birds Species Associated with Agricultural Crops

Some species of birds cause damage to variety of crops like cereals, pulses, oil seeds, fruits etc. as well as they disperse the weed-seeds, which causes crop losses.

The guava field the birds damage during early rind stage in upper canopy, while in the lower canopy the bird damage was during the ripened stage by Rose-ringed parakeet.

Management Strategies

1. Physical Method: This method include use of visual and auditory scaling device like netting scarring method, keeping human effigy toward of birds, automatic mechanical bird scarer, Bird reflective tape,wrapping method etc.

a. Netting: It is one of the best methods and is compete from of protection to the crop. The nylon net having a mesh sufficiently small to prevent passage of even small granivorous birds. Such method is too expensive for large acrages but recommended for high value trials or breeder seed experiments of multiplication trials.

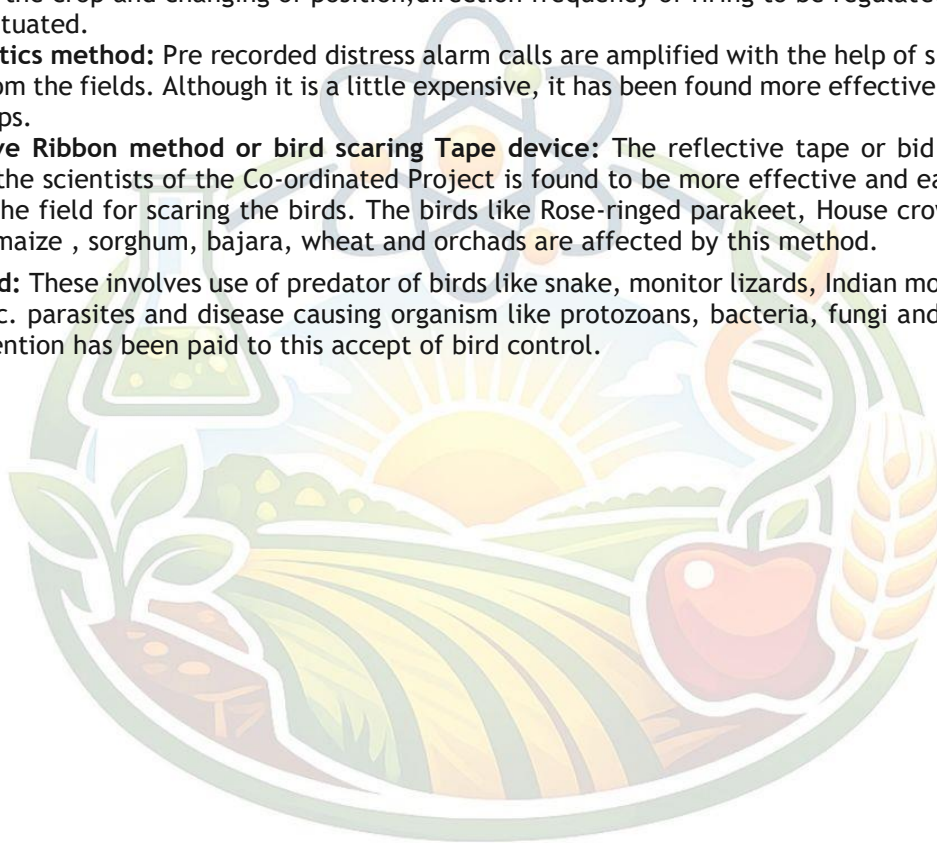
b. Scare crows: Display of inter specific model,especially of crows or dead crows was found useful to scare them at sowing and ripening stage of the crop.

c. Automatic mechanical bird scarer or pyrotechnique method: It is useful for scaring the birds in large acrages 4 to 5) aceres, particularly in orchads. Care must be taken to ensure that the cannon is operated at the time of bird visit to the crop and changing of position,direction frequency of firing to be regulated to prevent the birds getting habituated.

d. Bioacoustics method: Pre recorded distress alarm calls are amplified with the help of speakers to drive away the birds from the fields. Although it is a little expensive, it has been found more effective or archards and small acerage crops.

e. Reflective Ribbon method or bird scaring Tape device: The reflective tape or bid scaring tape method evolved by the scientists of the Co-ordinated Project is found to be more effective and easily adaptable by the farmers in the field for scaring the birds. The birds like Rose-ringed parakeet, House crow, Myna on crops like sunflower, maize , sorghum, bajara, wheat and orchads are affected by this method.

2. Biological Method: These involves use of predator of birds like snake, monitor lizards, Indian mongoose, Indian yellow throated marten etc. parasites and disease causing organism like protozoans, bacteria, fungi and viruses. However, in India very little attention has been paid to this accept of bird control.



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Miniature Magic Grows, Where Pottery Breaks

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“Broken Pots Can Be Good for Miniature Garden”.

Before you throw away that cracked pot, stop and imagine the possibilities. Broken pots can become charming miniature gardens tiny worlds filled with charm, plants and creativity. There are eco-friendly, budget-friendly and uniquely beautiful. In this complete guide, we'll show you how to turn broken pots into stunning miniature gardens step by step.

Beautiful Sustainable & Unique

Eco-friendly reuse broken pots and reduce waste while creating something green and beautiful.



What Materials You Need?

1. Broken terracotta pot (any size)
2. Potting soil
3. Small plants (succulents, moss, ground cover, herbs, etc.)
4. Small pebbles or white or grey gravel
5. Charcoal pieces (optional)
6. Miniature accessories (tiny houses, fences, animals, stones, etc.).

Tools

1. Gloves
2. Small trowel or spoon
3. Brush (for cleaning)
4. Scissors
5. Small watering can.

You don't need expensive materials. A broken pot and a little creativity is enough.

Step-By-Step Process

1. Plan Your Design: Look at the broken pieces and imagine how they can create levels and spaces. Sketch your idea if you like. No two designs are the same. Your miniature garden will be unique.

2. Prepare the pot and arrange the pieces: Clean the broken pot pieces. Remove dust and dirt using a brush. Let them dry completely. Place the largest piece at the back as a backdrop. Fill the potting mix for support the broken pieces. Use other pieces to create steps, walls, or curves.

Tip: Choose unglazed terracotta pots. They are easier to break and safer for plants.



3. Perfect for small spaces: Miniature gardens fit anywhere- your balcony, windowsill, desk, or garden corner. Add a tiny house, mini fence, and fairy figurines for a magical look. Use broken pieces to create terraced levels like a mountain trail. Small pebbles or gravel at the bottom for proper drainage. You can also add a bit of charcoal to keep the soil fresh.

4. Add miniature accessories: Add some beautiful house and benches.



Plants that work best for miniature gardens.

Choose small, slow-growing, and low- maintenance plants.

a. Succulents (Haworthia, Echeveria, Sedum) Mosses

Small ferns:

a. Creeping plants (Baby tears, Creeping Jenny)

b. Herbs (Thyme, Rosemary, Mint)

Add tiny houses, fences, stones, or figurines to bring your garden to life. Be creative.

5. Plant your mini garden: Fill the pot with potting soil. Make sure the soil is well-drain in all levels and crevices. Start planting, Place taller plants at the back and smaller ones in front. Cover the soil with small pebbles, sand, or moss. It adds a natural look and prevents soil from washing away. Water lightly using a fine spout can. Do not overwater. Let the soil settle.

Care Tips

Water only when the soil is dry. Keep in bright, indirect sunlight. Trim plants regularly to maintain size. Remove dead leaves and debris. Avoid heavy continuous rain.

Extra Tips

Use different sizes of broken pots for a multi-layered garden.

1. Seal cracks with waterproof glue if needed.
2. You can paint the pot pieces to add more colors.

Experiment with themes and accessories.

Conclusion

Broken pots are not the end—they are the beginning of something beautiful. With a little time and imagination, you can create a living masterpiece that brings joy for years. Whether you make a fairy garden, a mountain trail, or a zen retreat, your miniature garden will always remind you that even broken things can bloom. So next time a pot breaks, don't throw it away—plant a new story instead.



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Breeding for Quality Vegetables

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Introduction

There is continuous demand for superior vegetable cultivars with attributes that increase both crop productivity and quality. These include maximum early and total maturities, adaptation to different climatic zones, tolerance to drought stress, concentrated fruit set, increased nutrient content extended post harvest shelf-life, and adaptability to mechanization. Vegetable are important component of the daily diet and a fairly large number of vegetable crops serve to meet the need of nutrient requirements. Protein is an important nutrient and its deficiency has been realized in several countries. Breeding technology has been considerable improvement in several nutritional and processing quality attributes i.e. protein, amino acid, carotenoids, ascorbic acid, sugars, acidity and flavour. Quality is a component that adds values to the crops and their products. There is a recent development of quality awareness among the people. It refers to many aspects like colour, size, nutrient content, shelf life and suitability for fresh consumption, processing and conversion into value added products.

Crops improvement is possible because plants differ in their heritable characteristics. For most cultivar improvement, conventional breeding methods are based on the principles of Mendelian genetics. Heterosis alternatively known as hybrid vigour is the superiority of the F₁ hybrid over its parents with respect to yield and economical characteristics. Hybrids offer opportunities to improve productivity, earliness, informality, wider adaptability and quality and for rapid development of dominant for resistance to diseases and pests. F₁ hybrids of vegetables in India are primarily valued for their high production potential and quality. The incidence of pests and diseases adversely affect the quality and marketing value of vegetables. The farmers have to spend substantial amounts of resources to control the pests and diseases by chemical means, which may lead to residual on the development of high yielding, high quality and multiple diseases resistant F₁ hybrids.

Quality would mean the degree of excellence for a specific use or to serve a specific purpose. Therefore, the precise meaning of quality will vary depending on the crop, its proposed/implied use, human needs, available technologies, etc. Some aspects of quality are obvious to the consumer, and they greatly affect the consumer preference for the produce. Such traits are potent factors in determining the popularity of a variety. e.g. purple brinjals are liked in north state instead of white or green. Red carrots though poor in carotene content are preferred over orange. In cauliflower and cabbage medium size is more desirable than the larger size. In onion red colour is preferred as compare to white and yellow.

Quality breeding: Genetic improvement of crop plants in relation to various qualities attributes.

Quality Traits

A trait that defines some aspect of produce quality is called quality trait. Each crop has a specific and often somewhat to completely different set of quality traits. A various qualitative traits may be classified into five broad groups:

Morphological traits: These traits are related to produce appearance and are mainly concerned with size and colour of the produce. These traits are easily observable, and usually play the main role in determining consumer acceptance of the produce.

Organoleptic traits: These traits are concerned with the palatability of the produce, e.g. taste, aroma, smell, juiciness, softness, etc. they are easily detected and are very important in influencing consumer preference.

Nutritional quality: These traits determine value of the produce in human/ animal nutrition. The nutritional characters include protein content and quality, it content, vitamin mineral content etc. and also the presence of antinutritional factors. These traits are not easily appreciated by consumers and farmers, but they are of paramount value in determining human and animal health.

Biological traits: The traits included in this group define the actual usefulness of the produce when consumed by experimental animals; their usefulness to humans is usually predicted on this basis. e.g. protein efficiency ratio, biological value, body weight gain, etc. these traits are not obvious to consumers and growers, but are extremely valuable in determining the utility of the produce for human/ animal consumption.

Other traits: This category includes all other traits that are not included in the above categories. e.g. cooking quality of bean, keeping quality of vegetables etc.

Table1: Quality parameters in vegetable crops:

Crop	Quality parameters
Pea	Seed size, type, surface and colour, protein, tryptophan, ash, phosphorus, calcium, hydrocyanic acid, ascorbic acid and oil content, cooking quality(round white, bold, seed prefer type having dominant alleles of flower and seed colour ,gene have twice as much tannin as those having recessive allele
mustard	Size, colour, oil content upto (upto 46.25%), oil quality: low (near 0 or o) erucic acid and low glucosinolate contents.
Cowpea	Medium to large seeds, uniform attractive colour absence of black brown scar around haulm protein content, cooking quality.
Rajma	Seed size seed colour grain texture protein content (17-35%), protein quality(S-containing amino acid), cooking time, cooking quality.
potato	Tuber size,(medium),shape(round), colour and texture skin thickness, position of eyes(shallow eyes preferred) cooking quality, keeping quality,(associated with non-sprouting and resistance to storage diseases), nutritive value, freedom from after- cooking darkening, high vitamin C contents and protein contents, high specific gravity, low sugar content.
Tomato	Size, shape, colour, smoothness and uniformity of fruits, and freedom from external defects, flavour, vitamin A and vitamin C contents, processing quality(colour, pH, titrable acidity, total soluble solids, viscosity)
Brinjal	Fruit size, shape and colour, soft flesh, low alanine content.
Okra	Pods dark green, medium long, tender, thin, smooth, 4-5 ridged
Radish	White, long/ stump roots, thin taproots non- branching habit, no-pithy roots, pungency of roots as per consumer preference.
Onion	Size, shape, colour, pungency, firmness, dormancy(dormancy desirable for storage), high total soluble solids(important for dehydration industry), amount of S-alkyl cysteine suloxide precursors and the enzyme allinase determine the pungency of onion
Muskmelon	Attractive round /spherical fruit shape, thick flesh with attractive colour, small seed cavity, sweet, juicy muy flavoured fruits, TSS not less than 10%, tough netted skin.

Sources of Quality Traits

The quality traits may be obtained from the following sources:

1. A cultivated variety.
2. A germplasm line.
3. A spontaneous or induced mutant.
4. A somaclonal variant.
5. A wild relative.
6. A transgene (native, modified and synthetic).

Cultivated variety: Cultivated variety is the most preferred source for a quality or any other traits since they are the easiest to utilize in breeding programmes. Only when a trait is not present in the cultivated varieties of the concerned crop, a breeder should look elsewhere for the trait. In general, most quality traits are available in the current or old varieties. For example in U.S.A., Atlas 66 and Naphal have been used as sources of high protein content

Germplasm line: A quality trait not available in cultivated varieties may be found in a germplasm line if an extensive search were made.

Mutant: Many quality traits have been contributed by spontaneous /induced mutants. This is particularly true for protein and oil quality there are also example s of isolation line of desirable mutants from mutant lines for quality traits.

Somaclonal variant: Somaclonal variants may sometimes show an improvement in a quality trait. For example, somaclonal variant of sweet potato had deeper and more stable root colour, which is preferred by consumers; this variant was released as a new variety called Scarlet.

Wild relative: There are several instances where genes for improved quality were contributed by a wild relative. In many cases, the quality trait is not expressed as such in the wild species, but it is detected only in the segregants recovered from its cross with the cultivated relative; such traits are called latent traits. for example, *L. hirsutum*, a wild relative of tomato, produces small green fruits. Yet some of the lines extracted from a cross between tomato and *L. hirsutum* showed enhanced red colour, while some others showed considerably higher carotene content.

Transgene: A gene from any organism, including the species into which it is transferred, that is introduced into the genome of an organism using the techniques of genetic engineering is called transgene. Transgene provide a powerful means for the modification of quality traits. In order to use transgenes effectively and successfully, the biosynthetic pathway, or at least the key enzymes involved in the biosynthesis, leading to production of the concerned trait should be known.

Genetics of Nutritional Quality

Inheritance of nutritional quality characters may be governed by 1) Oligogenes with distinct individual effects 2) Polygenes with small additive effects, and 3) Cytoplasmic genes.

Oligogenic inheritance: When the inheritance is governed by one or few major genes, it is referred to oligogenic inheritance. In such inheritance, each gene has large and easily detectable effect on the expression of nutritional quality character. The difference between high and low value is clear cut. e.g. in tomato, high *beta* carotene is conditioned by two major genes plus modifiers.

Polygenic inheritance: When the inheritance is governed by several genes each with small additive effect, it is referred to as polygenic inheritance. In such inheritance, the variation for a character is continuous from one extreme to another. Thus classification of plants into clear cut is not possible. Characters governed by polygenes are sensitive to environmental changes and generally have low heritability. e.g. in carrot, high carotenoids content exhibits complex inheritance pattern.

Table 2: Genetics of nutritional quality characters in vegetables:

Crops	Quality character	Inheritance controlled by
Rape seed	Erucic acid and eicosenoic acid	Two genes with multiple alleles
Turnip rape	Erucic acid and eicosenoic acid	Single gene with multiple alleles
Tomato	High beta carotene content	Two major genes plus modifiers
Carrot	Carotenoids content	The inheritance is complex.

Improvement in Quality Traits of Selected Crops

Tomato: Fruit quality of tomato depends on several traits; the precise meaning of this term varies depending on the end use of fruits. The traits important in fruit quality are as follows

1. **Use as fresh fruit:** Appearance, colour, texture and firmness, flavour nutritional value.
2. **Processing quality:** fruit colour, fruit pH titrable acidity, total soluble solids (TSS) viscosity.

Fresh Vegetable

Appearance: fruit appearance depends on size, shape external colour and freedom from external defects. Usually, large size, round shape, red and uniform colour is preferred. This feature is of considerable importance for fresh use.

Fruit colour: red fruits are the most preferred. The allele *og^c* (crimson colour) increase lycopene (red pigment) concentration at the cost of *beta-carotene*, while *hp* gene (high pigment) increase total carotenoids and produces excellent fruit colour. But *hp* allele is associated with slow germination and growth, and premature defoliation; this has limited its use in tomato improvement.

Texture and firmness: for fresh consumption soft and juicy fruits are preferred. But firm fruits are desirable for mechanical harvesting and for transportation.

Flavour: sugar and acid contents are the most important factors affecting taste and overall flavour intensity; citric and malic acid contents are more important than sugar level in determining flavour. Flavour is also affected by volatile compounds, maturity and ripeness at picking and composition of locular and pericarp tissues.

Nutritional value: contents of vitamins A and C are the main nutritional traits in tomato. A more than 100 fold increase in provitamin A was obtained in the progeny derived from crosses of tomato with *L. hirsutum*. genes *ogc* and *hp* affect vitamin A content. *og^c* cause a 40% decline, while *hp* leads to a 40% increase in the content of *beta-carotene*.

Vitamin C content of tomato varieties range from 13-44 mg/100 g fresh fruit weight varieties with ~50 mg/100 g fruit fresh weight vitamin C have been developed in U.S.A., e.g. double Rich. High vitamin C varieties are poor yielders; this limited their processed commodity.

Processing Quality

Fruit colour: deep red is the preferred colour. Gene *og^c* has been employed to develop a deep red fruited variety Vermillion (in U.S.A). Fruit colour is assayed calorimetrically, and is indicative of fruit maturity it influence the grade and the standards of the processed commodity.

Fruit pH: It is desirable that fruit pH is less than 4.5. A pH meter is used to measure the pH of fresh juice obtained from fully ripe fruits. Acidity of fruit juice affects the time needed for sterilization of the processed product; it is the most significant factors affecting inactivation of bacillus coagulants. In tomatoes, pH varies from 4.26- 4.82

Titrate acidity: titrate acidity is negatively correlated with pH in tomato varieties, titrate acidity ranges from 0.4 to 0.91(as % citric acid content). This trait is polygenic, but a single major gene may be present; heritability is estimated as ~60%. high acidity has been transferred from small- fruited lines into commercially acceptable lines.

Total soluble solids (TSS): TSS is estimated as refractive index which is highly positively associated with the total solids present in fruits. TSS mainly consists of glucose, fructose and sucrose. High TSS varieties yield more processed product

and require less energy for processing. TSS is negatively correlated with yield and fruit size and determines types have lower TSS than indeterminate ones. Red cherry, A408 and A276 are good sources for high TSS content.

Viscosity: viscosity determines the consistency of juice and affects the quality of juice, sauce, soup and paste. It is high heritability -70%.

Viscosity may also be estimated as insoluble solids; this is estimated either as water insoluble solids (water is used to remove soluble compounds from the fruit pulp) or as alcohol insoluble solids (80% ethanol is used to remove soluble compounds). Alcohol insoluble solids show a very high positive correlation with juice viscosity.

Brinjal

For brinjal, the biological constituents such as anthocyanins, total phenols polyphenol oxidase contents are important for their quality.

Twenty one varieties of eggplant were analyzed for various chemical constituents. On the average the long-type varieties were rich in dry-matter, crude protein anthocyanin, phenolics and glycoalkaloid contents, while the oblong type were rich in total water soluble sugars. among the varieties the total water soluble sugars varied from 1.00 g/100g (PBr-129-5) to 3.63g /100g (Pusa purple round), free reducing sugars ranged from 0.38g/100g(PBr-129-5) to 1.73g/100g (Shanker vijay hybrid), anthocyanin from 0.16(T3) to 1.04(Arka Shirish) expressed as O.D. at 550 nm in their 10% (W/V) aqueous extracts. the total phenol varies from 0.44g/100g(Arka Navneet) to 0.138g/100g (Arka shirish) and the glycoalkaloid content in term of mg/100g varies from 6.25(Pusa kranti) to 20.25(Arka Shirish) .the variety Arka Shirish had the maximum dry matter, crude protein ,anthocyanin, phenolic and glycoalkaloid content. The polyphenol oxidase activity in arbitrary units/mg, protein/mg, orthodihydroxy phenols varied from 2.12(ARU-1) to 45.50(PBr-91-2). Bajaj *et al* (1979, 1981).

Kaur *et al* (1985) analyzed five varieties of eggplant for various chemical contents and biochemical properties at different stages of maturity. The Punjab Chamkila had maximum anthocyanin and total phenol contents at all stages of maturity. However orthodihydroxy phenols are maximum in variety P-8 in its first picking and in PPL in its 2nd picking is very suitable keeping in view the low level of peroxidase and polyphenol oxidase activities and that of orthodihydroxy phenolic compounds which cause discolouration in cut fruits.

Berry *et al* (1988) examined five varieties, namely BR-11, P-8, Jamuni Gola, Round Greeb Sel. and T-3 for their suitability to yield Bharata of acceptable quality. Bharata was canned in 310x409 lacquered cans and stored for six months to evaluate changes in quality. Though Bharata prepared from all the varieties of brinjal are acceptable that prepared from variety round green sel. was preferred most for its colour, aroma, taste mouth fell and overall quality during the entire period of storage.

Chadha *et al* (1988) reported that partial dominance for total chlorophyll *a* and chlorophyll *b* whereas both additive and non-additive genetic components were involved in the inheritance of anthocyanin. The narrow sense heritability estimates were medium for these characters. The reciprocal recurring breeding procedure seems to be effective.

Bajaj *et al* (1990) the mineral composition of (mg/100g) of the different varieties ranged for Zn from 1.645 to 4.00; Cu, .65 to 1.60; Fe, 5.00 to 12.5 and Mn, 1.375 to 3.25. Zn and Cu were more in the round white brinjal variety.

Onion

Onion majority of the quantitative traits are controlled by polygenes the characters like bulb shape, number of leaves, TSS, dry matter content, umbel stalk height and seed weight were controlled by both additive and non-additive gene action. However, some of the workers reported that the bulb yield, bulb shape, number of leaves and TSS were controlled by the non-additive gene action alone. Bulb size, days to bulb maturity and dry matter were controlled by additive gene action.

High heritability was reported for bulb yield, bolting percentage, bulb diameter (Sidhu *et al.*, 1986), bulb size, dry matter content (Padda *et al.*, 1973), sprouting percentage (Patil, *et al.*, 1986), and seed stalk per plant (Dadlani and Bhagchandrani, 1978), which indicated that these attributes can be improved by selection. Relatively low heritability was observed for seed yield and 1000 seed weight (Sandhu and Kalra, 1975; Dadlani and Bhagchandrani, 1978)

Table 3: Genetic control of some of the quantitative characters in onion:

characteristics	Gene action	references
Bulb yield	Additive and non-additive genes Non-additive genes	Joshi and Tandon, 1976, Aghora, 1985, Veere Gowda, 1988 Vedivel <i>et al.</i> , 1981
Bulb shape	Non-additive genes	Pandian and Muthukrishnan, 1979
Bulb size	Additive genes	Padda <i>et al</i> , 1973.
No. of leaves per plant	Non-additive genes Both additive and non-additive genes	Pandian and Muthukrishnan, 1979 Aghora, 1985, Veere Gowda, 1988
Time of maturity	Additive genes	Pandian and Muthukrishnan, 1979

Total soluble solids	Non-additive genes Both additive and non-additive genes	Pandian and Muthukrishnan, 1979 Aghora, 1985.
Dry matter content	Additive genes	Padda et al, 1973
	Non-additive genes	Aghora, 1985, Veere Gowda, 1988

Dehydrated onion is one of the important food products. It is better stage ability. onion varieties suitable for dehydration should be white and small-necked, with high pungency and high TSS (14 to 20%) some varieties showing high TSS and suitability for dehydration are :red Creole, Country Queen, Verma Giant and Punjab 48. bulb yield and dry matter production are negatively correlated. thus breeding of high dry matter content has the probe of low yield. onion variety for dehydration should have high pungency, white flesh, high TSS in India, No.106 has reported as promising for dehydration.

Carrot

Provitamin-A: A deficiency of vitamin A can cause blindness. Thus there is a need to increase vitamin a in the human diet. Carrot is an important sources of provitamin A. the carotenoids which are present in carrot roots can be divided into hydrocarbon pigments or carotenes and carotenol (Xanthophyllus) which also contain oxygen in the molecule. Carotenoids content in the root associated the colour of the root. A wide range of variation in the rot colour, white, yellow, purple, pink, reddish-orange and orange types has been reported. In some yellow and purple cultivars the rot ids due to anthochlor and anthocyanin. In red rooted carrot cultivars derive their colour by high lycopene content. *Alpha* and *Beta* carotenes are present in smaller quantities.

Orange colour roots are good source of carotenoids, especially in *Alpha* and *Beta* carotenes. There is a positive correlation between colour intensity and total carotenoids content.

Complex genetic systems control the colour of the root, *i.e* pigment- inhibiting gene, pigment-enhancing gene and genes controlling the specific pigment. In the study of a cross between orange (W93) and red (KHN, KOS and KDA) the orange is dominant over red. The segregation ratio indicated the involvement of at least two genes to differentiate orange and red colour. in another study, the *Daucus carota* var. *holandicus* cv. Nates3 has been deep orange: orange:yellow orange root in the ratio of 3:1:1, suggesting a heterozygous genotype ABcc, with ABcc giving deep orange ,aaBcc orange, AAbbcc yellow orange, and aabbcc pale yellow or white.

Table 4: Carotene content in carrot ($\mu\text{g/g}$ fresh weight)

Colour of root	β -carotene	α carotene	caretenoids
White	-	-	3.2
Yellow	2.5	.5	2.5
Light orange	35.6	15.5	50.6
Orange	50.5	25.4	95.2
Deep orange	68.2	45.2	120.5

Sugars /total solids: Sucrose, glucose. Fructose and maltose are the common sugars of the carrot the total sugars ranged from 3.5 to 10.8. Glucose and fructose are generally present in equal amount. Sugars and dry matter are important for the marketing and processing of the carrot they affect the quality of the processed roots. Concentration of the stored sugar is an important component of the overall performance. The total sugars can be studied by refractometer estimates of the total dissolved solids. Reducing sugar is also important for quality of root; it has some relationship with flavour and thus roots with high reducing sugars are preferred. a single major gene regulates the reducing sugar to sucrose balance in carrot with the dominance of a high percentage of reducing sugar. Improvement has been made for total soluble solids by repeated selection.

Peas and Beans

Protein: Protein is an important nutrient and its deficiency has been realized in several countries. Beans and peas are the main sources of protein among the vegetables. It is imperative to improve both quantity and quality of the protein. For quality, sulfur amino acid methionine, which is generally deficient in the bean and pea seeds, must be improved.

Ascorbic acid: In *Pisum sativum*, more than one factor governed the ascorbic acid content low ascorbic acid had partial dominance and there was predominance of additive gene effects.

Sugars/total solids: In garden pea sugar is present at about 12-14%. High sugar controlled by recessive gene. Reducing sugar content was studied at three stages, *i.e* before at and after technological maturity of the seeds. In the wrinkled seeded lines, the regression of reducing sugar content against tenderometer reducing was liner. However, in the smooth-seeded line it was exponential.

Breeding for Low Toxic Substances

In some grain, legumes, oilseeds, vegetables, fruits and forage crops toxics substances are found. These toxic substances adverse effects on human and animal health.

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Table 5: toxic substances found in vegetable:

Crop species	Toxic substance
Cowpea	Tripsin inhibitors
French bean	haemagglutinine
Mustard	Erucic acid
Potato	Steroidal alkaloids
Cucurbits	Cucurbitacins
Brinjal	Bitter principle
Cassava	CN glucocides
Yam	Alkaloids
Field bean	Anti vitamin E factor

Considerable progress has been made in the development of varieties with low toxin content in above crops. Breeding for reduction in toxic substances requires lot of chemical analysis. Hence development of simple, cheap, rapid and reliable methods of analysis is essential.

Breeding Approaches

The various breeding approaches used for the improvement of quality traits are as follows:

1. Evaluation of germplasm.
2. Mutagenesis.
3. Hybridization.
4. Interspecific hybridization.
5. Somaclonal variation.
6. Genetic engineering, are being used to improved specific quality trait, which drastically changes the end use pattern of a crop produce.

Screening of germless: screening of germplasm, including cultivated varieties, may often yield a source for a quality trait, especially for such traits that not obvious e.g. traits related to chemical composition. Ordinarily, further breeding effort will be required combine the quality trait with good agronomic features and or yield since the germplasm lines are expected to be inferior in yield and agronomic characteristics.

Mutagenesis: a desired quality trait may be present in a spontaneous/ induced mutant. Mutants affecting quality traits like protein and oil quality will by themselves be inferior in yield; however, they would serve as valuable sources of quality genes.

Some time a quality mutant may have some undesirable features associated with the desirable quality trait. The undesirable features of the mutant lines may be removed in one of following two ways.

- a. The mutant allele may be transferred into several diverse genotypes having excellent agronomic features and yielding ability.
- b. In some genetic backgrounds, the undesirable features of the mutant allele may be totally suppressed. Alternatively, the mutant line may be subjected to mutagenesis and mutants lacking the undesirable features, but having the desired quality trait, may be isolated.

Hybridization: This most widely used breeding approach to develop high yielding varieties with desirable quality traits. The breeding methods used to handle the segregating generations derived from appropriate crosses depend mainly on the type of parents involved in the cross. If the both the parents of a cross are high yielding varieties having good agronomic features, pedigree method will be the most suitable breeding scheme. But where the one of the parents has inferior agronomic features, backcross scheme will be most appropriate; only limited numbers of (2-3) of backcrosses may be made if the inferior parent has some desirable features as well.

Quality traits governed by polygenes may be improved by subjecting the segregating generations to a form of recurrent selection. Recurrent selection for two cycles increased seed protein of Rajma from 21.9 to 24.6 %

Interspecific hybridization: wild relatives often contribute useful quality genes, e.g., fruit colour, fruit size, provitamin A and vitamin C contents in tomato etc. such a hybridization Programme is quite demanding and may present several problems. In any case the high quality lines derived from such crosses will usually serve as parents in hybridization programmes; it is unlikely that will be used directly as varieties.

Somaclonal variation: genetic variation present in tissue culture- raised plants has been exploited for crop improvement and several somaclonal variants are being used as commercial varieties. There are several examples of such commercial varieties having improved quality. The ‘Scarlet’ variety of sweet potato has improved and more stable root colour. Citronella java somaclone Bio-13 has higher oil and citronellol yields and Khesari (*L. sativus*) somaclonal variety Ratan has low BOAA content.

Important Considerations in Breeding for Improved Quality

1. Improved quality should not be the cost of yield.
2. Breeding for quality should safeguard the economic interests of both the consumers and the farmers.
3. Improved quality trait must be present in a variety having high and stable yield with good agronomic features. Otherwise, the variety never grown the farmers.
4. A plant breeder must be provided with clear-cut objectives for quality breeding. In case of nutritional quality, human nutritionists must specify the objectives a breeder is expected to achieve.
5. In order to breed for improved nutritional quality, plant breeders must also become familiar with the problems of human nutrition.
6. Incorporation of quality characters should be integrated with the normal breeding procedures for yield. However, traditionally, new lines are developed mainly for enhanced yields and then they are evaluated for quality traits.
7. Increased the protein is usually associated with lower yields. Considerable breeding effort will be required to break this negative association.
8. A close interaction between nutritionists and breeders will increase the rate of progress in breeding for nutritional quality.
9. The success of the breeding Programme for improved quality depends primarily on the following factors. i) extent of genetic variability present in the germplasm for the trait, ii) heritability of the trait, iii) availability of an analytical tool for a rapid, nondestructive, inexpensive and reliable estimation of the trait, and iv) the undesirable associated/ pleiotropic effects of the trait.
10. In case of genetic variation for a trait for a trait is not present in the germplasm, a suitable transgene could be used to bring about the desired alternation in the quality trait.

Limitation of Breeding for Quality

1. Most of the quality traits are polygenic. Therefore, selection for quality traits during the segregating generations is difficult.
2. Quality traits further enhance the long list of traits a breeder has to select for order to develop an acceptable variety.
3. Many quality traits are difficult to estimate and evaluate. Therefore, quality breeding imposes considerable demand on resources, including money.
4. 4 many quality traits have low heritability and are markedly affected by the environment. This retards the progress under selection.
5. In view of the above, breeder has to familiar himself with physiological and biochemical aspects of the quality traits; this means additional burden to the breeder.
6. Quality is not a single trait; in fact, it is a conglomerate of traits. Therefore, unlike yield, it does not have a single estimate. The various quality traits have to be assayed and then interpreted to define the produce quality.
7. Most high lysine/high protein lines show poor grain filling and lower yield.

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Host Resistance for Diseases Control in Vegetables

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Introduction

Vegetables are susceptible to many diseases and losses of yield due to disease may be high as 70-95 %. The diseases are kept under check by following elaborate chemical spray programmed, which however involves environmental risks and high cost. Therefore genetic control of the diseases through developing the resistant varieties will be most effective, inexpensive, ecofriendly and long lasting means of disease control. In such cases disease resistance is inbuilt into the plant and is ready to provide protection under all circumstances. Whereas unfavourable weather, mechanical failure and the like can prevent application of fungicides.

Disease: is an abnormal condition in the plant produced by an organism.

Host resistance: is the inherited attribute of the host that reduces the incidence of pathogen.

Genetic resistance: it refers to that heritable feature of a host plant that suppresses or retard development of a pathogen.

Source of Disease Resistance

Resistance to disease may be obtained from the following sources

A known variety: disease reactions of most of the cultivated are varieties are documented and the breeder may be find it in cultivated varieties, e.g. resistance to cabbage yellows was isolated from commercial variety of cabbage. Locally cultivars are good source of resistance and are preferred because:

Such resistance may carry a smaller number of undesirable linkages than resistance in exotic materials.

Resistance in exotic cultivars may be linked with susceptibility to some disease or pest to which locally adaptive cultivars are generally resistant the use of exotic donor can had to incorporation of such susceptibility which may later stage serious problem.

Germplasm collection: if the resistance to new disease is not known in cultivated varieties, germplasm collection may be screened.

Related species: often the resistance to disease may not be present in the varieties of concerned crop, but may be available in selected species. In such cases resistance is transferred through interspecific hybridization. This type of resistance has been successfully used in many crops.

Mutation: resistance to some diseases may be obtained through mutations spontaneously or induced.

Somaclonal variation: somaclonal variants resistant to various diseases have been isolated in many crops and some of these have been released as variety.

Table 1: Sources of Resistance to diseases in cucumber:

Reference:	Disease	Host resistance
Barnes W. C.	Anthraco	PI197087
Barnes W. C.	Downy mildew	PI 197087
Iman, M. K.	Powdery mildew	Poinsett, Yomaki, Sparton salad, PI 197088
Walker J. C.	Cucumber scab	Wisconsin SMR9, Wisconsin SMR 12
Chand J. N	Angular leaf spot	PI 169400, MSU9402, Gy14A

Table 2: Sources of resistance to diseases in potato:

Reference:	Disease	Host resistance
Toxopeus H.J.	Late blight	<i>S. demissum</i> , <i>S. stoloniferum</i> ;
Bhatia S.K.	Early blight	Hybrids of Spatz x Atzimba, Binia x Atzimba, Brasovean x Grata
Droby,S.		The most promising donors were, Atzimba, Grata, Dobrin, up to date.
Bogucka,H.	Black scurf	Omega, <i>S. phureja</i> , Certa.

Koval, N.D.	Fusarium wilt	<i>S. acaule</i> , <i>S. bulbocastanum</i> , <i>S. phureja</i> , <i>S. demissum</i> , <i>S. andigenum</i>
Gough G.C.	Wart disease	Snowdrops, Reagent, Champion, Maincrop, Abundance, Bruce.
Dearborn C.H.	Common scab	Alaclear, Ontario
Anon	Bacterial wilt	<i>S. phureja</i> .

Table 3: Sources of resistance to diseases in tomato:

Reference:	Disease	Host resistance
Barksdale T.H.	Anthracoze	PI 272636
Andrus C.H.	Collar rot	<i>L. pimpinellifolium</i>
Locke, S.B.	Early blight	<i>L. hirsutum</i> f. <i>glabratum</i>
Gallegly, M.E.	Late blight	<i>L. pimpinellifolium</i> ;
	Buck eye rot	<i>L. esculentum</i> var. <i>cerasiforme</i> .
Andrus, C.H.	Leaf spot	PI153407, <i>L. hirsutum</i> , <i>L. pimpinellifolium</i> .

Table 4: Sources of resistance to diseases in pepper:

Reference:	Disease	Host resistance
Sankaralingam, A. Dempsey, A.H.	Fruit rot	Line 1951, 2158, Santanka
Kann, F.	Bacterial wilt	KAU cluster, White Khandari, Antibois, Conic
Pochard, E.A.	Cucumber mosaic	Rama

Table 5: Sources of resistance to diseases in French bean:

Reference	Disease	Host resistance
Goth, R.W.	Anthracoze	Michelite 62, seaway, PI304110, Cornell 49-242
Brock R.D.	Angular leaf spot	Alabama no.1, California, small white, Epicure
Wallace, D. H.	Fusarium root rot	PI203958
Zaumeyer, W.J.	Rust	U.S. Pinto 5 and 14

Source of Resistance

Solanum spp.: Potato and eggplant are important commercially grown crops. In potato *Phytophthora infestans* is a very serious disease. *S. demissum* is highly resistant to late blight. (Muller, K.O.1934) A study of hybrids obtained by crossing octaploid forms of *S. stoloniferum* with potato cultivars indicated that the wild species carry gene resistance to several races of pathogen. (Kotova, K.A.1972) There are several reports on the late blight resistance clones. According to Poos, 'CIV60/4' and 'CIV H55/8' are resistant. a higher resistant are reported the varieties like 'Anita', 'Elenita' 'Kandidat' 'Poznil' 'karpatski' 'Atzima' etc.

Early blight caused by *Alternaria solani* is a serious problem in potato production. Most promising donors of resistance were 'Atziba', 'Grata', 'Desire' 'wulkan' 'kaiyuga' and 'Erlaine' commercial variety up to date was found least susceptible while red bad was resistant¹⁸. Various species were tested for resistance against black scurf caused by *Rhizoctonia solani*. *S. phureja*, 'Omega' and 'Certa' were reported to be highly resistant. (Bogucka, H.1981)

Potato varieties 'Hudson' and 'Superior' were reported as resistant to fusarium wilt (Leach et al,1974).

Resistance to wart disease caused *Synchytrium endobioticum* was first recognized in UK in 1908 by Gough who confirmed previous report some varieties, particularly 'Snowdrops' 'Victoria', 'Regent' 'Champion' 'Maincrop', 'Abundance' and 'Bruce'.

In eggplant fusarium wilt, verticillium wilt, and bacterial are the serious diseases little leaf disease is a serious problem in eggplant and 'Pusa purple round' is tolerant to this diseases. Fusarium wilt resistance was observed in *S. incanum*, 'Florida market' 'Harries468special' 'Hibush' and 'Harries77631' highly resistant *Verticillium dahliae*. (Obrien, M.J.1981). The line 'SM6' was resistant to bacterial wilt and was accepted as a source of resistance in all India coordinated vegetable improvement project.

Tomato: Anthracnose fruit rot caused by various species of *Colletotrichum* is a major problem in the areas where fruits are harvested mechanically harvested. an ambitious programmed has been started by the U.S.D.A. to develop resistant varieties (Barsdale, T.H. et al,1974). *A. solani* cause collar rot and early blight diseases and early blight diseases and *Lycoersicon pimpinellum* was found to be resistant collar rot phase and *L. hirsutum* was found resistant to early blight phase (Locke, S.B.1947). The resistance gene from *L. pimpinellifolium* has been transferred in the cultivated varieties and several varieties having resistance genes available and can be used as source of resistance.

Resistance to bacterial wilt caused by *P. solanacearum* was reported in *L. pimpinellifolium* and combined in *L. esculentum*. 'Rodade' has been found resistant to race 1 of *P. solanacearum*. It is also resistant to races 1 and 2 of *F. oxysporum* f.s. *lycopersici* and *Verticillium dahliae* (Bosch, S.E., et al).

Pepper: Pepper is highly susceptible to a number of fungal, bacterial and virus diseases. PI201234 and PI 201232 of capsicum annum, *C. cubescens* and *C. pendulum* were resistant to *Phytophthora* root rot 'Mexican Woolly' and 'G2' 'Deva' from Ceylon were found resistant to bacterial spot of pepper in races 1,2,and 3 (Hibberd,A.M., et al).

Cole Crops

Six pathogenic races of *Plasmodiophora brassicae* woron. Causing clubroot has been identified on the basis of the differential reaction of various crucifers (Ayers, G.W.1956). Resistance has been reported in the male sterile lines *Iso*. The 'Badger shipper' variety of cabbage was developed which was resistant to races 1,2,5 and 6 but susceptible to races 2 and 4 resistant genotypes can be identified based on reaction to fungal toxin produced by the pathogen (Chand, J.N.1982).

Cabbage yellow is a serious disease caused by *F.oxysporum* f.sp. *conglutins* this is soil borne disease. For inoculation, seedling can be dipped in inoculation suspension. Two types of resistance, type A and type B have been reported. Type A is not thermosensitive. 'Bohmerwaldkohl 72755', 'bohmerwalkohl 72756' and 'Aichidaiban' (Ashizawa, M., et al 1981) and 'Badger Shipper' and 'Shetland cabbage' were resistant to clubroot and 'Market topper' 'komiya' 'Bansei', 'Saniyo F₁' 'Harutomi' and 'Herbst' were resistant to *Erwinia carotovora*. Pound et al developed two pollinated cabbage varieties, 'Badger blue boy' and 'Badger belle' and ten inbred lines resistant to cabbage yellow and mosaic virus. In cabbage, PI 436606 from China shows juvenile resistance to *Xanthomonas campestris*.

In Chinese cabbage, Chinese lines PI 3915560(1), PI 418959, and PI419069 showed immunity/ resistance to all the strains of turnip mosaic virus (Provvidenti,R1980.)

In spinach leaf spot resistance is found in Turkey, PI169685 and PI173809(Beiquan Mou etal,2005).

Okra

Yellow vein mosaic: germplasm lines to YVMV symptoms indicated that *A. pungens*, *A. manihot*, *A.caillei* and *A. tetraphyllus* were found resistant. Maximum resistant found in *A. tetraphyllus* followed by *A.caillie*. Which could be used to developing the resistant varieties and improvement of convectional varieties i.e. Punjab Padmini, P-7, Parbhani kranti, Arka Abhay and Arka Anamika (B.singh et al)

Cercospora leaf spot: *A.moschatus*, *A. crinitus*, *A.pungens*, *A.angulous*, and *A.manihot* are good source of resistance to this disease.

Powdery mildew: *A.moschatus*, *A. crinitus*, and *A. angulous* are good source for powdery mildew resistance.

Root rot: *A. caillei*, *A. angulosus* (B.Singh et al)

Cucumber

In Cucumber 'PI197088-5' is more resistant source for powdery mildew than 'Natsufushinari' or 'F-9-5-2.' 'PI179676' is more resistant source for the downy mildew of the cucumber. (Dimitar et al)

'PI179676' 'PI197085' PI197086, PI 197088 and 'Natsufushinari' are the highly resistant to *Pseudoperospora cubensis*. 'Poinset' and 'Asthley' moderately resistance to race1 and PI179676, PI197086, PI197088 highly resistance to race 2 (Dimita Angeler, et al)

Potential source of resistance to cucurbit powdery mildew in bottle gourd found in PI271353 (Chandrasekhar S. Kousik etal, 2006)

Muskmelon

Cultivars 'Dodai No.1' and 'Dodai No.2' are highly resistant to Fusarium wilt races1, 2, y (G.Hirai, H.akazumi).

Genetic of Host Resistance

It refers to those heritable features of a host plant that suppress or retard development of the pathogen. Resistance is always defined in relation to susceptible host variety the main feature of genetic resistance are:

Nuclear genes or cytoplasmic genes or both govern it.

It is measured in relation to susceptible varieties.

Breeding of resistant cultivar takes into account the genetic variability of both pathogen and host plants.

The resistance varieties may be susceptible after few years due to formation of new races of the pathogen.

Types of Genetic Resistance

Van Der Plank (1963) suggested two main types of resistance i.e. vertical and horizontal resistance.

Vertical resistance: it is also known as race specific resistance that means specific resistance of a host to the particular race of a pathogen. In other words the host carrying a gene for vertical resistance is attacked by only that pathotype

which is virulent towards that resistant gene; to all other pathotypes the host will be resistant. Thus avirulent pathotype will produce an immune response i.e. $r=0$, but the pathotype leads to susceptible reaction $r=1$ or >1 . This type of resistance is governed by one or few genes and therefore referred to as oligogenic resistance. When the resistance is controlled by single gene it is known as monogenic resistance. This is also known as qualitative resistance. Immune or susceptible response in case of virulent pathotypes. When the virulent pathotype becomes frequent, epidemics are common in the case of vertical resistance.

Main Features of Vertical Resistance

1. It displays discontinuous variation among the genotypes and classification of genotypes.
2. Transfer of oligogenic resistance from one host to genotype to another is simple.
3. It is usually short lived or less durable. The resistance can easily breakdown when new race of pathogen is formed.
4. It provides protection from one race of pathogen only.
5. It has high heritability and can be easily identified in the breeding programmes.

Horizontal Resistance

It is race non-specific, pathotype non specific resistance. It is generally controlled by polygenes i.e. many genes with small effects. In this type the host plant resistant to all the races of a pathogen. Horizontal resistance does not prevent the development of symptoms of the disease, but it slows down the rate of spread of the disease in the population. Here the reproduction rate of the pathogen is never zero, but it is <1 or >0 . This type of resistance is also known as general resistance, non-specific type and minor gene resistance.

Main Feature of Horizontal Resistance are

It exhibits continuous variation among genotypes and therefore classification of genotype into different distinct classes is not possible.

1. It has low heritability and therefore identification of resistant types is difficult.
2. It provides protection from several races of pest.
3. New races of the pathogen due to polygenic control cannot easily overcome the resistance.
4. It is difficult to transfer polygene resistance from one host to another, because individual allele in a parent cannot be identified.

Genetic Host Resistance for Different Vegetable Diseases

Solanum spp.: In potato (*Solanum tuberosum*) resistance to late blight in *S. demissum*, a wild Mexican hexaploid species is inherited monogenically with dominant effect. (Solaman, R.N.1911). A series of R genes have been reported to control the resistance against various races of *Phytophthora infestans*. The r gene is race specific, being immune to some races and susceptible to others. Kotova stated that the wild species *S. stoloniferum* carries genes for resistance to several races of pathogen and most hybrids had a complex combination of resistance genes, such as R2R3, R3R4 and R2R5. Most of them showed both vertical and horizontal resistance. The gene R1 and R3 controls resistance in hybrid 'Dorita.' (Kotova, K.A)

Resistance to *Verticillium dahliae* and resistance to *F. solani* appeared to be controlled by a single dominant gene. Lunden considered that immunity to most of the common race of *Synchytricum endobioticum* may be controlled either by a single dominant gene X, or by two complementary genes Y and Z. the genetics of wart resistance appears probably much more complex. A new theory is presented to account for the mechanism of resistance to *S. endobioticum* in *Solanum tuberosum*, and it is proposed that resistance is determined by single dominant gene A, the action of which can be inhibited by three complementary genes B, C and D. (Maris, B.1971)

Table 6: Genetic of resistance to diseases in potato:

Reference	Disease	Host resistance	Gene(s) involved
Muller K.O.	Late blight	<i>S. demissum</i>	A series of major (R) genes. Complex combination of resistance gene such as R2R3, R3R4 and R2R3.
Malcolmson, J.F.		<i>S. stoloniferum</i>	
Malamud, O.	Verticillium Wilt	<i>S. bulbocastanum</i>	Single dominant
Lunden P.	Potato wart	-	Single dominant gene X or two complementary genes Y and Z
French E.R.	Bacterial wilt	<i>S. phureja</i>	Three or more dominant and independent genes

Tomato

Early blight caused by *Alternaria solani* is a serious disease of tomato in India. Generally, the attack starts in the advanced stage of the crop and sometimes finishes the entire crop. Not much work has been done on this disease; however, two or more recessive factors have been considered on the basis of segregating data to control the disease. (Barksdale T.H. et al)

Fusarium wilt, caused by *Fusarium oxysporum* f.sp.*lycopersici* is a serious disease under high temperature and humid conditions. Two races of the pathogen, i.e., race 1 and 2 are prominent. Immunity in *Lycopersicon pimpinellifolium* was conditioned by a single dominant factor I resistance to race 2 is also monogenic dominant. But independent of the I gene. A linkage study has indicated that genes I2 and I are assigned on chromosome. There has been some deviation of monogenic control of resistance, which may be presumably due to gametophytic preference and linkage with the I gene. Several varieties have been developed carrying the I gene, which exhibits a high degree of resistance. Resistance to verticillium wilt, caused by *Verticillium albo-atrum* is also conditioned by single dominant factor, VeVe. (Kosuge, E. et al) However, the effect of resistance gene largely depends upon the temperature and photoperiod.

Inheritance of resistance to target leaf spot has been studied using resistant varieties PI12065 and PI 112215. Susceptibility was dominant and controlled by a single gene in PI12065. However, PI112215 might confer a higher degree of resistance than the recessive allele from PI12065, which indicates the involvement of a modifier gene to confer a higher degree of resistance. (Renish, W.J. et al)

The genetic of resistance to bacterial wilt, caused by *P.solanacearum*, is complex one. According to Ferrer, resistance in PI1256408 was polygenic. There is no clear finding regarding dominant or recessive, but probably it may be partially dominant to recessive. Resistance to bacterial wilt is not stable and may change with change of temperature or environment. Inheritance of bacterial cancer caused by *Corynebacterium michiganse* is polygenically controlled, but control of resistance depends upon host resistance. *L. hirsutum* f.sp. *glabratum* had multiple genes with incomplete dominant for resistance whereas resistance in *L. pimpinellifolium* and in *L. hirsutum* (PI 25305) was controlled by four major factors, along with a recessive. Bacterial wilt resistance has an unfavourable association with fruit size. (Ascosta, J.C., et al1963)

Table 7: Genetic of resistance to diseases in tomato:

Reference	Diseases	Host resistance	Gene(s) involved
Rattan R.S.& Saini S.S.	Buck-eye rot	<i>L. pimpinellifolium</i>	EC54725, Br.
Barksdale T.H.	Early blight	71B2	Two or more recessive factors
Reynard G.B.	Collar rot	<i>L. hirsutum</i>	More than one dominant factors
Boukkema, I.W.	Foot and root rot	<i>L. esculentum</i> lines from U.S.	One incomplete dominant major gene
Gallegly ,M.E.	Late blight	West Virginia Acc.36 and 106 <i>L. pimpinellifolium</i>	Tr 1 monogenis

Pepper

Mostly single dominant or single recessive genes control resistance to disease in capsicum annum. Resistance to *Phytophthora capsici* in *C. frutescens* as resistant parent was conditioned by a single recessive factor; F₁ was intermediate. (Saini, S.S.& Ratan R.S.1981) According to Galmarini, a dominant gene, along with a modifier may be involved in the control of resistance to *P.capsici*. A backcross method of breeding was followed to transfer the resistance characteristic from resistant lines 491 and 493 to susceptible variety. Among virus diseases, genetics of resistance to CMV was studied. No complete resistance to CMV has been discovered. More durable resistance, a combination in a single genotype of Ra, Rb, and Rc types can be used. Resistance to local lesion induced by CMV strain N was controlled by a major gene and this gene modified the reaction to tobacco mosaic virus on the presence of *Lycopersicon*. Resistance to etch virus (TEV) in PI 152225 was recessive monogenic. (Greenleaf, W.H.1956.)

Table 8: Genetic of resistance to diseases in capsicum.

Reference	Diseases	Host resistance	Gene(s) involved.
Saini S.S.& Rattan R.S.	<i>Phytophthora</i> fruit rot	<i>C. frutescens</i> Waxy globe	Monogenic recessive Single dominant
Dempsey, A.H.	<i>Xanthomonas vesicatoria</i>	Santanka	Monogenic dominant

Peas

Several races of the pathogen have been reported, of which resistance of pea cultivars to races1, 2, and 5 is conditioned by single separate dominant factors. Resistance to wilt caused by *Fusarium oxysporum* f.sp. *pisi* is controlled by gene Fw and near wilt resistance by Fnw in 'Admiral Selection.' (Hare, W.W., et al, 1948)

Damping off caused by *F. solani* f.sp.*pisi* and *Pythium ultimum* was associated with A, plus PL, and M (mottled seed), but not with I, R (smooth seed.)

Resistance to powdery mildew is conditioned by single recessive gene. Resistance to powdery mildew in P185, P6583, P6587, T-10 and T-56 is controlled by pair of recessive genes and in P-388 and P6588 by two pairs of recessive genes. Resistance in the T-10, P185, and P6583 is controlled by a single recessive gene in each of the three crosses.(Saxena, J.K., et al,1974)

The inheritance of resistance to *Ascochyta pisi* was studied by Wark. The resistance in the variety Austrian Winter was controlled by a combination of three dominant genes. However, resistance to pathotype 2 of *A. pisi* was determined by a single dominant gene located in linkage group 1. However, resistance to pathotype 1 controlled by a recessive gene. Inheritance of resistance to *A.pinodella* was studied in the 'Kinnauri' variety and it was found that 'Kinnauri' has a dominant gene for resistance to *A.pinodella*.(Rastogi, K.B & Saini S.S.1982)

Table 9: Genetic of resistance to diseases in bean:

Reference	Diseases	Host resistance	Gene(s) involved.
Singh A.K.& Saini S.S.	Angular leaf spot	PBL-257	Single recessive gene
Abawi,G.S.	White mold	<i>P. coccineus</i>	Ws
Barksdale T.H.	Common blight	GN Nebraska I	Polygenic (low heritable)
Ribeiro, R.	Rust	GN1140	Single dominant.RB ₁₁

Cucumber

Resistance to powdery mildew caused by *S. fuliginia* is a complex one. Line resistant to powdery mildew has a partially dominant gene for resistance that is epistatic to dominant genes for susceptibility in 'Market'. *Bw* gene on PI200815 controlling resistance to bacterial wilt *E. tracheiphila* was found linked with the *M* gene for pistillate flowers. (Iezzoni, A.F. & Peterson, C.E.,1980)

Powdery mildew was controlled by two recessive genes and plant with aaBB or aaBb show resistance under 26^oc condition and average susceptibility under 20^oc PI197088-5 is a novel gene source for resistance to powdery mildew.(Morishita et al).

J-13, a derivative of Wisconsin 2843, was found to be controlled by incompletely dominant gene(s). Resistance was expressed as small, chlorotic water soaked lesion with negligible sporulation of the fungus. No breakdown of the resistance was observed at 12^oc (Ludmila Petrov et al)

Table 10: Genetic of resistance to diseases in cucumber:

Reference	Diseases	Host resistance	Gene(s) involved
Abul-Hayja,Z.	Anthraxnose	South Carolina	<i>cla</i>
Iman M.K.	Powdery mildew	Poinsett, yomaki	Two pairs of duplicate genes
Robinson R.W.		Ashley	Three complementary recessive genes for tolerance
Vanvillet,G.J.A	Downy mildew	Poinsett	<i>p</i>
Chand J.N.	Angular leaf spot	--	polygenic

Application of Growth Substances

Growth substance can be used to reduce the incidence of diseases. 2-4-D, NAA,TIBA, and IAA have reduced the incidence of fusarium wilt diseases in tomato. The CC was applied as a foliar spray at the two and three true leaf stages in the rainy season. Leaf curl and TMV incidence was studied at maturity stage. Generally, the incidence was low in the years CCC effectively reduced the incidence of leaf curl and TMV increased the yield. Thus, CCC can be used on a commercial scale to reduce the incidence of these virus and where there is no resistant variety. Spraying flowers with demonized reduced the incidence of common scab in potato. The incidence of verticillium wilt in tomato was reduced with the allocation of CCC. Furthermore, the symptom severity of fusarium and verticillium wilt of tomato was reduced with the application of CCC. The treatment of tomato plant with low concentrations of catechol prior to inoculation with Fusarium reduced the appearance of disease symptoms. Furthermore, Retig and Lisker found that in catechol treated tomato plants the fungus produced the cell-wall degrading enzymes in the plants but the plants remained symptoms less. Application of growth substances thus can be used to reduce the incidence of diseases.

Biochemical Basis of Resistance

Preinfectious and positional inhibitors are involved to inhibit the incidence of pathogens. Preinfectious inhibitors in the plant are mainly catechol, rocatechuic acid, phenols, terpenes, flavanoids and tomatine. Prohibition content in the plant is the potential chemical to determine the resistance in the plants, the higher the prohibition the more the resistance. Tomatine and solanine have been reported to be important inhibitors in *Lycopersicon*.

Table 11: Prohibitors in vegetable crops:

crop	prohibitors
carrot	Chlorogenic acid, benzoic acid, n-oxybenzoic acid
radish	raphanin
potato	Saponin, solanine, demissie, tomatine, digitonin
tomato	Solanine Tomatine
pea	Amino- butyrylactone
onion	Protocatechuic acid S-methyl and S-propyl
Sweet potato	Caffeic acid, chlorogenic acid

1. Tomatine: The phytochemical α tomatine, a steroidal glycoalkoid, exhibited inhibited inhibitory activity against a number of organisms. According to Fontaine et al. Tomatine exhibited an antibiotic activity against a number of organisms. In *Lycopersicon*, tomatine or one of its derivatives is the only steroidal alkaloid present. Whereas in *Solanum*, tomatine is accompanied by other steroidal glycoalkaloids. There is variation in the presence of tomatine in various parts of the plants. In leaves 0.46%, stem 0.08% and laves 0.16%. the tomatine yield decrease with age of the plant. In *L. pimpinellifolium*, content was higher in the roots, which were resistant to *Pseudomonas solanacearum*, whereas in susceptible cultivars, tomatine content was less. There is disappearance of tomatine at the time of ripening, which may be due to actual degradation of the alkaloids.

Tomatine present in higher amounts proved resistant to wilt in tomato. The maintenance of a rate of tomatine production is important for resistance, otherwise the resistance is broken. Tomatine extract was found toxic to *F. oxysporum f. lycopersici* in vitro. Mature and partially purified tomatine contributed more inhibitory activity to the pathogen than that purified. Hyphal extension of *F. oxysporum f. lycopersici* was inhibited with the application of tomatine. A higher content of tomatine was found in the root and shoot of Venus a bacterial wilt resistant variety than Marglobe contained, a bacterial wilt susceptible variety. Venus contained 775 ppm whereas Marglobe contained only 213 ppm tomatine on the root. tomato plants having a higher content of α tomatine might exhibit resistance to tomato pathogens. The variation in the content of α tomatine was conditioned by segregation of two codominant alleles at a single locus.

2. Phenols: Phenolic content in the plants determine the resistance, but the exact mechanism of the control of resistance is not fully understood. It is responsible for disease resistance in a number of crops (Farkas and Kiralay, 1962). A classical example of the protective role of preformed phenolics is against incidence of the *Colletotrichum circinans* in onion. In tomato, a resistant combination of *Fusarium*-infected tomato accumulated more phenolics than the susceptible combination (Menon and Schaeffgen, 1957).

3. Alkaloids: The important alkaloids are α -tomatine, solanine, chaconine and solanidine. In potato, solanine, chaconine and solanidine inhibited the radial growth of *A. solani*. Solanidine was the most inhibitory of the three alkaloids, followed by chaconine and solanine respectively (Kalloo, 1988).

4. Phytoalexins: There are several reports on the postinfectious and secondary production of chemicals in plants attacked by bacteria, fungi and viruses and these phytoalexins are toxic to several organisms. In potato five phytoalexins are synthesized which were toxic to pipelicolic acid, an amino acid isolated from extracts of the leaf roll virus- infected potato tubers (McDonald, 1974). 820 . In resistant cowpea cultivar "Caloona" rapid accumulation of phytoalexin was observed after inoculation with *Phytophthora vignae* (Partaridge and Keen, 1976).

Multiple Disease Resistance

Multiple disease resistance mainly developed in *Solanum tuberosum*, *Lycopersicon esculentum*, *Capsicum spp.*, *Ipomoea batatas*, *Cucumis sativus*, *Cucumis melo*, *Citrullus lanatus*, *Phaseolus vulgaris*, *Vigna unguiculata*, and *Brassica oleracea*. In *Solanum tuberosum*, multiple disease resistance lines with *Meloidogyne spp.*, potato virus Y, potato leaf roll virus, and early dying diseases have been developed. (Martin, M.W., et al, 1967) Wild species *S. phureja* and *S. demissum* have been used to develop multiple disease resistant varieties (French, E.R.). A fairly large number of multiple disease resistant varieties developed in tomato, of which, 'Royal Red Cherry' and 'Short Red Cherry' are indeterminate. The vine of 'Short red Cherry' is more compact due to the *Brachytic gene (br)* and earliness. These varieties are resistant to the number of diseases. Other multiple disease resistance varieties are 'Tropic' and 'Walter'

Generally, both the methods (sequential and simultaneous selections) have been adopted independently to test resistance to *Fusarium solani*, *Xanthomonas campestris*, and *Uromyces phaseoli* in *Phaseolus vulgaris*. However

resistance affected by the interaction between the pathogens. Multiple disease resistances have been studied in cowpea extensively (Williams, R.J.1967). In this crop, 5000 lines were tested, of which 28 were resistant to *Colletotrichum lindemuthianum*, *Mycosphaerella spp.* and *Corynespora cassicola*. Lines showing multiple disease resistance had the capacity to give moderate to high yield under disease infected conditions. 'Iron' and 'Ohio' lines have also exhibited multiple disease resistance.

Several reports are available to exhibit multiple disease resistant varieties in cucumber the procedure for screening is important for developing multiple disease resistant varieties. Abul- Hayja has developed procedures for screening the seedling against eight diseases. These diseases are anthracnose (*Colletotrichum lagenarium*), downy mildew (*Pseudoperonospora cubensis*), fusarium wilt (*F. oxysporum*), scab (*Cladosporium cucumerinum*), powdery mildew (*Sphaerotheca fuliginea*), bacterial wilt (*Erwinia tracheiphila*), angular leaf spot (*Pseudomonas lachrymans*) and cucumber mosaic(CMV).all the inoculations are generally made at the cotyledonary stage, except fusarium wilt powdery mildew and CMV. For fusarium wilt, soil inoculation is done. However, for CMV and powdery mildew, inoculations are done at the initiation of true leaves, although for inoculation, sequential inoculation is safer than simultaneous inoculation. However, while inoculating for anthracnose, simultaneous inoculation can be done for downy mildew, scab, angular leaf spot and bacterial wilt, and subsequently survivors may be inoculated with CMV and powdery mildew. Other studies on screening have indicated that there was no interaction among the pathogens *C. cucumerium*, *P. lachrymans*, and *S. fulginea* with their simultaneous inoculation in *Cucumis sativus*. Wyszgrodzka and Williams advocated multiple inoculations to produce distinct, resistant, and susceptible genotypes. Complex multiple hybridization and complex crosses and backcrosses involving various sources of resistance can be used to develop multiple disease resistant varieties in cucumber.

In muskmelon a number of multiple disease resistant varieties have been developed. The 'Casaba' variety has been used to develop multiple resistant breeding lines. (Norton, J.D.)

In watermelon, multiple disease resistance has been reported in a number of varieties. 'Smoklyee' is resistant to fusarium wilt and anthracnose. 'Dixielee' is resistant to wilt and anthracnose and it is high quality also.(Crall,J.M.1980).It is superior to 'Charleston Gray' in respect of soluble solids, flesh firmness, and flesh colour. So this has the combination of multiple disease resistance and quality attributes.

Table 12: Multiple disease resistance cultivars:

Reference	Crops	Cultivars	Pathogens
Strobel,J.W.	Tomato	Tropic	<i>Verticillium albo-atrum</i> ; <i>fusarium oxysporum f.sp. lycopersici</i> ; <i>Stemphylium solani</i>
Beal, P.R.		Walter	Race 2 of <i>F.oxysporum f.sp. lycopersici</i> , TMV.
Jones R.A.		Royal Red Cherry	<i>F. oxysporum f.sp. lycopersici</i> race 1, <i>V.dahliae</i> (strain1), TMV, <i>alternaria alternate f.sp. lycopersici</i> .
Cook A.A.	Sweet pepper	Florida VR 4	Pepper mottle, tobacco etch virus, potato Y and tobacco mosaic virus
Peter K.U.	Hot pepper	Pant C-1	<i>Pseudomonas solanacearum</i> ; <i>phytophthora capsici</i> and <i>Meloidogyne incognita</i>
Peter K.U.		White Khandari	<i>Pseudomonas Solanacearum</i> ; <i>M incognita</i> ; <i>phytophthora infestans</i>
Walker J.C.	cucumber	Wisconsin SMR9 and Wisconsin SMR12	<i>Cladosporium cucumerinum</i> and cucumber mosaic virus, scab and mosaic
Barnes W.C.		SC 2 B 4-1 SC 2 B 4-3 SC 2 B 6-4	Resistant to powdery mildew, downy mildew race1, anthracnose, and moderately resistant to mosaic (CMV)
Ivanoff,S.S.	Muskmelon	Homegarden Gulfcoast Chilton	<i>P.cubensis</i> , <i>Erysiphe cichoracearum</i> <i>P. cubensis</i> ,; <i>mycosphaerella citrullina</i> and <i>S.fulginea</i>
Pound G.S.	Cabbage	Inbreds 1 to 10	<i>F. oxysporum f.sp. conglutinans</i> , cabbage mosaic, turnip mosaic virus, cauliflower mosaic virus
Walker J.C.		Globelle	Fusarium yellows and non-parasitic diseases, internal tip burn, <i>Rhizoctonia solani</i> , <i>Erysiphe polygoni</i> .
Williams P.H.		Hybelle, Sanibel	<i>F.oxysporum f.sp. conglutinans</i> ; <i>Erysiphe polygoni</i> ; <i>Rhizoctonia solani</i> ; cabbage mosaic virus and cauliflower mosaic virus.

In cabbage, classical work has done on multiple disease resistance, with the object to produce multiple disease resistant hybrids. Inbred lines were developed having resistance to certain diseases. Badger inbreds 12 and 13 were developed which resistant to cabbage yellows mosaic and tip burn, whereas variety 'Globelle' was resistant to cabbage yellows, powdery mildew, and *Rhizoctonia* by crossing Badger inbreds 12 and Globelle, 'Hybelle' hybrid and by crossing Badger inbred 13 and 'Globelle Sanibel' hybrids were produced. These hybrids, besides being resistant to number of diseases were of good quality and also resistant to the nonparasitic disease internal tip burn. (William, P.H. et al, 1968)

Williams and Leung have described the methods of breeding for multiple disease resistance in Chinese cabbage, especially the procedure for screening the segregating populations, either simultaneously or sequentially for resistance to turnip mosaic virus, *Peronospora parasitica*, and *Erwinia carotova*.

Factors Associated with Resistance

Several factors are involved in the expression of resistance attributes in plants. Inoculum concentration, temperature, light, moisture, soil factors, disease complex, etc. are associated with the expression of the disease. For the resistance to fusarium vascular diseases, control of temperature of the growing medium is most important. In the case of root-rotting fungi, other factors, i.e., seed quality, level of inoculum, depth of planting and moisture content of growing medium are important.

Effect of the pathogen: resistance is associated with the inoculum density and concentration. This is generally true with the soil-borne pathogens, e.g. wilt pathogens. However, there is no effect of concentration of inoculum on the resistance to fusarium wilt. A low level of resistance or polygenic intermediate resistance of potato verticillium wilt is overcome easily by increasing inoculum. The inoculum density of wilt fungi and resistance has been reviewed by Bell and Mace. There is a marked decrease in the disease incidence on the resistant plants as the bacterial wilt inoculum concentration is decreased in a number of solanaceous crops. Mew and Ho studied the five-inoculum levels (from 10^9 to 10^5 viable cells/ml) on susceptible and resistant varieties of tomato. The resistant varieties shifted from resistant to moderately resistant when inoculum density was increased; however, the susceptible varieties were not affected by a change in the inoculum concentration.

Temperature: resistance to bacterial wilt in tomato is not stable at high temperature (above 31°C) Mew et al. Krausz and Thurston studied the effect of temperature on the resistance to bacterial wilt in tomato under controlled conditions. Elevated temperature (32°C) significantly increased the severity of bacterial wilt in two tomato lines, i.e., 'Phillipine 1169' and 'Hawaii7580' resistant to *P. solanaceum*. However, the level of resistance of another line, Venus, to isolate 'K-60' was not significantly affected by temperature, but this line expressed no resistance to isolate 'LB-6' at all temperatures tested. In other cases the resistance was broken when temperature exceeded 22 to 30°C . Thus, temperature treatment maintained a moderate resistance to *P. solanaceum* at 26, 30 and 32°C the rate of wilting of the plant also differed among the varieties and different soil is essential. (Mew, et al, 1975)

Temperature has been reported to influence the effect of several genes for resistance to TMV. Tomato plants with *Tm-2* genes are almost resistant to the strain 0 at normal temperature, when temperature is increased severe systemic necrotic reactions have been reported *Tm-1* genes confer the resistance to common isolate of TMV. The symptom of the disease is completely suppressed, both under heterozygous (*Tm-1/+*) and homozygous (*Tm-1/Tm-1*) conditions of the plant. The inhibition of virus multiplication by the *Tm-1* gene is temperature dependent. In plants heterozygous for *Tm-1* it was over 95% at 20°C , but only 20% at 33°C . TMV strain 1 caused symptoms on *Tm-1* plants the higher the temperature the more severe the symptoms. Strain 1 multiplication of strain in both resistant and susceptible plants was much more temperature sensitive than was strain 0 multiplication. However, the multiplications of strain 1 are inhibited by *Tm-1* at 25°C , but not at 33°C . (Fraser, et al)

The incidence of leaf curl virus in tomato mainly depends upon temperature. At high temperature and humidity severity of the disease is very high. Expression of fusarium wilt caused by pathogen *Fusarium oxysporum* f.sp *pisi* race 1 has been broken at 28°C . The best resistance assay temperature for this race was 22°C . (Schroader, W.T. et al. 1940)

Further more, resistance to *Pythium* and *F. solani* of peas decrease at 18 to 24°C compared to 13°C the resistance to *F. oxysporum* decreased from 21 to 24 to 27°C compared to 18°C . Wells, D.G. et al. Shift in environment may lead to a useful change in the degree of penetrate or reversal of dominance. The incomplete penetrate of the resistant genes may be due to the temperature effect. Temperature affected the reversal of the dominance in the resistance of *Pisum sativum* to bean virus 2. The symptom expression in heterozygous is governed by temperature. The phenotypic at an air temperature of 80°F or above. Between these temperatures, symptom expression is delayed in heterozygotes. Thus heterozygote can be separated from homozygotes by manipulating the temperature.

For expression of cucumber scab caused by *Cladosporium cucumerinum*, optimum humidity and temperature are required. The optimum temperature is about 17°C . Cabbage yellows, a disease caused by the vascular parasite *F. conglutinans* developed from 17 to 35°C at 17°C it develops very slowly, even in the most susceptible variety. When temperature exceeds 17°C resistance is reduced or broken.

In certain cases resistance is decreased at low temperature. In beans, low temperature decreased to fusarium wilt and in eggplant and pepper to verticillium wilt.

The temperature of the plant affects big vein symptom expression in the lettuce. In the plants, susceptibility to big vein disease was high at 14°C but plants were resistant at 24°C. Predisposition to bacterial and fusarium wilt is at a moderate temperature. There is minimum resistance at moderate temperature (23 to 28°C) to bacterial canker and fusarium wilt. Thus, temperature manipulation has been used to distinguish the level of resistance against fusarium and bacterial wilt. (Alon, H. et al).

Light: resistance decreases with a decreased photoperiod and reduced light intensity. This has been observed in tomato with fusarium wilt and verticillium wilt. (Ben Yepheth et al, 1976). High light intensity is required for the better expression of resistance in potato to *Phytophthora*. However, in cabbage there is less resistance to clubroot under high rather than under low light intensity.

Moisture: soil moisture affects the resistance and generally resistance to fusarium root rot in beans is higher at low soil moisture than at high soil moisture. (Miller, D.E. et al) Humidity increases the incidence of *Sclerotinia* in bean, and *Cercospora* in celery. (Berger, R.D. 1974) Resistance to *Pythium* in peas and bean was decreased with wetness. Excess moisture in the soil may cause poor soil aeration. (Miller, D.E. et al, 1974) Resistance to fusarium root rot in French bean lines 'Gloria pink' and 'NY2114-12' was effective in well-aerated soil. But resistance was overcome by short period of poor soil aeration. In potato, resistance to early blight caused by *Alternaria solani* is associated with duration of leaf wetness (Holly, J.D. et al, 1983). At a high moisture level bacterial wilt resistance may be reduced as it favours the survival of bacteria.

Nutrient elements and soil pH: heavy application of fertilizer generally predisposes the plants. Potassium fertilizer generally exhibits a marked effect on the expression of resistance. Under potassium deficient conditions, severity of wilt is generally increased (Bell and Mace). At high nitrogen and low potassium level the resistance of tomato to bacterial soft rot is decreased the effect of nitrogen and potassium was studied concerning resistance of potato to *E. caratovora*. Increase in susceptibility due to potassium occurred only at the lowest potassium dose and reduction in susceptibility due to potassium occurred at the highest nitrogen dose. Phosphorus increases resistance to scab of potato (Davis, J.R et al). A high nitrogen level with a low potassium level reduces the resistance to verticillium wilt. Ammonium nitrogen increases the severity of fusarium wilt in tomato. Application of micronutrients, especially zinc and certain combinations of iron, manganese, and zinc has been found to increase the severity of fusarium wilt in tomato.

An acidic condition favours bacterial wilt disease development although it occurs in both acidic and alkaline soils. The ideal pH of 6.5 to 7.5 has been found for bacterial development. (Gupta, P.C. 1981) The high wilt incidence was observed at a pH of 3.5.

Herbicides: resistance to *F.oxysporum* and *Verticillium dahliae* was increased in eggplant and tomato with the application of trifluralin and nitratin. The resistance was upto 97 %. (Grinstein, A et al) Plants resistant to one condition may not be resistant to another condition. Expression of resistance to a disease is affected by the age of the host plants. Adult plants are more resistant than seedlings.

Table 14: Vegetable varieties resistant to diseases:

Crop	Variety	Disease	Source
Brinjal	BWR-12	Bacterial wilt	IIHR, Bangalore
	Pant Riturag	Bacterial wilt	Pantnagar
	Pant samrat	Bacterial wilt	Pantnagar
	Pusa Purple Cluster	Phomopsis blight	IARI, New Delhi
Cabbage	BB-7	Bacterial wilt	Bhubaneswar
	Pusa Bhairav	Phomopsis blight	Bhubaneswar
	SEL-8	Black rot	IARI, Katrain
Cauliflower	Pusa Shubra	Black rot	IARI, New Delhi
	Pusa Snowball K-1	Black rot	IARI, Katrain
Chilli	Punjab Lal	TMV	PAU, Ludhiana
	Pusa Sadabahar	TMV	IARI, New Delhi
Cowpea	Pusa Komal	Bacterial blight	IARI, New Delhi
Musk melon	Arka Rajhans	Powdery mildew	IIHR, Bangalore
	Punjab Rasila	Powdery mildew	PAU, Ludhiana
Okra	Sel-10	YVMV	IIHR, Bangalore
	Sel-2	YVMV	NBPGR, New Delhi
	P-7, P-8	YVMV	PAU, Ludhiana
	Parbhani Kranti	YVMV	MAU, Parbhani
Pea	PRS-4	Powdery Mildew	Pantnagar
	PM-2	Powdery Mildew	Pantnagar
	Arka jeet, Solan Nirog	Powdery Mildew & Rust	Pantnagar

	JP-4		
Tomato	BT-1 Pant Bahar	Bacterial wilt Verticilium wilt & Fusarium wilt	Bhubaneshwar Pantnagar

Varieties Resistant to Different Diseases in Vegetable Crops

Introduction

Sr.no.	Crop	Name of variety	Resistant to diseases
1	Capsicum	Chinese giant, Hungerium yellow wax California wonder, Hungerium Wax	Fruit rot Cercospora leaf spot.
2	French bean	Kentucky wonder Contender Pinto	Bean rust Powdery mildew & Mosaic. Powdery mildew.
3	Cucumber	Poinsette	Downy mildew, Powdery mildew, Anthracnose, Anguler leaf spot.

Hybridization:

Crop	Variety	Parents	Resistant to diseases
Brinjal	Hisar Shyamal	Aushey x BR-112	Little leaf, bacterial wilt.
Chilli	Pusa sadabahar Pant C-1 Punjab Lal	Pusa Jwala X IC-31339 NP-46A X Kandhari Perenial X Long red	CMV, TMV Mosaic & leaf curl virus TMV
Okra	Punjab Padmini	-----	YVMV
French bean	Pant bean-2	Turkish brown X Conteder	Rust & common mosaic virus
Cabbage	Pusa Mukta	EC-24855 X EC-10109	Black rot
Watermelon	Arka Manik	IIHR-21 X Crimson Sweet	Powdery mildew, Downy mildew, Anthracnose
Potato	Kufri Kuber Kufri Pukraj Kufri Giriraj Kufri lavkar		Leaf roll virus, potato virus. Early blight. Late blight

Mutation:

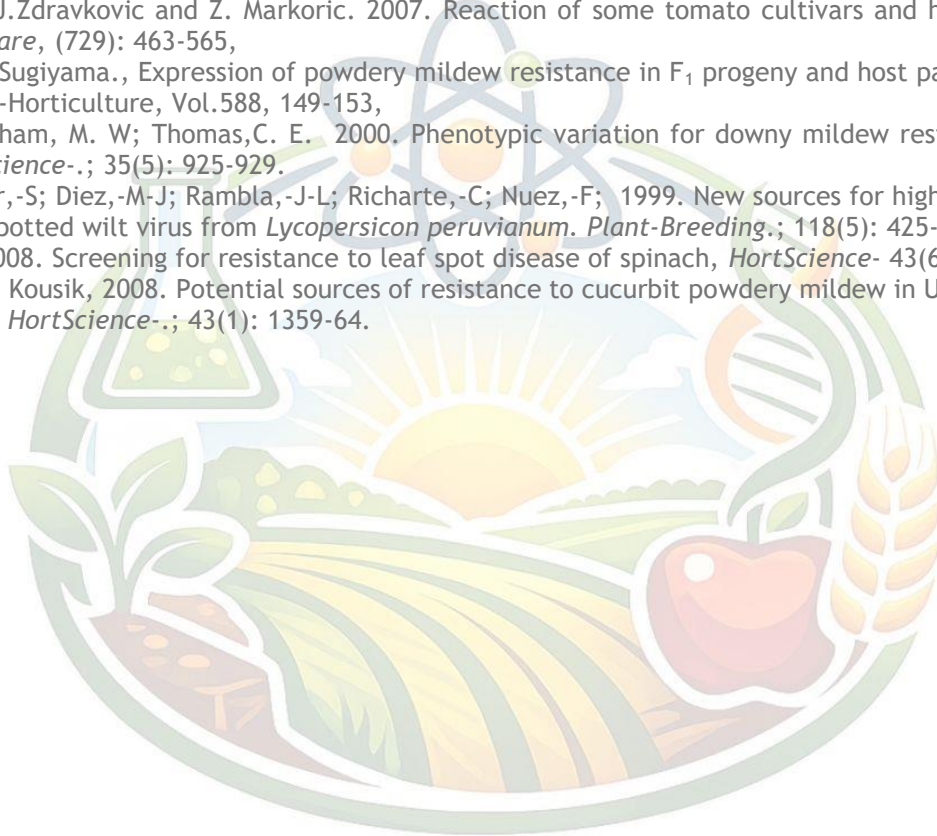
Crop	Mutant	Resistant to diseases
Pepper	Hargoskalatka	CMV
French bean	Pusa Parvati	Mosaic & powdery mildew
Okra	Punjab -8	YVMV

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Microgreens: New Era for Nutritional Security

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Microgreens are a powerhouse of nutrients, easy to grow, and a perfect addition to any greenhouse. Whether you're a seasoned gardener or just starting out, cultivating microgreens in a controlled greenhouse environment **ensures consistent growth and a fresh supply of these vibrant greens year-round**. Microgreens aren't a special kind of plant with some magical benefits to your body; most green plants and herbs go through a stage where they're considered a microgreen. This might leave you wondering what a microgreen is. A microgreen is the stage of a plant's life that's right after germination (when the seed starts to bud). They're perfect for harvesting when they've got a few leaves that you can see, typically when they're about a few inches tall. By harvesting them when they're so young, you're not compromising any of the nutritional value like you do when harvesting fully mature plants. If you collect them right before you use them, you minimize the loss in nutrients even more.

Growing microgreens inside a greenhouse comes with several advantages. One of the most significant benefits is the ability to control the environment. A greenhouse provides a stable temperature, proper humidity levels, and protection from extreme weather conditions. This ensures that your microgreens grow consistently, no matter the season. Another advantage is that greenhouses offer protection from pests and diseases: Unlike outdoor gardens, where insects, rodents, and other threats can hinder growth, a greenhouse creates a barrier that keeps your plants safe. Additionally, greenhouses allow for year-round harvesting, meaning you can enjoy fresh microgreens even in winter.

Since microgreens have a short growth cycle, having a dedicated space in a greenhouse allows for continuous harvesting.

Vegetables harvested at an immature growth stages:

Sprouts: germinated seeds with emerging root

Microgreens: 2-3 inches height; 7-21 days old (harvest stem, cotyledon and emerging true leaves)

Baby greens: 4-6 inches in height 21-40 days old

Mature greens : > 6 inches in height; 40-60 days old.

Crops Suitable for Microgreen

Turnip, Radish, Broccoli, Mustard, Cauliflower, Lettuce, Kale, Spinach, Cabbage, Amaranthus, Basil, Fenugreek, Beetroot, Swichard, sunflower, Coriander, Kohlrabi, Peas, Wheat, Arugula, Carrot, Cress, Celery, Dill, Leek etc.

Best Seasons for Growing Microgreens

Not all microgreens thrive in the same conditions. Some prefer warmer temperatures, while others grow best in cooler conditions. Knowing which varieties to grow during different seasons can optimize your greenhouse's productivity.

During spring and summer, microgreens such as sunflower, basil, amaranth, and mustard greens thrive in the warmth and longer daylight hours. These varieties proliferate and provide a burst of flavor to meals.

In monsoon and winter, consider growing kale, radish, broccoli, and collard greens. These hardy microgreens can tolerate cooler temperatures and even thrive with less sunlight.

Year-round staples include pea shoots, arugula, and Swiss chard. These microgreens are resilient and can adapt well to varying greenhouse conditions.

Growing Steps for Microgreens

Step 1: Collection of materials:

To successfully grow microgreens, you will need a few essential materials:

Invest in shallow trays with drainage holes to prevent waterlogging.

A high-quality potting soil or an alternative growing medium such as coconut coir is essential to provide nutrients and support root growth.

Choose organic microgreen seeds to ensure healthy plants free from chemical treatments.

A spray bottle will help you maintain moisture levels without overwatering.

If your greenhouse lacks sufficient natural light, consider [using grow lights](#) to supplement lighting, ensuring that your microgreens received at least 12 hours of light daily.

Step 2: Preparation of Growing Media:

Fill your trays with about 1-2 inches of soil or your chosen soilless growing media like Cocopeat, Vermicopmost, Perlite, Vermiculite, Peat moss etc. with proper ratio.

Ensure the soil is evenly spread and slightly damp before planting.

A well-prepared growing medium promotes root development and prevents uneven growth.

Step 3: Seeds Sowing:

Evenly sprinkle the seeds across the soil's surface, ensuring they are spread out well without overcrowding.

Lightly press the seeds into the soil, but do not bury them, as microgreens need light to germinate properly.

After sowing, mist the surface thoroughly to keep the seeds moist.

Step 4: Germination and Covering:

Cover the trays with a humidity dome or another tray to create darkness. This step helps promote strong root growth and germination.

Keep the trays in a warm location inside the greenhouse, ideally between 65-75°F.

Check daily and mist as needed to maintain moisture levels, but avoid overwatering, which can lead to mold growth.

Step 5: Provide Light and Ventilation:

Once the seeds have germinated, which usually takes 3-5 days, remove the cover and expose the seedlings to light.

Position the trays near a greenhouse window or use grow lights to provide adequate illumination.

Proper ventilation is also essential to prevent mold and fungal diseases.

Good air circulation strengthens plant stems and keeps the growing environment healthy.

Step 6: Watering and Maintenance:

Watering microgreens correctly is crucial for healthy growth. The best method is bottom watering, where you place the tray in a shallow water container, allowing the soil to absorb moisture from below. This technique prevents fungal issues and encourages strong root development.

Maintain a consistent watering schedule, ensuring the soil remains moist but not soggy.

Overwatering can cause root rot, while underwatering can slow growth.

Additionally, monitor the humidity levels in your greenhouse to prevent excess moisture from accumulating.

Step 7: Harvesting of Microgreens:

Microgreens are ready to harvest in about 7-14 days, depending on the variety:

Look for the first set of true leaves, which indicate they are mature enough to be cut. Using clean scissors, snip the microgreens just above the soil line.

Avoid pulling them out by the roots to maintain the integrity of the growing medium for future use.

After harvesting, gently rinse the microgreens and let them air dry before storage.

Store them in an airtight container in the refrigerator for maximum freshness. Fresh microgreens can last up to a week when stored properly.

Storage of Microgreen

You can store your microgreens in a fridge which will make them last longer. Put them dry in a sealed container and they'll last you a week or two.

If you put them in wet, they may get smelly or slimy microgreens; it's not worth the possibility of getting a bad taste.

What Happen if when Harvest its Early?

If you've heard of eating microgreens, then you've probably heard of eating sprouts. They're both packed with nutrients and healthy for you to eat, but they do have their differences.

Sprouts are the stage before microgreens, a step that you typically don't see unless you grow them very carefully. They grow slightly faster than microgreens because of it, and they don't need much light, and no soil is required.

Health Benefits of Microgreens



Microgreens are dense in nutrients, but what exactly does that mean? If you know about the benefits of eating sprouts, then you already know what microgreens have in them since they're virtually the same. The only difference is that microgreens have 4-6 times the amount of nutrients in them.

1. Neutralizing Anti-Nutrients and Phytic Acid
2. Increased Beneficial Enzymes
3. B-Vitamins
4. Carotene
5. Vitamin C
6. Non-Complete Proteins
7. Antioxidants
8. Minerals

If you're someone who relies heavily on daily vitamins to get all your nutrients in, then microgreens can help you eliminate the need for them! This can save you money, and who doesn't like getting their daily values from homegrown food?

Conclusions

Microgreens are a great way to begin growing some of your food. It's a cheap alternative to buying fresh, full seasoning plants such as basil or parsley. Plus, they're very easy to grow, whereas things like tomatoes are much trickier.

Other plants that grow until they're mature have a much longer growing process, and there are many more steps along the way that can go wrong. You have to worry about pests, water levels, and you also need more space, typically, including an outdoor area, which isn't available to everyone.

You can grow microgreens in pretty much every living situation. All you need is a place with some sunlight and water and space for containers. Besides that, all you have to buy additionally is soil and the seeds (and possibly a water mister to water the seeds with).

Whether you're living in an apartment, a room, or a house, you'll be able to grow microgreens. They also look beautiful, and adding some greenery to a room can liven it up. This is especially true when you grow them in glass jars.

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Scope and Perspective of Tomato Cultivation Under Protected Conditions

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Introduction

Protective cultivation is the technique where the microclimate in the surrounding area of plant is controlled partially or fully or modified to protect the crop from whether especially very low or high temperatures, hail storm and heavy rains. This technology is also useful for protection from birds and conserving the soil moisture simultaneously. Since vegetables are treated as high value crops and their regular supply in the market in fresh condition is an essentiality, the utility of protected structures has been found to be maximum with respect to these crops.

Tomato being a very popular vegetable is in constant demand throughout the year. However, it's climatic specificity limits outdoor cultivation during peak summers and severe winters. In cold countries it is not possible to grow tomatoes in the open field conditions during the winter months. Tomato is the principle vegetable of protected cultivation. The commercial cultivation of table tomatoes in greenhouses has become a profitable enterprise in Northern Europe, Canada and USA (Bose *et al.*, 2002). Production of tomatoes has revolutionized this industry and gives higher cash returns to the growers in Europe and Israel. In India, cultivation of tomato under protected condition is picking up speed especially for off season production.

Forty years ago, greenhouse tomato yield per year averaged 10kg/m². today the yield are approaching 70kg. In the future it is conceivable that tomato yield will reach 100kg/m²/year (Chandra, 2004).

Scenario of Protected Cultivation

Although definitive numbers are not available on the extent of protected vegetable production worldwide. Combining plastic and glass greenhouses and large and small plastic tunnels, protected cultivation covers 16,12,380 ha worldwide. The largest area of protected cultivation occurs in asia, with china having 55% of the total worlds plastic greenhouses acreage (including large plastic tunnels) and over 75% of the worlds small plastic tunnel (Costa *et al.*,2004). The next largest area is in Europe with 23% of the total plastic greenhouses and large tunnel acreage mostly in Italy and Spain. For non plastic glasshouses, the largest concentration is in the Neatherland, which has more than the quarter of the total 39,430 ha under glass worldwide.

The present area under greenhouse application in the country is 1000ha. However, there is large untapped potential in the states of Himachal Pradesh, Uttranchal, J&K and North eastern states for protected cultivation of vegetable crops. The adoption of greenhouse technology for cultivation of flower and vegetable has been adopted on commercial scale in few states namely Maharashtra, Karnataka and Tamil Nadu. In other parts it is being used for nursery raising and vegetable growing. However there remains huge potential for its adoption on a wider scale. The growth rate of greenhouse technology adoption in the country is around 30%. The area of 1000 ha greenhouse cultivation in India is insignificant as compare to China, Japan and South Korea. The miniature greenhouses i.e. low tunnels have also been used by farmers in Punjab and Uttar Pradesh for raising nurseries and vegetable during winters. These have been helpful in raising temperature by 4-5 degrees and advancing the harvest by 2-3 weeks (Choudhary and Shukla, 2005)

Area (ha) under different plasticulture application in selected countries:

Application	India	China	Japan	USA	Italy	Spain	France
Greenhouses	1000	380000	51042	9250	77400	49380	9200
Low tunnels	100	8000	6000	5000	12000	10000	10000
Mulching	10000	9600000	160000	75000	80000	104510	100000

Protected Structures

Protected condition of vegetable crops are created by using different types of structure to accomplish their better growth and development and use of various environmental factors. Since India has varied agro climate thus choice of structure can be utilized depends upon the prevailing condition in the area. These structures are designed and modified as per the agro climate of the area and geographical condition. Beside temperature, humidity, light intensity CO₂ availability, wind velocity, ventilation, soil conditions, assured water supply and other service facilities also play an important role in desiding the design and selection of plant protection structures to be installed. The different types of protected structures used in this industry are:

1. Greenhouses
2. Walk in tunnels

3. Polytunnels or plastic low tunnels
4. Shading net houses
5. Soil trenches
6. Hot bed and cold frames
7. Insect proof cages
8. Antihail nets/ Bird protection nets
9. Mulches (Black or Transparent)
10. Wind breaks
11. Floating crop cover etc.

Greenhouses

Of all these structures greenhouses is the basic and important for harnessing the full potential for greenhouse technology. It is covered by translucent and transparent material such as glass or plastic under which plants can be grown in controlled or partially modified environment or with open ventilation. Greenhouse technology is the most effective way to achieve the goal of protected cultivation since provides favourable and controlled environmental condition for the crop to grow and gave the high productivity round the year.

Greenhouse has mainly two parts:

1. The basic structure which is made up of bamboos/GI pipes/Aluminium pipes/wood or Iron pipes
2. The covering materials of glass, polycarbonate sheet/ acrylic or UV stabilized low density plastic sheet

Different types of greenhouses are given below (Prasad and Kumar, 2003).

1. Based on Environmental Control:

a. Hi- Tech environmentally controlled greenhouses: In this greenhouses all the components of environment are fully optimized and controlled. These suits to perfect to full automation and are generally designed to work as a big plant production or propagation factories like mist chambers.

b. Low tech greenhouses: These are the greenhouses with partial or no environment control. This category include fan and pad cooled or solar greenhouses, heated greenhouses or naturally ventilated polyhouses with opens ventilation and used in commercial production of crops depending upon the agroclimatic condition of the area.

2. Based on Shape: The shape varies depending on :

- a. Expected snow load
- b. Use of natural ventilation
- c. Whether a number of houses are to be joined at gutters
- d. Whether the covering is to be glass or plastic
- e. The growing system and
- f. Whether screens or artificial lighting are used

Straight sidewall greenhouse with arch roof: It is the probably the most common shape, because it can be covered with double layer of plastic and connected to other houses at the gutter to create a large open growing area. Sidewall height have been increasing and range from 3.5-6m in most new greenhouses. High sidewall allow for taller crop and for more climatic control equipment (such as horizontal airflow fans, screens for shading or energy conservation, lights and heaters to be installed above the crop. High sidewall also increase the effectiveness of natural ventilation in open roof system.

Lean to type greenhouse: It is constructed against the side wall of a building/ structure but allows the plant to make best use of sunlight and roof support are not needed. The roof of the existing structure is extending with appropriate cladding material and greenhouse area is properly enclosed.

Even span greenhouses: Such greenhouses are designed to be constructed on the leveled ground surfaces in India. These are small sized with two roof slopes of equal pitch and width having single or multispan types. The one span generally has 6-9 m width, 24-30 m length and 2.5-5 m height.

Uneven span type: For hilly or terraced areas, uneven span types of structures with roof of unequal width are constructed so that growers can make best use of side slopes and terraces of the hills. But the only drawback is that these structures do not suit to perfect automation in environment control and are also vulnerable to higher wind velocities but otherwise well adapted to terraced areas.

Ridge and Furrow type: These structures are specially designed to eliminate the side walls between the two greenhouses so that structures has large space for green houses environment. It reduces cost on automation and ideally suits to energy saving. Before construction the type of loads and wind pressure to be resisted by the greenhouses must be worked out to have a firm and fair construction.

Saw tooth type greenhouses: These are also similar to the above category except that there is special provision for natural ventilation at the top of each roof. The top vent should not be less than one meter and have 40 mesh insect proof net. Specific natural ventilation flow path is developed in the saw tooth type greenhouses and there is large area under this structures.

Quonset Greenhouses: These are the structures with firm construction as glazing material/ frames consists of iron pipes or trusses providing good quality support. It is less expensive than gutter connected green houses and covered by polyethylene sheet. These are specially used for small areas and are free standing. Highly suit to automation.

3. Based on construction: These greenhouses are classified as

- a. Bamboo or wooden framed,
- b. Galvanized Iron/ Aluminium pipes frames, or Truss framed structures

4. Based on covering material:

a. Glass houses: Traditionally greenhouses have been made from glass; hence the use of the term glasshouse and glazing (covering). Glass maximizes light transmission and requires only regular cleaning and sealing of the edges. In the part of world with temperate climate, generally glasshouses are constructed for growing of crops as glass allow high transmittance of sunlight which result in energy saving to optimize higher temperature inside greenhouses. The design such as even span and ridge and furrow type can be used in glass house construction. The life of glasshouse is more than plastic greenhouses. Glass is expensive compared to the polyethylene plastic film, but is generally less expensive than rigid plastics with comparable properties.

b. Plastic greenhouses: This is very important and widely used category as it offers most cost effective way of growing crop inside covers because the cost of plastic is very low in comparison to other cladding material. Only disadvantage is that life of UV stabilized film is less than other cladding materials and is about 5 years. Generally plastic greenhouses with quonset design or gutter connected design are constructed. These can be further classified as

- i. Low cost naturally ventilated polyhouses/ Solar greenhouse
- ii. Medium cost with fan and pad cooling system
- iii. High cost polyhouses with cooling and heating system

These are the cheaper and lower in cost than glasshouses, light in weight, flexible with simple design and suit to automation. The crop are also protected from the hazard of UV rays.

c. Rigid panel greenhouses: Rigid plastics used in greenhouse construction include fiberglass- reinforced polyester, polycarbonate, acrylic (polymethylmethacrylate) and polyvinyl chloride (Glacomelli and Roberts,1993). Some are energy efficient , have good light transmission in the first year of usage, but rigid plastics are more expensive than polyethylene film (Glacomelli and Roberts,1993). For mass propagation of micropropagated crop or plant production farm generally greenhouses with covering material consisting of fibre glasses, reinforce plastic, acrylic and polycarbonate sheet (plain or ridged) are used because these have long life upto 20-25 years. These suit to quonset type or ridge and furrow design and covering material is resistant to breakage or damage. It also provides the uniform light throughout the greenhouses. The only disadvantage attached to this covering material is that it accumulates dust or any other particles easily on its surface with the passage of time and needs proper washing of roof tops otherwise there is sharp reduction in the greenhouses.

Other Protected Structures

1. Walk in tunnel: Walk in tunnels are made up of iron pipes and plastic sheets (UV stabilized) having 100-150micron thickness. It is made over convenient length, but width should not be more than 4 m and height of 2-2.5m in the centre for more efficiency. The provision for ventilation is also made in the front and back sides of tunnel. Generally 2-3 beds are accommodated inside the tunnel in the width range. These are arc shape structure and commercially exploited for various types of crops which require low canopy surface especially capsicum, lettuce and bushy snap beans. These are specifically designed for area having mild winter and mild summer climate. There exist no provision for automation.

2. Plastic Low tunnels/ Poly tunnels: These are made up of LDPE or plastic sheets having lesser thickness ranging from 30-50 microns. These tunnels are also called as miniature greenhouses and are commercially exploited in early nursery raising, nursery raising during winters and early raising of various cucurbitaceous crops specifically watermelon, muskmelon and cucumber to fetch the early harvest potential in the markets. Poly or plastic tunnels are constructed from ground to ground having 1m width, .5-.7m height and 3m length (or any convenient size) and works on principles of greenhouse effect. Plastic tunnels increases the temperature and decreases the potential evapotranspiration and net radiation to give higher yields of leafy vegetables in winters.

3. Soil Trench: It is an underground solar greenhouse structure. A solar underground trench of 5m width, 2-3 m depth and of varying length depending upon the space is constructed in cooler parts especially cold deserts of the country to accomplish vegetable production especially leafy vegetables in otherwise very harsh winter climates. UV polythene film is spread over the structure. These structure harness the solar heat for growing vegetables when ambient temperature is below sub zero in winters for a longer period. In Leh and Ladakh region of the J&K and other cold desert of the country, these are very popular structures which can revolutionize fresh vegetable production in frozen and barren desert winters.

4. Plastic Mulches: Use of mulches in vegetable farming helps in many ways. Mulch is a material consisting of black or transparent polyethylene sheet or dried grass which is spread in the field around the root zone of the crop to cut the effect of direct sun on the soil or growing media. This can be achieved by organic matter and inorganic material. It facilitates early production of certain vegetables, reduces water requirement, conserve moisture and lowers or checks weed population. Plastic film is generally used as a mulch in the greenhouses which allows better nutrient and heat absorption and its gradual availability as per requirement of the crop thereby enabling early and higher productivity.

5. Shade net Houses: In the northern Indian plains, the use of shade net houses become popular during summer and rainy season to grow tomato, capsicum, cucumber and other crops. Shading net reduces the effect of scorching sun, heavy rains and hail storms and provides protection from strong winds and sometimes from frost. The basic structure is made up of GI pipes with single or double layer of net at the top depending upon the requirement of the crop. A nylon net which is generally green or black in colour is used. It has varying ability to cut the sunlight ranging from 40-70%.

6. Hot beds and cold frames: The hot beds are filled with layers of FYM/ good quality compost and soil layers are made over the ground and covered with polyethylene or plastic sheet. During the sunny days the sheet is removed and again spread over during the night. These are heated with hot air, hot water, electrically steamed pipes etc to accomplish vegetable production during winters in the frozen climate.

Cold frames are similar to hot beds except any form of artificial heat. These frames are used for early start of the crop and to harden the plants under temperate conditions.

7. Anti hail/ Bird protection nets: These are in common use to prevent the crops from the strong hail storms or from the damage by birds on various crops especially fruit trees.

8. Rain Shelters: The various vegetables like cucumber, melons, beans and many leafy vegetables require protection from the heavy and intermittent rains over the longer periods of rains. Rain shelters are used to such areas extensively to prevent crop from the damage inflicted on them by continuous rains and hailing. These structures also provide protection from disease which generally break out when there are rains for longer period.

9. Wind breaks and floating crop covers: Such structures have also been used for raising of crops and provide protection from adverse climate.

Need for Protected Cultivation

1. Intensive crop production under problematic areas: Out of the total 328.8 m. ha geographic area constituting Indian Territory the gross cropped area is about 143m. ha only. There is about 75m. ha of area comprising of such problematic conditions as barren, uncultivable, cultivable waste, fallow land, desert and severe cold regions which could be considered for bringing them under greenhouse cultivation. There is thus, a tremendous scope for bringing the vast problematic areas under greenhouse cultivation. Even a fraction of this area if brought under greenhouse, could produce substantial returns for the local and other inhabitants. (www.indiaagronet.com).

2. Proper Utilization of agricultural inputs: In greenhouse crop production, valuable agricultural inputs like: Water, fertilizers, land, planting materials, plant growth regulators and pesticides are required in less amount as compared to open field conditions. The nutrients in the form of fertilizer are not washed out of the soil by heavy rains and their composition can be regulated according to plants requirement and atmospheric humidity can be adjusted according to needs, by adopting ebb and flow method and nutrient film technique. About hundred percent water and fertilizers (in liquid form) can be utilized and recycled. It will not only help to minimize cost of cultivation but will also stop soil erosion and reduce environmental pollution.

Major portion of cultivated land (about 100m. ha) in India is not irrigated and depends upon the mercy of monsoon. Economic use of water in such areas is highly desired to raise the crops. Water economy is possible in greenhouse cultivation, because the transpiration rates can be considerably reduced by maintaining relative humidity higher than those in open field conditions. Water harvesting in conjunction with great help in increasing crop production in these regions.

3. Generation of rural employment: The management of cultural operation under greenhouse is a labour intensive one, therefore, labour requirements in greenhouse cultivation is much more as compared to open field conditions. The average labour requirement to traditional cultivation is 1-2 people per hectare, while the labour requirement for greenhouse cultivation is 8-10 people per hectare. Therefore crop production under greenhouse conditions has a great scope for creation of rural employment. Further, this employment would be of permanent in nature of our country.

4. Small and marginal farmers: In India, there are large number of farmers (76%) who have small and marginal land holdings(www.hindu.com). Such farmers can easily improve their income by adopting intensive form of cultivation under greenhouse conditions. During 1991 the average farm holding per head was 0.18 ha and it is estimated that by the end of this century the average land holding per head would go down by 0.14 ha per head.

5. Socio-economic consideration: As a profession, agriculture is not attractive for the educated youth, which is partly due to the drudgeries associated with field work. To motivate the educated youth agriculture has to be developed to be

a remunerative and drudgery-less industry as competitive as any other industry using agro-technologies like greenhouse. Then only a sense of pride will be associated with agriculture. (Sanwal et al.,2004)

6. Geographical consideration: Some of the areas are inaccessible as well as inhospitable where normal cultivation is not possible. To cater the needs of the population in the inaccessible areas greenhouse cultivation could be an answer. There is very good and sustainable demand for fresh vegetables around the cities and towns. (Sanwal et al.,2004)

Scope and Prospects of Protected Cultivation of Tomato

In view of the varied Agro-climatic conditions and potential of exports of some selected horticultural produces from the country, there is a tremendous scope to develop and popularize the greenhouse technology in India, which is summarized below:

Cold desart region: The greenhouses are ideally suited for growing of crops in the high hills and cold desart of the country. In the higher hills, the low cost polyhouses with open ventilation are very useful for growing tomato during summer and rainy season months. Growing of this crop is not profitable and successful as temperature are low during nights. Care should be taken in construction of greenhouses in these areas. Construction should be firm and of good quality to resist the snow load and tolerate high wind pressure.

Mid hill region: This technology has proved boon to the grower living in the mid hill conditions of the country where use of low cost naturally ventilated polyhouses has attracted many vegetable growers to setup such type of greenhouses. Since climate in these areas is mild except for certain periods, so very low cost structures can be constructed to raise tomato and other vegetable crops round the year and off season, thereby providing an excellent opportunity to the growers to fetch the early and good price of the produce. The polyhouses with top and side vents for ventilation and with external or internal shade have been found very effective and useful in this venture. The ventilation and shading is needed during summer and rainy seasons in these greenhouses to bring down the temperature and lowering the humidity whereas vents can be closed during very low temperature periods in winters to avoid the damage by severe frost outside.

Central and north Indian plains: In the central and north Indian plains of the country where temperature are too high in the summers and rainy seasons with higher humidity during rainy periods and extremely low temperature in the winters, the greenhouses with certain modifications especially fan and pad or evaporative cooling system in the summers and rainy season and heating devices in the winters, can be constructed for accomplishing cultivation of tomato. Even simple nets or shade houses with ability to cut 40-60% light intensity in the summers to grow tomato in the Indian plains. The farmers are already practicing it successfully.

Coastal and southern region: The polyhouse technology could be in great demand in the mild climatic areas of coastal and southern regions where naturally ventilated polyhouses are used for the round the year cultivation of tomato and flowers.

North eastern region: There is a good potential to promote the technology in this region for cultivation of vegetables. The Assam Agricultural University, Jorhat has developed low cost technology for construction of green houses and rain shelters with the use of locally available material like bamboo, which could be availed. Rain shelters are used in areas extensively to prevent crop from the damage inflicted on them by continous rains and hailing. These structures also provides protection from disease which generally break out when there are rains for longer period.

During winters in NEH region, the temperature and solar radiations are sub-optimal for growing off season vegetables namely tomato, capsicum, brinjal, cucumber, okra and chilli. In temperate areas, vegetable growers can increase their income by raising early crops in protected structures mainly in low-cost greenhouses. Thus in the NEH region during winter, it may be useful to grow tomato and capsicum in plastic tunnels as the plants which are protected from cold and frost will manifest faster and better growth resulting in earlier fruiting than the crops grown in the open.

Raising of vegetable nursery in protected structures has many fold benefits such as easy management, early nursery, and protection from biotic and abiotic stresses. This technology is highly productive, amenable to automation, conserve water and land. (Sanwal et al.,2004).

Benefits of Protected Cultivation: (www.indiaagronet.com)

1. Vegetable forcing for domestic consumption and export: In tomato, low temperature and low radiation cause puffiness and blotchy ripening. Hence during extreme conditions of winter season (October-February), these vegetables will be cultivated under polyhouse. In a medium cost greenhouse, an yield of tomato and capsicum can be taken @ 98.6-110.5 tonnes/ha and 87.2 tonnes/ha, respectively. The protected environments would be well adapted in the field where winter is prolonged. A polyhouse can be made which will receive sunlight for growing chilli, tomato, brinjal, capsicum and cucumber. The high priced vegetables- asparagus, broccoli, leek, tomato, cucumber and capsicum are most important crops for production around metropolis and big cities during winter season or off-season.

2. Raising off season nurseries: The cost of hybrid seeds is very high. So, it is necessary that every seed must be germinated. For 100% germination, it requires the controlled conditions. Seedlings of tomato, chilli, capsicum, brinjal, cucumber, cabbage, cauliflower and broccoli can be grown under plastic cover protecting them against frost, severe

cold and heavy rains. The environmental condition, particularly increase in temperature inside polyhouse hastens the germination and early growth of warm season vegetable seedlings for raising early crops in spring summer. Vegetable nursery raising under protected conditions is becoming popular throughout the country especially in hilly regions. Management of vegetable nursery in protected structure is easier and early nursery can be raised. Needless to emphasize, this practice eliminates danger of destruction of nurseries by hail storms and heavy rains because world highest rains occur in this region and the period of rainy season is also wide (April to October). Protection against biotic and abiotic stresses becomes easier. Inside a low cost polyhouse this time period has been found to be reduced by more than one third, besides increase in the seedling population.

Effect of environment on seedling production of tomato (Chadha, 2002 ed.)

Environment	Mean days required for germination	Time taken to reach stage transplantable (Days)	Seedling population/m ² from 5g seeds
Polyhouse (low coast)	9.37	22.1	1038
Low plastic tunnel, mulching with paddy straw + plastic film	14.75	60.6	715
Mulching with paddy straw + plastic film in open	14.37	70.4	565
Mulching with plastic film in open	16.62	72.9	719
Mulching with paddy straw in open (Control)	26.25	76.8	619

3. Productivity is manifold: Marsic and Cerne (2003) evaluated two landraces (Milka and Maribor), one hybrid (Arletta F1) and 2 cultivars (Marmande and San Marzano) of tomato in 1998 in an unheated wooden plastic house and in the open field near Maribor, Slovenia. The average total yield was 74% higher and the average marketable yield was 182% higher in the plastic house than in the open field. The lowest total marketable yield was obtained from Marmande and San Marzano. There was no substantial difference in the marketable yield between Arletta F1, Milka and Maribor. From the same planting date in the plastic house, the harvesting time was prolonged in comparison to the open field cultivation for 48 days for Arletta F1. Gualberto et al (1998) evaluated the long-life-type salad tomato cultivars Diva, Carmen, Graziela R-190, Vita, Donador and HE-295 grown outdoors and under greenhouse conditions at the UNIMAR Experimental Farm, Sao Paulo, Brazil. Marketable fruit yield was 40.45% higher in the greenhouse (134.8 t/ha) than in the field. Root rot was the main reason for fruit depreciation in open field cultivation. Average fruit weight was not affected by cultivation environment and was highest in cv. Vita (160.4 g/fruit). Cultivars Vita and HE-295 were suitable for growing under greenhouse conditions.

Performance of tomato varieties under polyhouse and open field conditions in NEH region (Barapani) (Sanwal *et al.*, 2004):

Varieties	Polyhouse yield (q/ha)	Open field yield (q/ha)	% increase in yield	Varieties	Polyhouse yield (q/ha)	Open field yield (q/ha)	% increase in yield
BT-117-5-3-1	342.00	115.00	197.39	Selection-2	233.00	73.83	215.58
KT-10	283.60	117.40	141.57	Selection-1	2000.98	84.03	139.17
BT-10	294.00	111.65	163.32	KT-15	211.60	51.65	309.68
Arka Alok	260.00	57.90	349.05	H-24	243.17	58.75	313.90
BT-12	302.40	101.00	199.40	Arka Abha	193.50	70.33	175.13

4. Better growth and yield attributing character: Ganesan (1999) studied the effect of changes in microclimate produced by poly greenhouse conditions on plant growth characteristics and fruit yield of tomato was studied during 1999 in experiments conducted at the JRD Tata Eco horticulture farm of M. S. Swaminathan Research Foundation located at Tamil Nadu Livestock Research Station, Kattupakkam, Kancheepuram district, Tamil Nadu. UV stabilized plastic film covered greenhouse recorded higher day temperature than the open environment but relative humidity at 8 am was lower inside the greenhouse except from May to August. The light intensity inside the greenhouse was lower than in the open. Height of the plant, number of nodes, internodal length total dry matter production and average fruit weight increased under greenhouse conditions as compared to open field condition.

The yield performance inside the greenhouse was highest 2145 g/plant and 2156 g/plant in the first and second season, respectively) than the open field crop. The fruit yield inside the greenhouse was nearly two times more than in the open field condition.

Comparison of plant growth and yield attributing characters under poly-greenhouse and open field condition (Ganesan, 1999):

Growth and yield attributing characters	First season (January to May)		Second season (June - October)	
	Poly-greenhouse	Open field	Poly-greenhouse	Open field
Plant height (cm)	106.0	75.0	84.0	69.0
Node number	27.4	24.3	19.7	18.9
Internodal length (cm)	3.8	3.0	4.2	3.6
Average fruit weight (g)	86.5	65.1	90.0	84.4
Yield per plant (g)	2145.2	981.0	2156.2	1382.3
Dry matter production (g)	74.6	34.1	171.1	89.0

5. Hybrid seed production: In 21st century, protected vegetable production is likely to be commercial practice not only because of its potential but out of sheer necessity. In vegetable production hybrids seeds, transgenic, stress resistant varieties, micropropagated transplants, synthetic seeds are likely to replace conventional varieties. For hybrid seed production of solanaceous and cucurbitaceous vegetables polyhouses help to higher seed yield of quality. Maintenance of parental lines for hybrid seed production is easier and less cumbersome in polyhouses.

6. Export of horticulture produces: There is a great potential for increasing the export of horticultural produce from India. In export oriented business of horticultural crops production of high quality yields and assurance of their regular supply in huge quantity are two essential factors, which have great impact in international market, these could be restored only by cultivation of crops under greenhouse conditions.

7. Round the year crop production: All the crops can not be grown in all season at a given place. Vegetables and flowers are however, perishable materials for which storage costs are prohibitive or not possible, which the result that all the vegetables and flowers are not available all the times in a year. Because of the control of environmental parameters like temperature, relative humidity, carbon dioxide, light, etc in the, it is possible to deliver the vegetables and flowers whenever desired. The greenhouses growers can harvest their produces in such a way that their produces do not have to complete with the field grown produce and fetch higher prices in the market.

8. Greenhouse food production for extra terrestrial voyages: When humans embark on long duration mission such as the establishment of the bases on the lunar surface or travel to the mars for exploration, they will continue to need food water and . For these long duration missions, it may not be economical or practical to resupply basic life supporting material from earth. Today controlled environment agriculture (CEA) is also finding application in space with NASA (Natural Aeronautics and Space Administration) where scientists have developed a space growth chamber to provide a variety of fresh vegetables for astronauts.

9. Organic farming: Organic farmic of tomato is easier in the greenhouses and these structures are ideally suited for the mass and commercial production of crops which are raised through different techniques of biotechnology.

Tomato Production Under Protected Condition

1. Planting material: The selection of planting material is of utmost importance depending upon the market demand and comparatively high cost of cultivation under protected condition. In India mainly indeterminate hybrids are used for protected cultivation. Other different types of tomato grown under protected condition are described below: (<http://www.britishtomatoes.co.uk/facts/varieties.shtml>, Heuvelink, 2005)

a. Classic round tomatoes: The most popular varieties with a round shape, containing two to three locules and with an average fruit weight of 70-100g and diameter 4.7-6.7cm. Used in salad or for grilling, backing or frying and as ingredient for soups and souces.

b. Beefsteak type: Larger than the traditional round tomato, weighing 180-250g and containing five or more locules. Used for stuffing and baking whole, and sliced for salads and sandwiches. Wide range available, varying in shape colour (Red, pink), texture and flavour. The large red multilocular beefsteak type of tomato with an indeterminate growth habit is the industry standard in North America. 'Trust' has been the most popular red multilocular type in North America, reportedly planted on 80 % of the beefsteak tomato acreage, but 'Quest' and 'Rapsodie' are becoming more widely grown. Rapsodie is also the most widely grown beefsteak tomato in Europe.

c. Cherry and cocktail tomatoes: Smaller than the classic tomatoes, with weight varying between 10-20g and diameter 1.6-2.5cm. Cherry tomatoes are generally red, but golden orange and yellow varieties exist. Eaten whole and raw or cooked. Cocktail tomatoes can be halved for salads, or skewered whole for grilling. Currently almost all cocktail varieties are sold attached to the stem. Cherry tomatoes are the most common types grown in Europe, and a few areas also produce some pink and yellow tomatoes. Eclipse, Prospero and Aromato are widely grown cultivars in Europe.

d. Vine or Truss tomatoes or On the vine tomatoes: Quality attributes of cluster types include uniformity of fruit size within the cluster, maintaining a fresh green calyx and vine after harvest, simultaneous ripening of all the fruit on the cluster and fruit staying on the vine after harvest. Such tomatoes are marketed still attached to fruiting stem, as it is the stem that gives the distinct tomato aroma, rather than the fruit themselves. In Arizona and Canada, Campri is widely grown in large greenhouse operation, but seed availability is limited.

e. Plum and baby plum tomatoes: Typical oval shape but the baby plum tomatoes are smaller. The flesh is firm and less juicy in the centre. Used for barbecues and processed for pizzas and pasta dishes. In BC, Canada beefsteak tomato represents 24% of total greenhouse vegetable sold and cluster tomatoes 34% (BC MAFF, 2003).

2. Important Climatic Factors: The climatic factors play a major role in plant growth. The detail of which are as under:

Climate Factors	Important for	Desirable level in polyhouse
Radiation/light	Photosynthesis, Photomorphogenesis and photoperiodism	50,000 Lux
Temperature	Cell division and elongation, respiration, Photosynthesis water uptake, Transpiration etc.	18-25 °C
Relative humidity	Quality of plant	60-80%
CO ₂	Photosynthesis	350-1000ppm
Air movement/ Wind	Influences temperature, humidity and CO ₂ condition in polyhouse and structural stability	Inflow: Outflow ratio should be 1:1
Rainfall/precipitation	Influences RH and	

Ideal climatic requirement for tomato crop:

Day temp (° C)	Night temp. (° C)	Humidity (%)	Light Intensity (Lux)
22-27	15.5-19	60-65	50,000-60,000

Technical option for greenhouse environment modification:

Capability	Equipment	Influences
Heating	Heater, Hot water and steam heating	Temp., RH, Air movement
Cooling	Venting, fogging and shading	Temp., RH, Air movement
Ventilation	Vents, Exhaust fans	Temp., RH, Air movement, CO ₂ conc.
Shading	Shade nets, screens and white washing	Light, Temp., RH, Air movement
Artificial lighting	Incandescent lamps, Fluorescent tubes, High intensity discharge lamps (HID)	Light
Humidity and wetness	Humidifiers, foggers- to increase RH Heater, Venting, Dehumidifiers- to decrease RH	Temp., RH, Air movement
CO ₂ enrichment	CO ₂ burner, Pure CO ₂ , Fuel gases	CO ₂ concentration

Raising healthy tomato seedlings: Healthy nursery raising is very important for successful growing of crops under protected cultivation since it sets foundation for harvesting full potential of greenhouse technology with providing strong and disease free planting material for commercial planting and ultimately contributes higher earnings at the growers level. The only precaution is that it should be raised under covers/ protected structures for the following reasons:

- Every single seed germinates and there is no loss of seed and no fear of poor germination as seed cost of greenhouse grown hybrids are very high.
- Planting material is generally free from various soil born diseases and insect-pest as maximum infestation occurs during seedling stage.
- The damage of adverse climatic conditions can be easily avoided especially hailing and icy winds.
- The nursery can be raised during off season/ round the year.
- Hardening of plants are easier than open field condition.

Popular Plant Protection Structure Used in Growing of Healthy Planting Materials are

1. Plastic low tunnels or polytunnels: These structures are commonly used in the hilly and cold desert region of the country for growing nursery of crops.

2. Insect Cages: These are also popular among the growers as the insect cage restricts the entry of insects which generally lay eggs on the young seedlings and also provide some shade especially in the summers. The insect proof nets of 60 meshes are considered excellent for this purpose.

3. Glass Houses or Mist Chambers: Such structures are being used by the commercial nursery growers in the form of big plant production factories throughout the world to provide the quality planting material. These also provide an additional advantage of total/partial environment control and many layers of plants/ young seedlings are accommodated to utilize to full canopy area.

The planting material can be raised on the direct sown seed beds or in the plastic trays.

Raising Tomato Seedlings in the Seed Beds

The nursery area must have sufficient amount of organic matter. The length of nursery beds can be increased or decreased according to the availability of land and the requirement of the nursery but the breadth of the bed should be 1 m. and in no case more than 1.20 m. This ensures weeding without entering the nursery beds.

Generally nursery beds 3 m long, 1 m wide and 15 cm raised are recommended. At the time of the land preparation, add 20-25 kg well rotten farmyard manure per bed along with 200g single super phosphate and 15-20 g each of the fungicides like Dithane M-45 or Brassicol. The detailed procedure is as follows:

1. Before sowing the seed should be treated with fungicides like Captan/Bavistin @2-3 g.
2. Sow the seeds in lines 5 cm apart and cover with thin layer of farm yard manure or soil.
3. Cover the seeds with dry grass.
4. During summers irrigate the beds twice, once in the morning and once in the evening. During winters one irrigation is sufficient. The beds must remain moist but not wet otherwise 'damping off of seedling' disease appears. Thick sowing or sowing with broadcasting also leads to increase the incidence of this disease.
5. After germination, remove the dry grass during day time but cover the beds at night during winter period.
6. If the disease "damping off of the seedlings" appears in the nursery, spray the nursery beds with 0.25 percent solution of Brassicol or Dithane M-45.
7. For good healthy seedlings urea spray of 0.3 per cent can be given when the plants are 8-10 cm tall.
8. After 4-6 weeks the plants become 10-15 cm tall and are ready for transplanting. Inside a low cost polyhouse this time period is reduced by more than one third, beside increase in the seedling population.
9. Stop irrigating the nursery beds 3-4 days before the date of transplanting so that the plants harden but on the day of the transplanting, first apply water to the nursery beds and then take out the plants for transplanting.
10. Select healthy plants for transplanting and always transplant the seedlings in the afternoon. Before transplanting the uprooted seedlings should be dipped in the solution of 0.25% Dithane M-45 and 0.05% Bavistin.
11. Fix the plants well and water them daily till they establish well in the polyhouse.

Raising the Tomato in the Seedling Trays

Tomato nurseries generally grow the, seedlings of F1 hybrids, which are gradually replacing the open pollinated varieties. Since the hybrid seeds are expensive, the tray grown vegetable are becoming popular and this method of raising the seedlings minimizes the loss of seedling and seeds. The seedling trays are known as pot trays, flate trays and plug trays. These trays made of polypropylene can be used upto six times to grow seedlings. Before using it is necessary every time these trays are thoroughly washed and disinfected with fungicides. The holes at the bottom of the cells control the moisture properly. Equispaced cells facilitate the growth of the seedlings. Portrays with 98 cells are used to raise the seedling of tomato and other vegetables like capsicum, cabbage, cauliflower chilli and Brinjal. The size of the container vary from 2.5 to 10.5 cm diameter for tomato pepper and watermelon transplant.

Well decomposed and sterilized media is essential to grow disease free seedlings. The traditional potting mixture of soil-manure-sand has been replaced over years by peat vermiculite-sand or perlite mix. Such growing media are biologically inert, uniform in texture and maintain optimum porosity (85%), water holding capacity (20-30%), pH (5.5-6.5), soluble salts (200ppm) and EC (10-30 meq/100g dry weight) (Prabhakra,2005).

Root Grafting

Since the late 1920s grafting has been carried out in the production in soil to reduce infection by soil born diseases cause by pathogens such as *Fusarium oxysporum*. For soilless cultivation in greenhouses, therefore plants were not grafted. However, recently it has been found that grafting results in higher resistance against virus and fungal diseases such as verticillium, as grafting results in more vigorous plants (Heijens,2004). Grafting of tomato cultivars on rootstocks has also been found to increase high temperature tolerance (Rivero *et al*,2003), drought tolerance (Bhatt *et al*, 2002) and salinity tolerance (Fernandez Garcia *et al*, 2002).

Plant performance depends on the combination of root and scion. For example the rootstock effect on the tomato salinity response depends on the shoot genotype (Santa Cruz *et al*,2002). These interactions make it difficult to predict the

rootstock effect in a particular rootstock- scion combination. Zijlstra and Den Nijs (1987) tested the contribution of the roots to growth and earliness under low temperature condition for nine genotypes making reciprocal grafts using the same genotypes as scion and as rootstock (81 combinations). Although they reported little interaction between rootstock and scion, they observed that tomato genotypes selected for growth and early production under low temperature performed very poorly when used as a rootstock at low temperature.

The use of rootstocks is common in greenhouse production in the Neatherland. The most widely used rootstock is Maxifort (De Ruiter Seeds), Eldorado (Enza Zaden), Beaufort (De Ruiter Seeds) and Big Power (Rijk Zwaan) are also used (Heijens, 2004). Rootstocks are sown 7-10 days earlier than scion cultivar. The scion is sown 5 days earlier than non grafted plant, to obtain equal sized plants on the desired planting date, as grafting results in a small delay. Also the number of leaves below the first truss is usually one ore than non grafted plants (Heijens, 2004). Grafted plants are 50-100% more expensive and therefore two stems per plant are kept. The second stem is obtained as a side shoot below the first, second or third truss, or grafted plants are decapitated above the cotyledons. The latter procedure will result in two equal stems when light levels are high enough (planting from mid march onwards). Decapitation above the cotyledon results in a delay of 14 days compare with retaining a side shoot on a standard plant. A third method is decapitation above the second leaf. In that case there is the risk of unequal shoots, as the highest one will dominate the lower one (Heijens, 2004).

Tomato plants are mainly grafted by conventional cleft grafting. Tube grafting has recently been developed for vegetable seedlings grown by plug culture.

1. Cleft grafting: In cleft grafting the seeds of the rootstock are sown five to seven days earlier than those of the scion. The stem of the scion (at the fair-leaf stage), and the rootstock (at the four to five-leaf stage) are cut at right angles each with 2-3 leaves remaining on the stem. The stem of the scion is cut in a wedge, and the tapered end fitted into a cleft cut in the end of the rootstock. The graft is then held firm with a plastic clip.

2. Tube Grafting: Tube grafting makes it possible to graft small plants grown in plug trays two or three times faster than the conventional method. The smaller the plants, the more plants can be fitted into healing chambers or acclimation rooms. For this reason, tube grafting is popular among Japanese seedling producers. The optimum growth stage for grafting varies according to the kind of plug tray used. Plants in small cells must be grafted at an earlier growth stage, and require tubes with a smaller inside diameter. First, the rootstock is cut at a slant. The scion is cut in the same way. Elastic tubes with a side-slit are placed onto the cut end of the rootstock. The cut ends of the scions are then inserted into the tube, splicing the cut surfaces of the scions and rootstock together.

Root stocks for tomato and their specific resistance to some selected soil borne diseases (Yamakawa, 1983).

Major tomato diseases						
	<i>Pseudomonas solanacearum</i> (E.F.) Smith	<i>Fusarium oxysporum</i> (Schlect.)	<i>Verticillium dahliae</i> Kleb.	<i>Pyrenochaeta lycopersici</i> Schn. & Gerl.	Root knot nematode	Tobacco mosaic virus
BF	R	R	S	S	S	S
LS 89	R	R	S	S	S	S
PFN	R	R	S	S	S	S
PFNT	R	R	S	S	S	R
KNVF	S	R	R	R	R	R
KNVF Tm Singnal	S	R	R	R	R	R
KCFT-N	S	R	S	S	R	R

R=Resistant; S=Susceptible.

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Soilless Culture

Soilless culture is the art and science of growing plants without soil by feeding them on nutrient solution. Initially greenhouse tomato production was in soil (Brooks, 1969), but today much of the greenhouse tomato production is done hydroponically: and in the future Jensen 1997 suggests this method of tomato production is becoming fashionable again.

Hydroponics: Hydroponics is a system of soilless culture. The word Hydroponics was derived from the greek word hydro having to do with the water and ponos means labour. Thus meaning of hydroponics is working with water. Hydroponics in its true sence strictly means/include water (liquid) or solution culture. The nutrients are provided as per need. In fact the system is correctly known as nutriculture. The principal advantage of hydroponics include high density maximum crop yield, crop production where no suitable soil exist, more efficient use of water and fertilizers, minimum use of land area and suitability for mechanization and disease control. This technology is better exploited under polyhouse. The DARL pithorgarh, has standardize the technique of commercial cultivation of tomato, and cucumber and capsicum using hydroponics in polyhouses. Crop productivity is increased many fold under hydroponics in polyhouses. Tomato (Marglobe) and Cucumber (Long Green) in polyhouse under hydroponics gave 1466 and 980 q/ha respectively compared with 470 and 105q/ha. (Singh, 2005).

Nutrient film technique (NFT) and Aeroponics, a modified form of hydroponics were successful in many countries for production of tomatoes in greenhouses.

Nutrient film technique (NFT): In NFT system plants are batched in a shallow layer (<1cm) of flowing nutrient solution that is continuously recirculated. The main component of the system is a catchment tank containing a complete nutrient solution. A pump delivers the solution, via plastic pipes, to the upper ends of the polythene gullies (Channels) in which plants grow. The solution then flows through the root mat under gravity. It is collected from the lower end of the gullies by a return pipe and is discharged into the catchment tank in a cascade, thus aerating and mixing the contents for recirculation. Tomato plants were found to grow well in NFT or plane plant hydroponics (PPH). Fruits obtained in hydroponics culture had low acidity but higher sugar content. But plants grown in nutrient film technique produced better quality fruits than PPH culture (Averswald *et al.*, 1996).

Aeroponics: In an aeroponic system, the plant roots are suspended in a fine mist of nutrient solution that is supplied on continuous or intermittent basis. Aeroponic growing systems have been described by Soffer, (1985 & 1988) and commercial details on the method has been given by Adi Limited (1982) however, aeroponic technique has yet to be found economically suitable for the large scale production of plants.

In contrast to NFT, Yang *et al.*, 1989 observed better root growth of seedlings in aeroponic culture. They also found that plant growth, fruit yield and size were highest in aeroponics culture. Solution sprays frequently at interval of 5 minutes gave the best result in the aeroponic culture.

Olympios *et al.* 1994 observed that under hydroponic culture substrates like natural pumicious perlite (CKP), row perlite (YP) and pumice (EC) gave better performance than horticultural perlite. Plant growth parameters height, number of leaves and total yield (number and weight of fruits) were also better on natural pumicious perlite and pumice. Xing *et al.* (1997) observed faster rate of plant growth, higher dry matter productivity and higher fruit yield in a new multilayer soilless culture system and suggested as a replacement of soil based production system to achieve significant yield improvement in greenhouse grown tomatoes.

Growing Media: In Europe and Canada, and in large greenhouse complexes in USA, 95% of greenhouse tomatoes are grown on inert artificial substrates, a system usually referred to as soilless culture.

Rockwool is the most common substrate for soilless culture (Soneneid, 1988). A distinctive characteristics of rockwool is its high air holding capacity even when fully saturated. Slabs are available with high and normal density. High density slabs have good structural stability, high water holding capacity and good capillarity. Normal density slabs are less compact and have a slightly lower water holding capacity.

For tomato crops, rockwool of density 10-12 lbs/m² is recommended (Sonneveld & Welles, 1984). Although the rockwool is the most common substrate in soilless culture, perlite, peat and to some extent pumice also (rock and limestone) are also used.

Rockwool and perlite have the following similar advantages:

- Excellent aeration and water holding capacity
- Sterile and lightweight when dry
- Easily installed and cleaned up

Both types of medium are steamsterilized, rebagged and used again once or twice. Successful reuse of medium without sterilization has been reported.

There may be increased commercial interest in perlite, pumice or other substrates in near future, since disposal of rockwool is difficult, reuse is limited and some consider peat to be renewable source.

Growing media varies from place to place. Blain (1998) reported that agrobags containing 24 litre of sphagnum peat based substrate measuring 90 X 20 X 12 cm and weighing 7kg with an air filled porosity of 20% and an available moisture capacity of 25% gave higher yield. The light utilization efficiency was optimum. Good yield on rockwool was reported by Tannis, 1990, Abou Hadid *et al.*, 1993 and Pivot *et al.*, 1999. Pivot *et al.* 1999 obtained good yield when tomato plants were grown on substrate coir, pozzolano (volcanic ash) or pumice as compared to soil. Sohini *et al.*, (1998) recommended that peat alone for growing media consisting 50% peat to grow under glass which gave better growth, yield and quality of tomato fruits. Rodica *et al.*, (2003) obtained high vitamin C content in Organic culture comprised of brown peat (80%) than soil culture in the greenhouse grown tomato. Inden and Torres (2004) reported higher number of fruits per cluster, increased productivity and TSS for tomato grown on coconut coir in comparison to rockwool, perlite + carbonized rice hulls and Cyprus bark.

In soil based growing media, all the three components (soil: organic matter: Coarse aggregates) are mixed in a defined ratios as per the requirement of the crop/conditions whereas use of aggregates is prominent in substrate culture with higher doses of fertigation and no soil. Under Indian condition presently soil based growing media is practice for growing of greenhouse crops since it provides some ease to the farmers as well as well conversent with it's use and properties. Soil is important constituent of growing media and important sources of organic matter are peat and peat like substances, farm yard manure/vermicompost, decomposed saw dust, smoked rice husks, spent mushrooms and

enriched coir peat/ coco peat. Sand, perlite, vermiculite, peat and pumice and many other locally available material can be used as coarse aggregate sources (Kohli *et al.*, 2007).

Spacing: Kohli *et al.*, 2007 recommended the spacing of 40 X 20 cm for single stem training and 70 X 30 cm spacing for two stem training. Ihran *et al.*, 1988 recommended a spacing of 115 X 25 cm for single stem and 115 X 40 cm for 2 stem training for short production cycles. According to Papadopoulos and Urmrod (1988) closer spacing decreased the leaf area thereby reducing the net photosynthetic area but upper leaves were not affected. At closer spacing higher CO₂ (510ppm) increased the yield of harvested fruits as well as those remaining on the plants (Rijsdijk *et al.*, 1991). Kanthaswamy *et al.* 2004 recommended the spacing of 60 X 45 cm in comparison with 30 X 22.5 cm.

Mulching: The type of mulch selected exerts a distinct effect on weed control. Black plastic mulch prevents light from reaching the soil surface, which in turn prevent weed growth. Intact plastic control essentially all the annual and some perennial weeds. Clear mulch does not prevent weeds from growing and may enhance their growth beneath the plastic. Mulching reduces leaching of fertilizers. Plastic mulch prevent tomato fruit from contact with soil. This reduces soil rot and keeps the fruit clean. Fruit cracking and blossom end rot is reduced in many cases. Fruits tends to be smoother with fewer scars (Choudhary and Shukla, 2005)

It was reported from Italy that in an unheated greenhouse mulching of tomatoes with polyethylene, grown in double rows at 40,000 plants per ha did not affect date of flowering or fruit set but significantly increased fruit yields for cultivars Count (90t/ha) and Dake (75t/ha) (Marcheri, 1986). Pimpini *et al* (1987) reported that the use of 1.6m wide and 0.6 m high clear polythene tunnels of polypropylene sheets placed directly on the plants and of mulching with clear polythene advanced earliness of the cultivar Arodo 320 and Pakela grown in the greenhouse.

Fertilization: The nutrients are supplied in the form of chemicals. It is possible to supply nutrients in regulated amount with irrigation. P, Ca, Fe and Mg were added to peat before planting; basal dressing to crop grown in soil were rarely necessary. Varis and George (1985) recommended high level of nitrogen (100g/m²) for increased flower number, fruit and seed yield and early flowering and ripening. The most favorable combination for high fruit and seed yield was 100g N, 43.69g P and 166g K. Vaicon *et al.*, 1989 obtained the highest yield with 240 Kg N + 160Kg P + 200Kg K/ha.

Fruit yield and quality could be controlled through fertigation in greenhouse .Kanthaswamy *et al.*, 2004 recommended basal application of 50:50:50 Kg NPK/ha and fertigation schedule of 250:250:250 Kg NPK/ha with water soluble fertilizer, which favored the growth characters that ultimately resulted in increased fruit yield with better quality. Hao and Papadopoulos 2003 reported that high Ca concentration increased fruit yield and reduced the incidence of blossom end rot as compared to the low concentration of 150 mg/lit. The plants grown at 20mg Mg/lit showed the leaf chlorosis. The optimum Ca/Mg concentration for tomato is estimated to be 300/50-80mg/lit. The Mg concentration may be started with 50 mg/lit and gradually increased to 80 mg/lit towards the end of the season to improve the plant growth and fruit firmness.

Irrigation: Tomato requires ample supply of moisture in glasshouse. Water stress leads to stunted growth of the plant and dropping of the flowers. Soil water management based on leaf water potential was found to be very useful in the forcing cultivation of tomato in greenhouses. Water potential of -0.1 MPa in the early growing stage (from planting to flowering on third cluster) and -0.5 MPa thereafter were recommended as indicator for irrigation, with a soil depth of 40 cm (Araki, 1994). Norrie *et al.*, 1994 reported that PET (potential evapotranspiration) and electronic tentimeter technology were used jointly to improve irrigation management for tomato grown in peat based substrate by responding more accurately to the crops water and nutrients need. Irrigation to the greenhouse crop was scheduled every 3 days or daily on the basis of pan evaporation coefficient. The best pan coefficient for maximum early and total yield was found to be 1.2 and irrigation was scheduled accordingly (Tuzel *et al* 1994). According to Pulupol *et al* (1996) deficit irrigation (DI) in which water potential was allowed to decrease from -0.5 to -1.2 MPa, reduced plant growth, fruit yield, size counts and caused blossom end rot. But the fruits had higher concentration of sucrose, glucose and fructose thus enhancing the fruit desirability.

Drip Irrigation is the most commonly used method of irrigation under protected conditiuon. Tanis (1990) found greater fruit weight under drip irrigation. An irrigation regime of 15-20 KPa is found ideal for tomato production in the growing media comprising of soil compost and sand Kohli *et al.*, 2007)

Micro irrigation is boon in areas experiencing frequent water shortage. The quantum of water that can be saved by employing drip irrigation in comparison to conventional method in tomato is 39%. The fertigation and chemigation study have shown a saving of 40-60% in fertilizers and chemicals, and also an enhanced in quality of produce and yield (Choudhary and Shukla, 2005).

Training: Training of plants is essential for greenhouse cultivation of tomato. The usual method is to put the strings twined all along the stem to be hung from support above. Arch method of training is extremely used. Many wires are placed over the rows of plants 180 cm above soil (Bose, 2002)

In 1970s and 1980s plants were trained upto a wire and then allowed to drop down the other side (the up and down system). The negative effect of plants heads hanging down in the shade is now understood and the most widespread training system in the Netherlands and USA is the high wire system. In this system growing tip remains at the top of the

canopy, but the stem is lowered and trails along the base of the plant. The high wire system requires early training of the main stem. As soon after transplanting as possible, plants stem should be secured to plastic twine hung from horizontal wires that run at a height of 3.2m above the ground. The objective of leaning and lowering is to keep the head of the plant upright for pollination and light interception and still have the clusters at a convenient height for workers even when crop are in the greenhouse for a long period.

De-Leafing: When wines are lowered , leaves are removed to prevent disease development. To avoid the introducing Botrytis, leaves should be cut with knife or pruned flush to the stem. The purpose of de-leafing is higher up the plant stem to increase light penetration and air circulation. Typically all leaves are removed from the bottom fruit cluster. Martinez et al (1998) observed that defoliation increased the correlation between fruit weight and grades of the fruits. Defoliation also decreased the negative correlation between fruit weight and fruits per cluster thereby enhancing the total yield of tomatoes. Another factor to be considered in de-leafing is the effect on diseases and pest. Removing lower leaves from the greenhouse and then destroying them will remove whitefly immatures developing on lower leaves.

Pollination: Before the early 1990s each flower cluster has to be vibrated with an electric pollinator at least three times weakly to release the pollen. Poor pollination results in flower abortion and / or small puffy or misshapen fruit. It is particularly important to get good fruit set on the first three clusters to establish an early pattern of generative growth. Pollination should takes place at mid day , when humidity conditions are more favorable (50-70%). If humidity is too high, temperature can be raised by 2°C at mid day to reduce humidity, but in summer too high mean daily temperature reduces pollen development and release (Sato *et al.*, 2000). Temperature that are too low (night temp. below 16°C) (Portree, 1996) have the same effect compensation with high day temp. is possible. Commercially, bumble bees are now used for pollination. Generally one worker bee can service 40-75 m² (Portree, 1996) and so 5-7.5 hives/ha are required. As well as saving labour, increases in yield and quality have been reported (Portree, 1996) compared with manual vibration. Hives are placed on stands 1.5 m above the ground along the centre aisle and protected from ants and sticky bands or water troughs. Hives should be shaded by foliage or covers, and marked distinctively above the hive and around the entrance so that bees can return to the correct hive (Portree, 1996).

Fruit pruning and development: The purpose of fruit pruning is to increase fruit size and fruit quality and to balance fruit load. Pruning can also be used to maintain uniform fruit size. Misshapen fruits and small undersized fruits at the end of the cluster are always removed, as these will not grow to the marketable size and are thought to reduce the size of other fruits on the cluster. In some cases, clusters are pruned to leave only the four fruits nearest the plant (proximal end).

When some greenhouse tomato cultivars are grown under relatively low light condition, the peduncle of inflorescence become too weak to support the weight of the fruit they bear and liable to bend (Horridge and Cockshell, 1998) or kink. Another reason given for kinkiking is too high temperature during the vegetative phase, which causes the truss to become always vertical (Stick trusses). As fruit developed on these trusses become kinkled.

Topping: The growing point is removed 5-8 weeks before the anticipated crop termination date. A week later all remaining flowers are removed. An indivisual fruit requires 6-9 weeks from anthesis to harvest, and so flowers and small fruits present after topping will not have enough time to develop to maturity. It may be helpful in summers to leave some shoots or leaves at the top to shade the fruit and prevent sunscald.

Harvesting and yield: The superior taste and texture of greenhouse tomato is often attributed to the fact that they remain longer on the wine and reach the consumer sooner than field tomatoes. For direct marketers fruits are harvested virtually red ripe. For large operations shipping cross country or even overseas, beefsteak tomatoes may be harvested earlier, but never before the breaker stage. For both type of sales attractive packaging and presentation are critical. Generally they are packed in single layer, rather than being stacked (as is the practice with field tomatoes).

In beefsteak tomatoes, the calyx and stem are usually removed at harvest to prevent puncture and wounds. In cluster tomatoes, the entire cluster is cut off at the main stem and kept together either by placing in a single layer in boxes clamshells, plastic sleeves or mesh bags.

Labour requirements to grow and harvest the crops must be reduced through automation. Automation is needed to save production and harvesting time. At the same time, it is very important for both nutritional and psychological reasons. The tomato harvester robot is able to locate and pick ripe tomatoes; the robot's "eye" scans the tomato plant and determines the number and position of ripe fruit. Image processing algorithms created specifically for the robot are able to detect ripe fruit even if it is partially obscured by branches or leaves. Using this data, the four-fingered prosthetic hand locates a tomato, opens the fingers and takes hold of the fruit. The robot balances pulling, bending and torsion movements to detach the tasty treat.

The robot has been tested here on Earth; success rates of fruit sensing are running at 95% and fruit picking success is rated at 85%. This technology is also planned for use right here on Earth. (www.technovelgy.com)

Yield are increasing worldwide because of better cultivars and more intensive use of technology. However in comparison production figures, it is important to note the length of the production season, plant density and number of the crops per year. In general greenhouse tomato yields are much higher than outdoor production. Recent estimates in Neatherland

range from 47 kg/m² for cluster tomatoes to 53 kg/m² for beefsteak tomatoes. In European countries, tomato yields 63-145 tonnes per ha. In India at IARI, new delhi an average yield of 100 tonnes /ha has been obtained from hybrid Naveen grown in a medium cost greenhouse (Chadha,2002).

Constraints in protected tomato production: High cost and non-availability of various components are the two major limiting factors in the adoption of polyhouse technology for commercial cultivation. Many of the polyhouse components like fibreglass, cooling pads, fans, etc., have to be imported at high costs including freight and custom duty. Greenhouse and other structures design for different agro-climatic of the region is not standardized. Lack of awareness among farmers pertaining to potentials of protected vegetable production and lack of major research programme on protected vegetable farming are other limiting factors. Moreover, India has varied agroclimatic regions and there is throughout year availability of tomato in one region or other. Therefore growing tomato under protected condition is profitable for specific farming like organic farming and export oriented quality production.

Conclusion

In 21st century, protected tomato production is likely to be common commercial practice not only because of its potential but out of sheer necessity. Production of greenhouse tomatoes is demanding in terms of capital, energy, labour and management. Although production levels might be raised further to as much as 100kg/m² in the coming decades. Profitable operation requires excellent management and tight integration of the various production processes. Hence, tomato production for domestic consumption and export in low and medium cost greenhouse is a technical reality in India. Such production system has not only extended the growing season of tomato and their availability but also encouraged rural employment.

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Nutritional Phenotyping: Can We Measure How Individuals Respond to the Same Food?

Article ID: 74480

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Summary

Nutritional phenotyping measures how an individual's body responds to specific foods using dynamic biomarkers such as postprandial glucose, triglycerides, inflammatory markers, metabolites and gut microbiome features. Large-scale continuous glucose monitoring and multi-omics studies reveal substantial interindividual variability in postprandial metabolic responses to identical meals which is driven by genetics, gut microbiota, body composition and lifestyle factors. Emerging wearable sensors, CGM devices and integrative machine learning models enable the identification of metabolic phenotypes and predict personalized glycemic and lipid responses with higher accuracy than traditional carbohydrate counting or glycemic index. Randomized trials show that CGM-guided and microbiome-informed dietary interventions improve HbA1c, postprandial glucose, triglycerides, weight loss and liver enzymes more effectively than standard diets in prediabetes and type 2 diabetes. Applications are expanding to obesity, metabolic syndrome and cardiovascular risk stratification where phenotyping refines risk assessment and tailors macronutrient, fiber and meal-timing strategies. Despite progress, barriers including cost, lack of standardization, algorithmic bias, regulatory uncertainty and limited long-term outcome data must be resolved for equitable clinical translation. Nutritional phenotyping is emerging as a foundational tool for next-generation evidence-based personalized nutrition and precision medicine.

Keywords: Nutritional phenotyping; Postprandial glucose; Continuous glucose monitoring; Precision nutrition; Gut microbiome; Multi-omics; Interindividual variability.

Introduction

Two people can eat the same plate of white rice and dal yet show very different blood glucose curves on continuous glucose monitoring (CGM): one has a modest, short-lived rise while the other experiences a sharp, prolonged spike. Nutritional phenotyping captures this reality by measuring how an individual's body actually responds to foods and dietary patterns using observable biological readouts (phenotypes) such as postprandial glucose and insulin curves, lipid responses after fatty meals, inflammatory markers, metabolite profiles and gut microbiome features in real time via wearables and omics technologies. The goal is to shift focus from "what is in the food" to "what does this food do in this person." This enables the identification of distinct metabolic response patterns that can guide tailored dietary advice.

Traditional dietary recommendations have largely followed a one-size-fits-all model population-level guidelines based on average responses in large cohorts, expressed as fixed targets for macronutrients, glycemic index/load or food groups. While useful for public health, this approach cannot account for substantial interindividual heterogeneity driven by genetics, epigenetics, gut microbiota, body composition, sleep, stress, medications and lifestyle. Precision and personalized nutrition address this by using individual biological and contextual data to predict and optimize how a specific person will respond to specific foods and meal patterns, with direct relevance to chronic diseases (e.g., type 2 diabetes, prediabetes, cardiovascular disease, metabolic syndrome) and everyday decisions around appetite, satiety and weight management.

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Interindividual Variability in Postprandial Metabolic Responses

Large-scale continuous glucose monitoring (CGM) and standardized meal-test studies show that postprandial glucose curves to the same meal can differ between people and even within the same person on different days. In cohorts without diabetes, the coefficient of variation for postprandial glucose responses (PPGRs) to identical meals often ranges from ~25% to >50%, with peak glucose, time-to-peak, and recovery slope all varying substantially across individuals. Similar heterogeneity is reported for postprandial triglycerides and inflammatory markers after fatty or mixed meals.

This variability reflects underlying differences in metabolic physiology. Analyses from the PREDICT studies suggest that meal composition explains only part of the variance in PPGR (Post Prandial Glucose Response), while individual-level factors such as gut microbiome features, baseline insulin resistance, body composition and habitual diet contribute a measurable share of the response. For example, stool microbiome features have been estimated to account for around 7% of the variance in postprandial glucose after adjusting for meal macronutrients and genetic variation in starch-digesting enzymes and glucose transporters further shifts an individual's glycemic trajectory.

Multiple interacting layers shape why two people eating the same plate can have very different glucose and lipid curves. Gut microbiome composition and function influence carbohydrate fermentation, short-chain fatty acid production and bile acid metabolism, all of which modulate postprandial glucose and lipids. Genetic and epigenetic background, metabolic health and behavioural factors further determine how efficiently nutrients are processed and cleared.

Technologies and Biomarkers for Assessing Nutritional Phenotypes

Nutritional phenotyping relies on wearable sensors, dynamic metabolic tests and multi-omics platforms that capture how an individual's body processes nutrients in real time. Continuous glucose monitoring (CGM) has emerged as the most accessible and clinically validated technology as it provides high-resolution interstitial glucose curves that reveal peak magnitude, time-to-peak, area-under-the-curve and recovery dynamics after meals. When combined with standardized meal challenges or dietary logs, CGM enables the identification of reproducible glycemic phenotypes (e.g., high-spike/slow-recovery vs low-spike/fast-recovery) that are more informative than single fasting glucose or HbA1c values.

Wearable and minimally invasive biosensors are further expanding the phenotyping landscape to include lactate, ketones, triglyceride-rich lipoproteins, inflammatory cytokines and stress hormones in interstitial fluid, sweat or breath. These devices shift biochemical assessment from episodic laboratory testing to continuous, context-rich monitoring. For example, non-fasting triglyceride measurements and lipoprotein profiles captured 2-6 hours after a standardized fatty meal can identify individuals with postprandial lipemia who appear normal on fasting lipid panels thereby refining cardiovascular risk stratification.

Machine learning models that integrate CGM data with gut microbiome composition, metabolomic profiles and polygenic risk scores have demonstrated superior prediction of postprandial glucose and triglyceride responses compared with traditional carbohydrate counting or glycemic index alone ($R^2 \approx 0.77$ vs 0.38 in the PREDICT study). Such integrative frameworks are paving the way for nutri-types or metabotype-guided dietary prescriptions, where individuals are clustered based on their multi-omics signatures and dynamic postprandial phenotypes to receive tailored food recommendations that minimize glycemic variability, improve lipid handling and modulate inflammation.

Translational Applications of Nutritional Phenotyping in Health and Disease

Clinical trials now show that nutritional phenotyping can move from research into routine care. In a 24-week randomized trial among Chinese adults with prediabetes and unmedicated type 2 diabetes a CGM-guided diet achieved significantly greater reductions in HbA1c (-0.46% vs $+0.06\%$), fasting glucose, 2-h OGTT glucose and postprandial glucose exposure compared with the standard Chinese Diabetic Diet. The personalized group also showed larger improvements in LDL-C, triglycerides, HDL-C, greater weight loss (-6 kg vs -0.5 kg) and better liver enzyme markers. Similar benefits have been reported in microbiome-informed precision nutrition trials where machine learning models integrating gut microbial features with host data generated individualized food recommendations that lower postprandial glycemic responses, triglycerides, inflammatory markers and HbA1c relative to control diets.

Nutritional phenotyping is also applied to obesity, metabolic syndrome and metabolic dysfunction associated steatotic liver disease (MASLD). Multi-omics and CGM-based phenotyping help identify normal-weight obesity. In cardiovascular risk management, postprandial triglyceride and lipoprotein phenotyping refines risk stratification in individuals with normal fasting lipids. This enables targeted interventions such as low glycemic load meals, specific fat quality adjustments and prebiotic/probiotic regimens to blunt postprandial lipemia and inflammation. As digital health platforms integrate CGM, microbiome testing, and AI-driven recommendation engines, nutritional phenotyping is transitioning from a research tool to a scalable component of precision medicine for chronic disease prevention and management.

Limitations

Despite its promise, nutritional phenotyping faces several practical and scientific barriers before widespread clinical adoption. CGM and multi-omics testing remain costly and inaccessible for many populations. This raises equity concerns and limits scalability in low-resource settings. Standardized protocols for meal challenges, biomarker sampling windows and data interpretation are still evolving which makes cross-study comparisons difficult. Machine learning models that predict postprandial responses require large, diverse training datasets and their performance can drop when applied to underrepresented ethnic or dietary groups. Regulatory frameworks for classifying CGM devices and microbiome-based dietary recommendations as medical tools are still in fluctuation. Finally, long-term adherence to phenotype-guided diets and their impact on hard clinical endpoints need validation in larger, multi-center randomized trials before nutritional phenotyping can be fully integrated into routine practice.

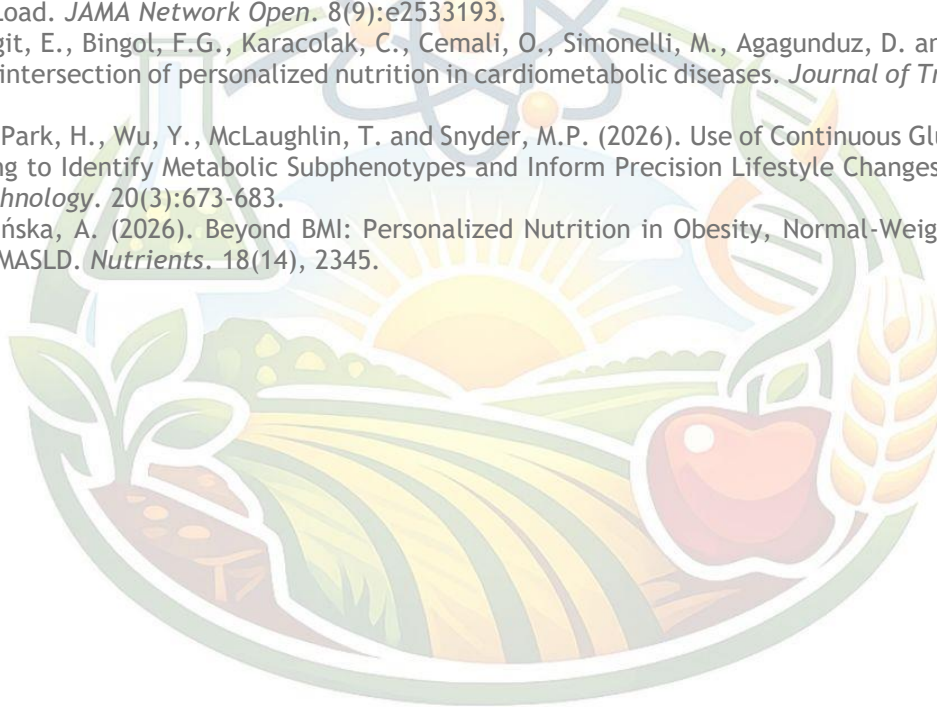
Conclusion

Nutritional phenotyping represents a paradigm shift from population-based dietary guidelines to individualized, data-driven nutrition that accounts for the substantial interindividual variability in postprandial metabolic responses. Continuous glucose monitoring, wearable biosensors and multi-omics platforms now enable the measurement of dynamic glycemic, lipid, inflammatory and microbiome phenotypes that explain why the same food produces different metabolic

outcomes in different people. Clinical trials demonstrate that phenotype-guided dietary interventions can achieve superior improvements in HbA1c, postprandial glucose, triglycerides, body weight and liver health compared with standard dietary advice. However, challenges related to cost, standardization, algorithmic generalizability, regulatory oversight and long-term clinical outcome data must be addressed before nutritional phenotyping can be equitably and effectively integrated into routine healthcare. As these barriers overcome, nutritional phenotyping will become a cornerstone of precision medicine for the prevention and management of cardiometabolic diseases.

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Higher Wheat Yield, Higher Profit: Success through On-Farm Research Scheme (Success Story)

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Traditionally, I used to cultivate *desi* varieties of wheat on my farm. During the rabi season, I got an opportunity to participate in the On-Farm Research (OFR) Scheme of ICAR, implemented by Sardarkrushinagar Dantiwada Agricultural University, Khedbrahma. Under this programme, I was selected for the OFR-1 experiment, conducted under the guidance of Dr. L. J. Desai, Chief Agronomist (IFS). The experiment aimed to evaluate and compare different farming approaches, including natural farming, organic farming, and conventional farming, under farmer's field conditions. Six different treatments were included in the experiment to assess their effect on wheat growth, productivity, and economic returns. The wheat variety GW-513 was used during the rabi season. Compared with the *desi* varieties that I had traditionally cultivated, GW-513 showed better crop performance, particularly in terms of higher number of tillers per plant. Among all the treatments, T₂ - ICM Wheat (*rabi*), consisting of 90:60:30 kg NPK/ha, 10 tonnes FYM/ha, and seed treatment with Azotobacter @ 30 g/kg seed, performed exceptionally well. This treatment recorded higher grain yield and straw yield compared with the other farming treatments. The improved crop growth and yield demonstrated the effectiveness of integrating balanced chemical fertilization, organic manure, and beneficial microorganisms in wheat production. The adoption of this treatment also resulted in higher net returns and a better Benefit:Cost (B:C) ratio, making it economically attractive for farmers. The improved yield on my farm encouraged me to continue with the recommended package of practices. The performance of the crop also attracted the attention of neighbouring farmers, who visited my farm to observe the experiment and learn about the improved cultivation practices.

Yield kg/ha	Selling price	Gross return	Cost /ha	Net profit
3720	25	1,26,480	63396	63083



Dr. H. F. Patel, Associate Research Scientist, visited (OFR -1) Wheat experimental Plot

“Earning a Bumper Income through Value Addition in Turmeric Cultivation under Natural Farming” (Success Story)

Article ID: 74482

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Alpeshbhai has been practicing natural farming for the last six years. He cultivates crops such as groundnut, wheat, and turmeric. He starts growing turmeric on June 2nd during the Kharif season. In the turmeric crop, he grows the Kesar-Salem variety. This turmeric crop takes 8 months to mature. For turmeric cultivation, He uses about 100 liters of jivamrut, 300 kg of Ghanjivamrut and six tractor trolley loads of farmyard manure to cultivate turmeric. He also uses 2-3 sprays buttermilk and cow urine. According to him, in the turmeric crop grown some weed problems remain after weeding. The seed rate is 700 kg per acre. 1 kilogram of seed costs 80 rupees. Furthermore, grinding 20 kg of turmeric produces 3 kg of turmeric powder.

Cost of cultivation for 1 acre.

Seed cost	-	56000 Rs.
Grinding cost	-	15000 Rs.
Cultivation cost	-	10000 Rs
Other cost	-	5000 Rs.
Total cost	-	86000 Rs



Production (kg)	Selling price (Rs.)	Total (Rs.)	Cost (Rs.)	Profit (Rs.)
900 kg powder	350 Rs.	3,15,000	86,000	2,29,000



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Crop Diversification success through On-Farm Research Scheme (Success Story)

Article ID: 74483

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During 2024-25, I got an opportunity to participate in the On-Farm Research (OFR) Scheme of ICAR, implemented by Sardarkrushinagar Dantiwada Agricultural University, Khedbrahma. I was selected for the OFR-2 experiment, conducted under the guidance of Dr. L.

J. Desai, Chief Agronomist (IFS). The experiment focused on evaluating different cropping systems under actual farmers' field conditions to identify suitable and profitable options for crop diversification. Three cropping systems were evaluated in the experiment: 1. Groundnut - Wheat - Fallow, 2. Cotton - Wheat - Fallow and 3. Soybean - Wheat - Fallow. The objective was to compare the productivity and economic performance of these cropping systems and identify the system providing better returns to farmers. The performance was evaluated mainly in terms of gross return, net return, and increase in profitability. Among the three cropping systems, the Groundnut-Wheat-Fallow cropping system performed exceptionally well. It recorded higher gross returns and higher net returns compared with the other cropping systems. Most importantly, it resulted in the highest increase in net profit of about 47% in both low- and high-productivity blocks of Sabarkantha district. The results demonstrated that proper crop diversification and selection of suitable cropping sequences can significantly improve farm profitability. The OFR experiment also provided me with practical knowledge about evaluating research-based technologies under real field conditions. The success of the Groundnut-Wheat-Fallow system encouraged me to consider crop diversification as an effective strategy for improving farm income and reducing dependence on a single cropping system. The OFR programme successfully connected agricultural research with farmers' fields and demonstrated the value of research-based, economically viable farming practices.



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Weed Management in Oilseed Crops

Article ID: 74484

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Oilseed crops are plants cultivated for their seeds, which are rich in oil used for both edible and industrial purposes. Oilseed crops are the second most important determinant of agricultural economy, next only to cereals within the segment of field crops. India is the fourth largest oilseed producing country in the world after USA, China and Brazil and contributes about 10 per cent of the world oilseeds production (Choudhary *et al.* 2022). The major oilseed crops are soybean, sunflower, mustard-rapeseed, groundnut, *etc.* and oil content ranges from about 20% in soybean to over 40% in sunflower, linseed (37-47%), mustard-rapeseeds (35-46%) and groundnut (46-51%). In India, three major oilseed crops viz., soybean, rapeseed-mustard and groundnut contribute 88 per cent of total oilseed production (Choudhary *et al.* 2022). In India, oilseeds are cultivated over an area of 30.27 million hectares with a production of 42.61 million tonnes (Anon., 2024). In Gujarat, oilseeds are cultivated over an area of 3.30 million hectares with a production of 7.53 million tonnes (Anon., 2024). Weeds are the major biological constraint in oilseed crops. It is responsible for about one-third of biotic stress losses, causing 45 % yield loss. Weed interference, not only reduces the seed yield, but also reduce quality. Hence it is very essential to control weeds during the critical period of crop-weed competition.

Weed Problems in Oilseeds

Weeds are a major problem to crop production through their ability to compete for resources and their impact on product quality. In crop production, biotic and abiotic stress are major yield-limiting factors. The yield loss caused by biotic stress ranges from 20-40%. Among the various yield impellers weeds are crucial in causing qualitative and quantitative yield reduction in oilseeds. Weeds are the major biological constraint in oilseed crops. Because the majority of oilseed crops are slow growing during their initial stage of development. Weed interference, not only reduces the seed yield, but also reduce quality. Critical period of weed control in oilseeds is generally from 15 to 45 DAS. Weed removal during the critical period is essential to reduce the yield loss. Therefore, judicious weed management is essential to manage weed population below the threshold level to reduce the yield losses in oilseed crops.

Table 1: Status of oilseed crops in India:

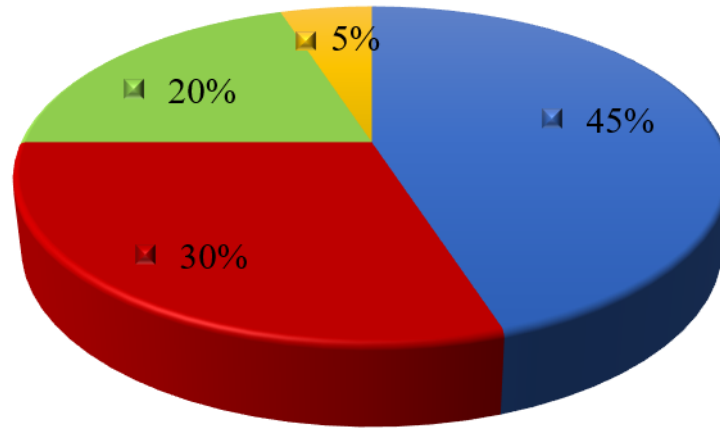
Crop	Area (m. ha)	Production (m. tons)	Yield (t/ha)
Soybean	12.96	15.18	1.17
Groundnut	5.75	11.90	2.07
Rapeseed & mustard	8.63	12.61	1.46
Sunflower	0.17	0.20	1.12
Safflower	0.06	0.04	0.75
Sesame	1.53	0.83	0.5
Niger	0.05	0.01	0.29
Castor	0.93	1.73	1.85
Linseed	0.18	0.11	0.63
Total	30.27	42.61	1.40

What is Weed?

“Weeds are the plants, which grow where they are not wanted” (Jethro Tull, 1731).

Characteristics of Weeds

1. Deep root systems
2. Rapid seedling growth
3. Dual mode of reproduction
4. Prolific seed production
5. Environmental plasticity
6. Quick maturation
7. Dormancy mechanism
8. Physical similarity to crop seeds.



■ Weeds ■ Insects ■ Disease ■ Other

Fig. 1: Total annual loss in agriculture produces (%)

Table 2: Critical period of crop-weed competition and yield loss due to weed in oilseed:

Crop	Critical period (Days)	Yield loss (%)
Castor	30-60	30-35
Groundnut	40-60	40-50
Linseed	20-45	30-40
Mustard	15-40	15-30
Safflower	15-45	15-40
Sesame	15-45	15-45
Soybean	20-45	40-60
Sunflower	15-30	30-60

Table 3: Weed flora of oilseeds:

Kharif season	Rabi season	Summer season
<i>Cyperus rotundus</i> L.	<i>Cyperus rotundus</i> L.	<i>Digera arvensis</i> L.
<i>Portulaca oleracea</i> L.	<i>Parthenium hysterophorus</i> L.	<i>Amaranthus viridis</i> L.
<i>Echinochloa colona</i> L.	<i>Avena fatua</i> L.	<i>Trianthema portulacastrum</i> L.
<i>Eragrostis minor</i> L.	<i>Solanum nigrum</i> L.	<i>Dactyloctenium aegyptium</i> L.
<i>Digitaria sanguinalis</i> L.	<i>Euphorbia hirta</i> L.	<i>Chloris barbata</i> L.
<i>Phyllanthus niruri</i> L.	<i>Chenopodium album</i> L.	<i>Cyperus iria</i> L.

What is Weed Management?

Weed management is a combination of practices by which weed infestation is kept to the minimum for successful and profitable crop production.

Principles of Weed Management

1. Prevention: Weed prevention comprises all measures which deny the entry and establishment of new weeds in an area. It also includes farm hygiene that prevents every year production of seeds, tubers and rhizomes of the weed species already present on the farm. The popular saying "prevention is better than cure" in medical sciences could be bit modified to "prevention is better than intervention" in weed sciences.

Various prevention methods are given below:

- Use clean weed-free crop seeds
- Use of clean farm equipment
- Clean water courses and irrigation channels
- Keep vigilance
- Avoid contamination of manure pits
- Keep non-crop areas clean
- Legal measures

2. Eradication: It is the complete removal of all live plant parts and seeds of a weed from an area, which may be a field / farm / village / geographical region, depending upon the need.

3. Control: It is the process of limiting weed infestations so that crops could be grown profitably and other activities of man conducted efficiently.

Weed control methods are:

- Cultural methods:** These include crop rotation, stale seedbed, summer fallowing, smother cropping, proper irrigation, timely sowing, proper fertilizer application, intercropping, mulching, and blind tillage.
- Physical methods:** These include hand weeding, hand hoeing, tillage, digging, churning and dredging, mowing, flooding, burning, and soil solarization.
- Chemical method:** Chemicals that are used to kill plants or weeds are called herbicides. Their use has been increasing rapidly since 1944 when 2,4-D was first used as herbicide. In many instances, they offer most practical, effective and economic means for controlling weeds. Examples of herbicides are: Pre-emergence herbicide (E.g. Pendimethalin, Oxadiargyl)
 - Post-emergence herbicide (E.g. Quizalofop-p-ethyl, Sulfentrazone)
 - Pre-plant incorporation herbicide (E.g. Fluchloralin, Trifluralin)

4. Biological method: The biological control of weeds involves the use of living organisms. Such as insect, herbivorous fish, other animals, disease organisms and competitive plants to limit their infestations.

An important aspect of biological weed control is that at a time, it is applicable to the control of only one major weed species that has spread widely. With perennial weeds the main objective of bio-control is the destruction of the existing vegetation, in the case of annual weeds prevention of their seed production is generally more important. There are two approaches for biological control:

- Classical / Inoculative approach
- Augmentative / Inundative / Bio-herbicide approach.

Table 4: Examples of classical biological weed control:

<i>Cactoblastis cactorum</i>	<i>Niphograpta albiguttalis</i>
<i>Crocosema lantana</i>	<i>Neochetina bruchi</i>
<i>Cyrtobagous salviniae</i>	<i>Zygogramma bicolorata</i>

Bio-Herbicide Philosophy of Weed Control

A bioherbicide is a biologically based control agent for weeds. Bioherbicides may be compounds derived from microbes such as fungi, bacteria, viruses, or protozoa; or phytotoxic plant residues, extracts or single compounds derived from other plant species.

When the active ingredient used is a fungus, the product is called a mycoherbicide. A mycoherbicide can be both specific and non-specific.

Table 5: Some commercial mycoherbicides in use abroad:

Product	Content	Weed controlled
De-Vine	A liquid suspension of fungal spores of <i>Phytophthora palmivora</i> it causes root-rot in the weed.	Strangle vine (<i>Morrenia odorata</i>) in citrus orchards.
Collego	Wettable powder containing fungal spores of <i>Colletotrichum gloeosporioides</i> .	Joint vetch (<i>Aeschynomene</i> spp.) in rice fields. The bio-herbicide causes stem and leaf blight in the weed.
Bipolaris	A suspension of fungal spores of <i>Bipolaris sorghicola</i> .	Johnson grass (<i>Sorghum halepense</i>)
Biophos	A microbial toxin produced as fermentation product of <i>Streptomyces hygroscopicus</i> .	Non-specific, general vegetation.

Conclusion

Weeds are one of the major biotic constraints that reduce seed yield of oilseed crops by about 15-60%. Therefore, efficient weed management strategies are essential to minimize weed infestation during the critical crop-weed competition period. Weed infestation can be effectively reduced manually through hand weeding and interculturing operations without causing harm to the environment. Alternatively, the adoption of suitable integrated approaches, including the application of pre- and post-emergence herbicides such as pendimethalin, diclosulam, oxyfluorfen, imazethapyr and their mixtures as per recommendation, has been found to be an effective and economical method for enhancing crop growth, yield and profitability.

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From Agricultural Waste to Food: Valorization of Underutilized Leaves for Value-Added Product Development

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Summary of Article

A large proportion of leafy biomass generated in agricultural systems - thinning, trimmings, root-crop tops and leaves of minor or under-marketed plants such as sweet potato, amaranth and moringa - continues to be treated as waste and is either ploughed back, fed to livestock in an unregulated manner, or simply discarded at the farm and market level. Recent research shows that several of these leaves carry a nutrient density comparable to, or exceeding, that of conventional leafy vegetables, and that they can be converted into stable, functional ingredients through simple drying and milling operations (Knez et al., 2024; Yi et al., 2024). This article reviews recent evidence on valorizing such agricultural waste and underutilized leaves into value-added food products, outlining the processing pathway from raw leaf to finished product, the categories of products that have been developed and validated in recent studies, and the nutritional and economic rationale for wider adoption.



Introduction

The concept of 'waste' in agriculture is often a matter of market definition rather than biological fact. Knez et al. (2024) found that many underutilized and neglected leafy greens preserve agro-biodiversity while offering nutritional and environmental benefits that remain undervalued by mainstream food systems. Similarly, Yi et al. (2024) reviewed sweet potato leaves - a by-product of tuber cultivation that is discarded as waste across large parts of Asia – and reported that these leaves are a rich, underexploited source of protein, polyphenols and micronutrients whose nutraceutical value is substantially retained when appropriate processing methods are applied. The scale of such discarded leafy biomass is considerable, and its disposal, whether through open dumping or uncontrolled decomposition, represents an overlooked opportunity cost for the food system.

Valorization, in this context, refers to the deliberate conversion of low-value or discarded leafy material into higher-value, market-ready food products, most commonly by drying and milling the leaves into a stable powder that can be blended into staple food matrices. Khan et al. (2023) found that supplementing whole wheat flour bread with dehydrated moringa leaf powder significantly improved its antioxidant activity, mineral content and total phenolic content relative to unsupplemented bread, while maintaining acceptable sensory quality. In a related study on bakery fortification, Rahman et al. (2026) developed an oil-assisted debittering method for moringa leaf powder and found that biscuits fortified with up to 20 percent debittered leaf powder showed higher protein, fibre and mineral content, improved

oxidative stability, and even a reduction in acrylamide formation during baking, without compromising consumer acceptance.

Qumbisa et al. (2022) found that partial substitution of wheat flour with 1-3 % *Amaranthus* leaf powder in instant noodles measurably improved the nutrient profile of the product while keeping consumer acceptability comparable to the unfortified control. Olusanya et al. (2023) found that a traditional steamed bread supplemented with up to 2 % *Amaranthus* leaf powder was rated as acceptable as the control sample, with significant improvements in ash, protein and mineral content, although acceptability declined at higher inclusion levels, underscoring that sensory thresholds, not nutrient content alone, govern the practical ceiling for leaf powder fortification. A systematic review by Santhanam et al. (2026), covering studies published over the last decade, similarly concluded that incorporating underutilized green leafy vegetables into bakery products consistently enhances mineral and fibre content, though optimum inclusion levels vary by product type and leaf source.

Taken together, these recent studies point to a common valorization pathway: hygienic collection and sorting of the leaves, blanching or a comparable pre-treatment to reduce anti-nutrients and stabilize colour, shade- or cabinet-drying, fine milling, and formulation trials to identify the maximum leaf-powder inclusion level that preserves sensory acceptability. Products validated in the recent literature include moringa leaf powder-fortified bread and biscuits (Khan et al., 2023; Rahman et al., 2026), *Amaranthus* leaf powder-fortified noodles and steamed bread (Qumbisa et al., 2022; Olusanya et al., 2023), and a wide range of bakery applications reviewed by Santhanam et al. (2026), alongside emerging work on sweet potato leaves as a food-processing raw material (Yi et al., 2024).

Personal Opinion

In the author's view, the consistency of findings across these recent, independently conducted studies is itself a strong argument for moving leaf-powder valorization out of the research laboratory and into small-scale commercial practice. What is needed most is not further proof of nutritional benefit, since that evidence base is now well established (Knez et al., 2024; Santhanam et al., 2026), but investment in collection logistics, low-cost drying infrastructure, and, as Olusanya et al. (2023) and Rahman et al. (2026) both note in different product contexts, careful optimization of inclusion levels so that nutritional gains are not undermined by loss of consumer acceptability.

Summary

Recent peer-reviewed research consistently demonstrates that underutilized and waste agricultural leaves - including moringa, amaranth and sweet potato leaves - can be converted through simple blanching, drying and milling operations into stable, nutrient-dense powders suitable for fortifying breads, biscuits, noodles and other staple foods (Khan et al., 2023; Qumbisa et al., 2022; Olusanya et al., 2023; Rahman et al., 2026; Yi et al., 2024). Sensory acceptability, rather than processing feasibility, remains the primary constraint on inclusion levels across product categories, as highlighted by the systematic review of Santhanam et al. (2026). Continued work on standardizing inclusion levels for different leaf-product combinations, and on building collection and market-linkage systems, will be key to translating this now well-documented nutritional potential into mainstream commercial food products.

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Cordyceps: The Miracle Mushroom

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Abstract

Cordyceps, popularly known as the “miracle mushroom,” represents a fascinating group of fungi that connects traditional knowledge, modern biotechnology and sustainable agriculture. Many Cordyceps-related fungi are entomopathogenic, naturally infecting insects and contributing to the regulation of insect populations. Among the best-known species, *Ophiocordyceps sinensis* and *Cordyceps militaris* have attracted considerable attention because of their distinctive life cycle, bioactive compounds and medicinal potential. Cordyceps produces a diverse range of metabolites, including cordycepin, polysaccharides, nucleosides, sterols, peptides and other secondary metabolites, which have been investigated for antioxidant, anti-inflammatory, immunomodulatory and antiproliferative activities. Their ability to infect insects, produce bioactive metabolites and secrete cuticle-degrading enzymes highlights their potential as biological pest-management agents. Although many of these effects are supported mainly by laboratory and preclinical studies, they have stimulated considerable interest in Cordyceps biotechnology.

Keywords: Cordyceps, miracle mushroom, cordycepin.

A Fungus with an Extraordinary Life Cycle

Cordyceps is a group of fungi belonging to the phylum Ascomycota. Many species are entomopathogenic, meaning that they infect insects and other arthropods. Among the best-known medicinal species are *Ophiocordyceps sinensis* historically referred to as *Cordyceps sinensis* and *Cordyceps militaris*.

In nature, *O. sinensis* is associated particularly with insect larvae in the high-altitude regions of the Tibetan Plateau and Himalayas. The fungus infects its host, grows through the insect body and eventually produces a reproductive structure that emerges from the host. This extraordinary phenomenon has contributed to the traditional description of Cordyceps as a fungus that changes from a “worm” in winter to “grass” in summer.

From Traditional Medicine to Modern Biotechnology

For centuries, Cordyceps has been used in traditional Chinese and Tibetan medicinal practices. It was traditionally valued as a tonic and was associated with vitality, stamina and general well-being. Modern research has shifted the focus from folklore to the chemical and molecular basis of its biological activities (Das *et al.*, 2010).

Scientists have identified numerous compounds from Cordyceps, including nucleosides, polysaccharides, sterols, proteins, peptides and other secondary metabolites. Among these, one compound has received exceptional scientific attention i.e. cordycepin.

Cordycepin: The Star Molecule

Cordycepin, chemically known as 3'-deoxyadenosine, is structurally related to adenosine. It was first isolated from *C. militaris* and has become one of the most extensively studied bioactive compounds associated with the genus (Jędrejko *et al.*, 2021).

Laboratory and animal studies have reported several biological activities of cordycepin, including anti-inflammatory, antioxidant, immunomodulatory and anti-proliferative effects. A systematic review found substantial experimental evidence for anti-inflammatory and anti-proliferative activity, while also emphasizing that much of the evidence comes from cell and animal studies rather than definitive human clinical trials.

This distinction is important: Cordyceps is promising, but “promising” does not mean that it is a proven treatment for every disease.

What makes Cordyceps Biologically Interesting?

The remarkable potential of Cordyceps comes from its chemical diversity (Chou *et al.*, 2024).

1. Cordycepin: Cordycepin is perhaps the most famous metabolite associated with *C. militaris*. Its molecular similarity to adenosine allows it to interact with cellular biochemical pathways, making it an important molecule for pharmacological research.

2. Polysaccharides: Cordyceps produces complex polysaccharides that have attracted considerable interest because of their antioxidant and immunomodulatory properties. Their biological activity can depend strongly on molecular structure, extraction method and source material.

3. Adenosine and other nucleosides: Nucleosides such as adenosine are important chemical constituents of Cordyceps and are frequently investigated as markers of its bioactive composition.

4. Other metabolites: Research has also identified compounds such as D-mannitol, sterols, peptides and other secondary metabolites, adding to the biochemical complexity of the mushroom.

Could Cordyceps Support Human Health?

Cordyceps has been investigated for several potential biological effects.

Energy and exercise: Because of its traditional reputation as a tonic, Cordyceps has become popular among athletes and fitness enthusiasts. Recent human research has investigated whether *C. militaris* supplementation can influence exercise performance and recovery. However, the available clinical evidence remains limited and heterogeneous, so stronger and better-designed trials are still required.

Immune modulation: Cordyceps extracts, polysaccharides and cordycepin have demonstrated immunomodulatory effects in experimental studies. Importantly, different extracts can produce different immune responses, showing why the chemical composition of a Cordyceps preparation matters (Zhou *et al.*, 2009).

Anti-inflammatory potential: Cordycepin has attracted attention because of its ability to influence inflammatory signalling pathways. Experimental evidence is particularly strong compared with many other proposed benefits, although translation into clinical therapies requires further research (Yue *et al.*, 2013).

Anticancer research: Cordycepin has shown anti-proliferative and antitumour activity in numerous laboratory models. This makes it an interesting lead molecule for drug discovery, but it should not be interpreted as evidence that Cordyceps itself can cure cancer.

From Rare Wild Fungus to Laboratory Cultivation

Wild *O. sinensis* is difficult to obtain and occurs naturally in restricted high-altitude environments. Its scarcity and high value have encouraged researchers to develop controlled cultivation systems.

In contrast, *Cordyceps militaris* can be cultivated under controlled laboratory and commercial conditions, making it particularly attractive for producing fruiting bodies and bioactive metabolites. Researchers are investigating substrate composition, light, temperature, culture duration and other factors to improve biomass and metabolite production.

This transition from wild harvesting to controlled cultivation has an important environmental advantage: it can reduce pressure on natural populations while providing a more consistent source of fungal material.



Cordyceps and its Potential as a Natural Crop Protectant

Modern agriculture faces a major challenge i.e. how to protect crops from insect pests and diseases while reducing excessive dependence on synthetic pesticides. In this search for safer and more sustainable alternatives, entomopathogenic fungi (fungi that naturally infect and kill insects) have emerged as important biological crop protectants. Among the most fascinating members of this fungal group are the Cordyceps-related fungi, which have evolved remarkable mechanisms for infecting insects (Chhipa, 2024).

Although Cordyceps is popularly known for its medicinal and nutraceutical value, its greatest ecological role in nature is associated with host infection and insect population regulation. This natural ability provides an important foundation for exploring Cordyceps and closely related fungi as components of biological pest-management systems (Saminathan *et al.*, 2025).

How can these Fungi Protect Crops?

The crop-protection potential of entomopathogenic fungi can be understood through several mechanisms.



1. Direct infection of insect pests: The most important mechanism is mycosis, or fungal infection of the insect. Unlike many chemical insecticides, fungal pathogens do not necessarily need to be ingested. Their spores can infect insects directly through the cuticle. This makes fungal biocontrol particularly interesting for pests that are difficult to manage through conventional insecticides.

2. Production of insecticidal metabolites: Entomopathogenic fungi can produce a variety of secondary metabolites during infection. Some metabolites interfere with insect physiology, immunity, development or cellular metabolism. This chemical arsenal is one reason why fungal pathogens can successfully overcome insect immune defenses. The discovery of such metabolites also demonstrates the importance of fungal secondary metabolism in agricultural biotechnology.

3. Enzymatic degradation of the insect cuticle: The insect cuticle acts as the first physical barrier against fungal infection. Entomopathogenic fungi produce extracellular enzymes, including chitinases, proteases and lipases, which help weaken and penetrate this protective layer. Understanding these enzymes can help scientists improve fungal biocontrol formulations and identify strains with superior insect-pathogenic activity.

4. Natural multiplication: One of the most attractive characteristics of biological control agents is their ability to reproduce under favourable conditions. After an infected insect dies, the fungus can produce new spores on the host surface, potentially allowing the pathogen to spread within an insect population. This provides an important ecological advantage over conventional pesticides, which generally do not reproduce in the field.

A Promising Green Shield for Agriculture

The story of Cordyceps reminds us that fungi are not merely decomposers or organisms of medicinal interest. They are also powerful participants in natural ecosystems, where they regulate insect populations and produce an enormous diversity of bioactive molecules.

While Cordyceps itself should not be portrayed as a ready-made agricultural pesticide, its remarkable insect-pathogenic biology and the wider group of related entomopathogenic fungi provides valuable inspiration for developing next-generation biological crop protectants.

The future of sustainable agriculture may therefore involve a shift from a purely chemical approach toward a more balanced system in which beneficial microorganisms, fungal metabolites, resistant crops and precision technologies work together to protect plants.

From the forest floor to the farmer's field, fungi may become one of nature's most valuable allies in building a safer and more sustainable agriculture.

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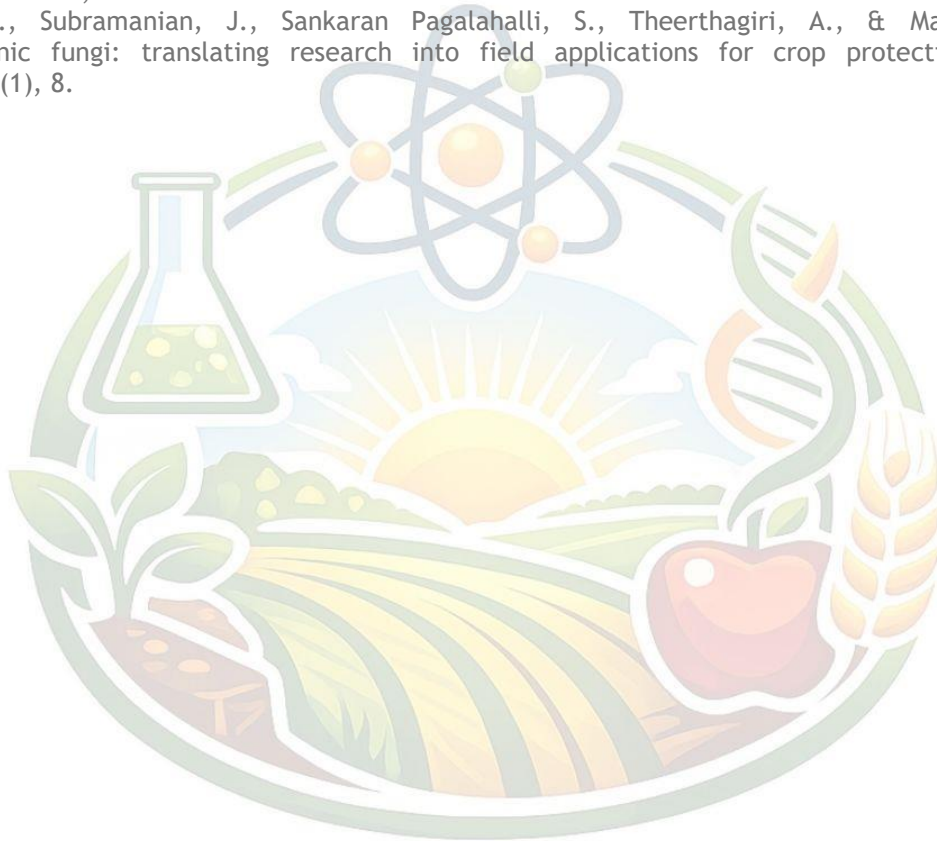
Conclusion

The future of Cordyceps research is moving from simple extraction toward precision production. Scientists are increasingly interested in identifying the genes responsible for valuable metabolites, understanding environmental regulation of biosynthetic pathways and improving metabolite production through fermentation and metabolic engineering. In the future, it may become possible to develop optimized fungal strains specifically designed to produce particular bioactive molecules at higher concentrations. Such approaches could contribute to the development of:

1. Novel pharmaceutical lead molecules;
2. Standardized nutraceutical ingredients;
3. Functional foods;
4. Bioactive formulations;
5. Natural antioxidants;
6. Immunomodulatory products; and
7. New platforms for microbial metabolite production.

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Nutrition Security and Livelihood Enhancement through Fruit Plantations

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Abstract

Nutrition security and sustainable livelihood generation remain major challenges in developing economies, particularly in rural regions where malnutrition, underemployment, and income instability persist. Fruit plantations offer a dual solution by improving dietary diversity and generating long-term economic opportunities. Fruits are rich sources of essential vitamins, minerals, dietary fiber, and bioactive compounds that play a crucial role in preventing micronutrient deficiencies and non-communicable diseases. Simultaneously, fruit-based production systems provide stable income, employment, and scope for value addition due to their perennial nature and increasing market demand. This article examines the role of fruit plantations in enhancing nutrition security and livelihoods, highlighting their nutritional, economic, environmental, and social benefits. It also discusses policy support, institutional interventions, and strategic approaches required for effective implementation. The study emphasizes that nutrition-sensitive horticulture, supported by scientific management and market integration, can significantly contribute to sustainable rural development.

Keywords: Nutrition security, fruit plantations, livelihood enhancement, horticulture, sustainable agriculture, value addition.

Introduction

Nutrition security encompasses not only the availability of sufficient food but also access to safe, diverse, and nutrient-rich diets essential for a healthy and productive life. Despite progress in food grain production, malnutrition in the form of micronutrient deficiencies, anemia, and poor dietary diversity remains a major public health concern. This paradox highlights the need to shift focus from calorie-centric food security to nutrition-sensitive agricultural systems.

Fruit crops play a pivotal role in addressing this challenge due to their high nutritional value and adaptability across agro-climatic regions. In recent years, fruit plantations have gained importance as a sustainable agricultural enterprise capable of improving household nutrition while strengthening rural livelihoods. The integration of fruit cultivation with income generation, employment creation, and environmental sustainability makes it a strategic intervention for holistic rural development.

Role of Fruits in Nutrition Security

Fruits are widely recognized as “protective foods” because of their rich composition of essential nutrients. They are major sources of vitamins such as vitamin C (citrus, guava), provitamin A carotenoids (mango, papaya), and folates, along with minerals like potassium, calcium, and iron. Dietary fiber present in fruits improves digestive health and reduces the risk of lifestyle-related diseases.

Horticulture is a key agricultural enterprise that provides nutrient security to rural, semi-urban, and urban populations. Fruits are rich sources of naturally available vitamins (A, B1, B12, C, E), minerals, dietary fibre, phytonutrients, carbohydrates, and antioxidants—often referred to as protective foods. The nutraceutical properties of coloured fruits also help reduce the risk of heart disease, anaemia, diabetes, and chronic ailments. Fruit crops supply essential micronutrients that are often missing in the diets of economically weaker populations.

According to the Indian Council of Medical Research (ICMR), the daily requirement of fruit is 100 g per capita, but only about 80 g per capita is available. Despite technological advancements in horticultural production, meeting the nutritional needs of an ever-growing population remains a major challenge. To bridge the gap between fruit availability and consumption, it is essential to establish fruit plants in backyard kitchen gardens, village common lands, schools, community and government areas, roadside plantations, and industrial zones. While space availability is often not a limitation, the lack of knowledge about proper planning, planting, and selection of geographically suitable cultivars is a significant drawback. In recent years, trends have been changing—both rural and urban populations are increasingly utilizing available space to grow fruit crops in kitchen gardens. The successful establishment of fruit trees in kitchen or nutrition gardens, ensuring year-round fresh and nutritious produce, ultimately depends on the size of the available plot.

Regular consumption of fruits enhances immune function, supports child growth, and helps prevent chronic conditions such as cardiovascular diseases, diabetes, and obesity. Promoting fruit plantations at household, community, and institutional levels ensures year-round access to fresh fruits, particularly in rural and tribal areas where market availability may be limited. Thus, fruit cultivation directly contributes to improved dietary diversity and nutrition security.

Fruit Plant Distribution and Terrace Gardening Promotion

SAGE University of Indore, through the Institute of Agricultural Sciences, promotes fruit plant distribution and terrace gardening as part of its extension and outreach activities to enhance nutritional security, environmental sustainability, and livelihoods in Madhya Pradesh. Fruit plants suitable for evergreen and deciduous crops are distributed during appropriate planting seasons through Kisan Melas, farmers' training programs, and university-led extension events, in collaboration with Krishi Vigyan Kendras, the State Department of Horticulture, and local agricultural agencies. Faculty members regularly conduct lectures, demonstrations, and field-level awareness programs to encourage kitchen gardening, terrace gardening, tube-well and boundary plantation, and the establishment of commercial orchards among farmers, students, and urban households, thereby strengthening sustainable horticulture practices in the region.

Fruit crops such as papaya, strawberry, cape gooseberry, grapes, and other short-stature plants can also be grown in terrace gardens. Hanging baskets, boxes, and tubs are suitable for strawberries due to their small plant size. Grape vines can be grown on rooftops in large pots, boxes, or drums using basal spur-pruned varieties. In some cases, grapes are planted in backyard or roadside spaces, with the vine trained to grow onto rooftops, allowing for proper canopy development using the Bower or Y-trellis system.

Fruit Plantations as a Source of Livelihood Enhancement

Fruit plantations offer multiple livelihood benefits due to their long productive life, high value, and increasing domestic and export demand.

Income Stability and Economic Returns: Compared to seasonal field crops, fruit plantations provide higher and more stable returns once the orchards reach bearing stage. Crops such as mango, banana, citrus, guava, papaya, and pomegranate are economically viable and suitable for small and marginal farmers. The perennial nature of fruit crops ensures sustained income over several years, reducing vulnerability to market and climatic risks.

Employment Generation: Fruit cultivation is labor-intensive and generates employment throughout the year in activities such as nursery raising, planting, training and pruning, harvesting, grading, packaging, and marketing. This contributes to rural employment, reduces seasonal migration, and strengthens local economies.

Scope for Value Addition and Entrepreneurship: Post-harvest processing and value addition significantly enhance income from fruit crops. Processing fruits into juices, jams, jellies, pulp, dehydrated products, and pickles creates additional employment opportunities and promotes rural agro-industries. Women and rural youth can actively engage in processing, packaging, and marketing enterprises, thereby fostering inclusive growth and entrepreneurship.

Environmental and Sustainability Benefits: Fruit plantations contribute positively to environmental sustainability and climate resilience. Tree-based systems help in soil conservation by reducing erosion and improving soil organic matter. Fruit trees act as carbon sinks, contributing to climate change mitigation. Orchards also enhance on-farm biodiversity by supporting pollinators, birds, and beneficial insects. Adoption of resource-efficient technologies such as drip irrigation, mulching, and integrated nutrient management improves water-use efficiency and reduces production costs. Integration of fruit crops with agroforestry, intercropping, and organic farming further strengthens ecological sustainability while maintaining productivity.

Social and Community-Level Impacts: Fruit plantation initiatives generate significant social benefits when implemented at community and institutional levels. Household nutrition gardens improve family nutrition and reduce dependence on market-purchased fruits. School and Anganwadi fruit plantations support child nutrition programs while serving as learning platforms for nutrition education. Community orchards promote collective ownership, equitable access to nutritious food, and social cohesion. Participation of women through self-help groups in fruit production and processing enhances financial independence and decision-making power. Such initiatives contribute to awareness about balanced diets, sustainable agriculture, and health-oriented food choices.

Policy Support and Institutional Interventions

Government policies and institutional support play a critical role in promoting fruit plantations. National and state horticulture missions provide subsidies for planting material, irrigation systems, and infrastructure development. Capacity-building programs, farmer training, and promotion of Farmer Producer Organizations (FPOs) strengthen production and marketing capabilities. Academic institutions, research organizations, and extension agencies contribute by developing improved varieties, providing technical guidance, and disseminating best management practices. Collaboration among farmers, institutions, and policymakers is essential for scaling up fruit-based nutrition and livelihood initiatives.

Scientific Approaches to Fruit Nutrition Garden Development and Care: Evergreen fruit plants such as citrus, sapota, ber, jamun, and guava are planted during February to March (spring season) and August to September (rainy season), while deciduous fruit plants are usually planted before the dormancy period ends or before the onset of new growth. Proper planning regarding irrigation channels, planting distance, and garden demarcation is essential. Pits measuring 1 m × 1 m × 1 m should be dug and filled with a mixture of equal parts topsoil and dry farmyard manure, along with 15 ml Chloropyriphos 20 EC in each pit to protect against white ants. After refilling, the pits should be irrigated to allow the

soil to settle. The budded portion of the fruit plant should remain 6 to 9 inches above ground level, and plants should be supported with sticks for upright growth. Planting material must be procured from reliable nurseries of SAU/ICAR institutes, the state horticulture department, or accredited private nurseries, ensuring that the plants are budded or grafted on suitable rootstocks and free from pests, nematodes, and diseases. The trunks of young plants should be whitewashed with a mixture of 25 kg slaked lime, 500 g CuSO₄, and 500 g gum or *suresh* and dissolved in 100 l of water. Eco-friendly measures such as non-woven bags, fruit fly traps, slippery bands for mealy bug control, and neem-based formulations should be adopted for pest and disease management. To conserve moisture and suppress weeds, paddy straw or plastic sheets may be used around plant basins. A fruit nutrition garden not only provides fresh produce and nutritional security but also helps save the expenses a family would otherwise incur on purchasing fruits from the market. During the pre-bearing stages, the vacant space between rows and plants can be used for growing annual fruit crops such as Cape gooseberry and strawberry, along with seasonal pulses and vegetables. Strawberries can be planted between rows at a spacing of 30 cm × 30 cm in September-October, with harvesting from December to March when fruits reach the pink or three-fourths coloured stage, ensuring they are picked with the cap or calyx and a small stalk of one to two inches.

Strategies for Effective Implementation

To maximize the impact of fruit plantations on nutrition security and livelihoods, the following strategies are recommended:

1. Selection of location-specific fruit crops based on agro-climatic suitability
2. Promotion of high-yielding, nutrient-rich, and climate-resilient varieties
3. Integration of fruit production with nutrition awareness and behavior change programs
4. Adoption of climate-smart and sustainable cultivation practices
5. Strengthening post-harvest management, value addition, and market linkages
6. Active involvement of women and youth through skill development and entrepreneurship

A participatory, nutrition-sensitive horticulture approach ensures long-term sustainability and wider adoption.

Challenges and Way Forward

Despite their advantages, fruit plantations face challenges such as long gestation periods, pest and disease pressure, post-harvest losses, and market price fluctuations. Limited access to credit, insurance, storage, and cold chain facilities further constrains profitability.

Addressing these challenges requires investment in research and development, improved extension services, access to institutional credit, crop insurance, and development of efficient supply chains. Digital platforms and farmer collectives can enhance market access and price realization. Aligning agricultural production with nutrition outcomes through policy and planning is essential for sustained impact.

Young plants should be irrigated as needed, depending on soil and climatic conditions, with a preference for using a drip irrigation system for efficient water management. It is advisable to remove dead wood, diseased branches, and intermingling shoots to promote healthy growth. Water shoots or suckers emerging below the bud union should be removed immediately. In deciduous fruit plants, training and pruning are essential to develop a strong framework. Branches should be oriented evenly in all directions, with the main stem headed back at a height of 75-90 cm from the ground. In the following year, 3-4 well-spaced shoots should be selected in different directions, maintaining a gap of 15-20 cm between them. The first shoot should be positioned about 45 cm above the ground. Phalsa plants should be trained in a bush form and pruned annually in January-February to a height of around 1 m from the ground level. Fruits should be ripened using indigenous, safe, and eco-friendly ripening technologies to ensure quality and consumer safety.

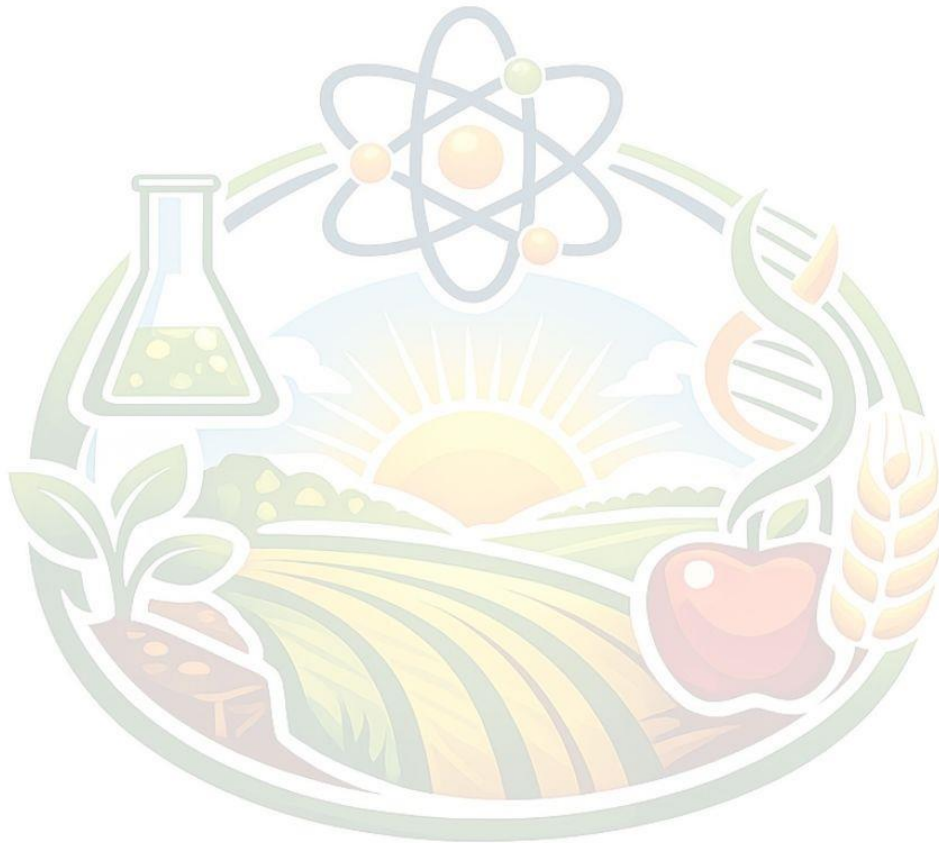
Conclusion

Fruit plantations represent a sustainable and effective pathway for achieving nutrition security and livelihood enhancement. By providing nutrient-rich foods and stable income opportunities, fruit-based farming systems address key challenges of malnutrition, poverty, and environmental degradation. Large-scale and community-based fruit plantation initiatives, supported by scientific management, policy backing, and institutional collaboration, can significantly contribute to improved health, economic resilience, and sustainable rural development. Strengthening nutrition-sensitive horticulture should therefore be priority in future agricultural and rural development strategies.

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Carbon Sequestration and its Importance

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Growing concerns regarding global warming and carbon emissions have spurred interest in techniques for carbon sequestration, aimed at capturing and storing carbon released from the burning of fossil fuels. Human activities already have a significant impact on almost half of the terrestrial biological carbon cycle (Hughes and Benemann, 1997). Effectively managing this cycle could make a substantial contribution to CO₂ mitigation (Farrelly et al., 2013). A significant portion of the carbon dioxide (CO₂) emissions generated by human activity stems from the combustion of fossil fuels for energy production. The adverse effects of elevated CO₂ levels in the atmosphere on the environment are widely acknowledged. Consequently, we are progressively increasing the concentration of carbon in the atmosphere, which ultimately leads to global warming and climate change (Soon *et al.*, 1999; Farrelly et al., 2013). Various approaches can be explored to reduce carbon in the atmosphere and mitigate the negative impacts of climate change. One such approach is carbon sequestration, which can range from being affordable and straightforward to expensive and intricate. This includes natural carbon sequestration as well as geological carbon sequestration.

Carbon Sequestration

Carbon sequestration is a fundamental process aimed at mitigating climate change by capturing carbon dioxide (CO₂) emissions from the atmosphere and storing them in long-term reservoirs. This process assumes great significance due to the role of CO₂ as a primary contributor to global warming. Lal (2007) defines soil carbon sequestration as the process of capturing atmospheric CO₂ and securely storing it within the pedosphere, thereby enhancing its mean residence time (MRT) while minimizing re-emission sources. It is widely acknowledged that carbon sequestration plays a crucial role in the battle against climate change. However, to achieve substantial reductions in atmospheric CO₂ levels, a combination of diverse methodologies may be necessary. Ongoing research and development efforts in the field of carbon sequestration technologies remain indispensable in meeting the challenges posed by climate change.

Important Sources and Methods of Carbon

- 1. Forests as a carbon sink:** Afforestation, reforestation, plantation, and agroforestry are all practices that contribute to carbon sequestration. These approaches involve the uptake of atmospheric carbon through photosynthesis, which is then stored in the form of biomass or wood. The success of carbon sequestration in these practices relies on ensuring that the carbon does not return to the atmosphere through burning processes.
- 2. Wetland restoration:** Wetland soils serve as significant natural carbon pools or sinks. Globally, wetlands retain approximately 14.5% of the soil carbon, despite covering only 6% of the Earth's land area.
- 3. Oceans as a carbon sink:** Oceans act as absorbers of carbon dioxide from the atmosphere, primarily due to the higher concentration of CO₂ in the atmosphere compared to that in the oceans. The difference in CO₂ partial pressure between the atmosphere and oceans leads to the absorption of CO₂ into the world's oceans (Raghuvanshi et al., 2006).
- 4. Subterranean injection or geological sequestration:** Carbon dioxide can be injected into depleted oil and gas reservoirs, geological formations, or deep ocean regions, a process known as subterranean injection. This method of carbon sequestration involves selecting appropriate sites for injecting CO₂, such as depleted oil and gas reservoirs, to securely store the carbon dioxide (Dhanwantri et al., 2014).

These scientific approaches contribute to the understanding and implementation of carbon sequestration strategies, playing a crucial role in mitigating the impacts of carbon emissions and addressing climate change.

The Key Reasons Why Carbon Sequestration is so Important

- 1. Mitigating greenhouse gas emissions:** Carbon sequestration plays a vital role in mitigating greenhouse gas emissions, particularly by reducing the concentration of carbon dioxide (CO₂) in the atmosphere. By effectively removing CO₂ from the atmosphere, carbon sequestration contributes to mitigating the impacts of climate change, such as rising global temperatures, altered precipitation patterns, and increased frequency of extreme weather events. This is essential for safeguarding ecosystems, reducing vulnerabilities, and preserving biodiversity.
- 2. Advancing sustainable land management:** Numerous carbon sequestration methods necessitate changes in land use, such as afforestation, reforestation, and sustainable agricultural practices. These land management strategies not only facilitate carbon capture but also promote sustainable land use practices. They help protect and restore ecosystems,

enhance soil quality, preserve water resources, and support the livelihoods of local communities. By integrating carbon sequestration into land management practices, we can achieve multiple environmental and socio-economic benefits.

3. Enhancing soil fertility and productivity: Soil carbon sequestration enhances soil health, which has direct implications for plant growth, nutrient cycling, and overall agricultural productivity. Increased carbon content in soils improves soil structure, water retention capacity, and nutrient availability, fostering optimal conditions for plant growth. By enhancing soil fertility, carbon sequestration practices contribute to sustainable agriculture, food security, and the resilience of agricultural systems in the face of climate change.

4. Fostering technological innovation: Carbon sequestration is a rapidly evolving field, constantly exploring new technologies, methodologies, and monitoring techniques. Investing in carbon sequestration research and development promotes technological innovation, driving advancements in carbon capture, storage, and utilization. This fosters the growth of a green economy, stimulates job creation, and catalyzes the emergence of novel solutions for addressing climate change challenges.

5. Meeting international climate targets: Carbon sequestration constitutes a critical component of international climate agreements and commitments, such as those outlined in the Paris Agreement. By actively implementing carbon sequestration strategies, countries can contribute to achieving their emission reduction targets, promoting sustainable development, and transitioning towards a low-carbon future. The integration of carbon sequestration into climate policies and strategies strengthens global efforts to limit global warming and mitigate the impacts of climate change.

The Objectives of Soil Carbon Sequestration Encompass Various Scientific Considerations, Including

1. Offsetting anthropogenic emissions: Soil carbon sequestration aims to counterbalance carbon emissions originating from activities such as fossil fuel combustion, cement production, and deforestation. By capturing and storing carbon in the soil, it mitigates the net increase in atmospheric CO₂ concentration and helps maintain carbon equilibrium.

2.Reducing atmospheric CO₂ concentration and pool: An important objective of soil carbon sequestration is to curtail the rise in atmospheric CO₂ levels, which surpassed 400 parts per million by volume (ppmv) in 2013. Additionally, efforts are directed towards expanding the soil carbon pool, which currently stands at approximately 800 petagrams of carbon (PgC).

3. Enhancing soil organic carbon concentration: Soil carbon sequestration endeavors to elevate soil organic carbon (SOC) concentration above the critical threshold range of 1.5-2.0%. Higher SOC levels promote soil fertility, augment nutrient cycling dynamics, and improve water retention capacity. These enhancements contribute to enhanced soil quality and bolster ecosystem functions.

4.Restoring soil quality and ecosystem functions: Soil carbon sequestration initiatives prioritize the restoration of soil quality and the associated functions and services it provides. This includes the preservation and promotion of biodiversity, heightened nutrient retention capabilities, improved water infiltration rates, and the reduction of soil erosion and nonpoint source pollution.

5.Improving water and nutrient retention capacity: An objective of soil carbon sequestration is to enhance the soil's ability to retain water and nutrients. This improvement increases the efficiency of resource utilization in managed ecosystems, leading to sustainable agricultural practices with reduced losses of valuable inputs.

6.Creating climate-smart soils and agroecosystems: Soil carbon sequestration contributes to the development of climate-smart soils and agroecosystems. These systems exhibit resilience to climate change, actively mitigate greenhouse gas emissions, and enhance carbon storage while ensuring sustainable food production.

7. Increasing productivity and advancing food security: By implementing effective soil carbon sequestration practices, it is possible to augment and sustain agronomic productivity. This achievement has far-reaching implications for food security, particularly in regions where agricultural productivity is hampered by degraded soils.

In summary, soil carbon sequestration aligns with a range of scientific objectives. By offsetting anthropogenic emissions, reducing atmospheric CO₂ concentrations, enhancing soil organic carbon levels, restoring soil quality, improving resource efficiency, fostering climate resilience, and promoting food security, it emerges as a scientifically informed approach to address climate change and foster sustainable development.

Shuttle Breeding: An Innovative Approach for Developing Climate-Resilient and High-Yielding Crop Varieties

Article ID: 74489

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Introduction

Agriculture is continuously challenged by climate change, increasing population, emerging diseases, pests and shrinking agricultural land. Plant breeders are therefore required to develop improved crop varieties that are high-yielding, disease-resistant and adaptable to diverse environmental conditions. Traditional breeding methods often require several years to complete one breeding cycle because only one generation can be grown annually in a single location. To overcome these limitations, shuttle breeding was developed as an innovative breeding strategy. The method allows breeders to grow successive generations at two or more geographically distinct locations with contrasting climates within a single year. As a result, two or more generations can be advanced annually, significantly reducing the time needed to develop new crop varieties.

Definition of Shuttle Breeding

Shuttle breeding is a plant breeding technique in which breeding populations are grown alternately in two or more contrasting environments during the same year. This enables rapid generation advancement while simultaneously selecting plants with broad adaptability, disease resistance and superior agronomic performance.

Steps of Shuttle Breeding

Norman Borlaug's shuttle breeding technique accelerated wheat development by producing two generations every year. In this approach, one generation was produced at CIMMYT in or near Toluca, Mexico, at an elevation of 2090 m, and the following generation in Ciudad Obregon, Mexico, at 38 m elevation. Typically, it takes ten to twelve generations to combine desirable traits from two varieties by implementing classical breeding and selection methods. Borlaug believed that if two wheat crops could be grown annually, a new variety of wheat could be made in five years. Fortunately for Borlaug, this opportunity was available in Mexico. In Sonora, wheat is sown in October and harvested in April. In the mountainous region of Toluca Valley in central Mexico, wheat is sown in April and May and harvested in October.

Thus, taking advantage of this, Borlaug began shuttle breeding. As soon as the wheat crop was harvested in Sonora (in April), Borlaug sent these seeds for sowing in Toluca. In same manner, after the harvesting of crop in Toluca (in October), new seeds were sent to Sonora.

Initial Crossing: Mate selected wheat parents in Mexico to create hybrid seeds (F_1)

Summer Generation (High Altitude): Grow plants at high altitude near Mexico City (cool, humid, high rainfall) to select for disease resistance (like stem rust) and robust stalks.

Seed Harvest & Transfer: Harvest seeds from the surviving high-altitude plants immediately.

Winter Generation (Desert/Valley): Transport seeds to the Yaqui Valley in Ciudad Obregón, northern Mexico (arid, irrigated Sonoran Desert) for the winter planting.



Selection for Adaptability: Grow the crop under irrigation and intense sunlight; select lines insensitive to day length.



Repeat the Shuttle: Move selected seeds back to central Mexico for the next summer cycle, repeating twice per year until stable, homozygous lines emerge in 4 to 5 years.

The concept gained worldwide recognition through the pioneering work of Dr. Norman E. Borlaug at the International Maize and Wheat Improvement Center (CIMMYT). His successful application of shuttle breeding led to the development of semi-dwarf, rust-resistant, high-yielding wheat varieties that transformed agricultural productivity during the Green Revolution.

Principles of Shuttle Breeding

The success of shuttle breeding depends on several important principles:

1. Alternating breeding populations between contrasting environments.
2. Growing two or more generations each year.
3. Applying continuous selection under diverse climatic conditions.
4. Maintaining genetic variability during early generations.
5. Selecting plants with stable performance.
6. Evaluating disease resistance under natural infection.
7. Identifying broadly adapted genotypes.

Advantages of Shuttle Breeding

Shuttle breeding provides several significant benefits.

1. Reduces breeding time.
2. Produces multiple generations annually.
3. Develops broadly adapted varieties.
4. Improves disease resistance.
5. Enhances stress tolerance.
6. Increases breeding efficiency.
7. Improves yield stability.
8. Accelerates genetic gain.
9. Supports climate-smart agriculture.

Disadvantages of Shuttle Breeding

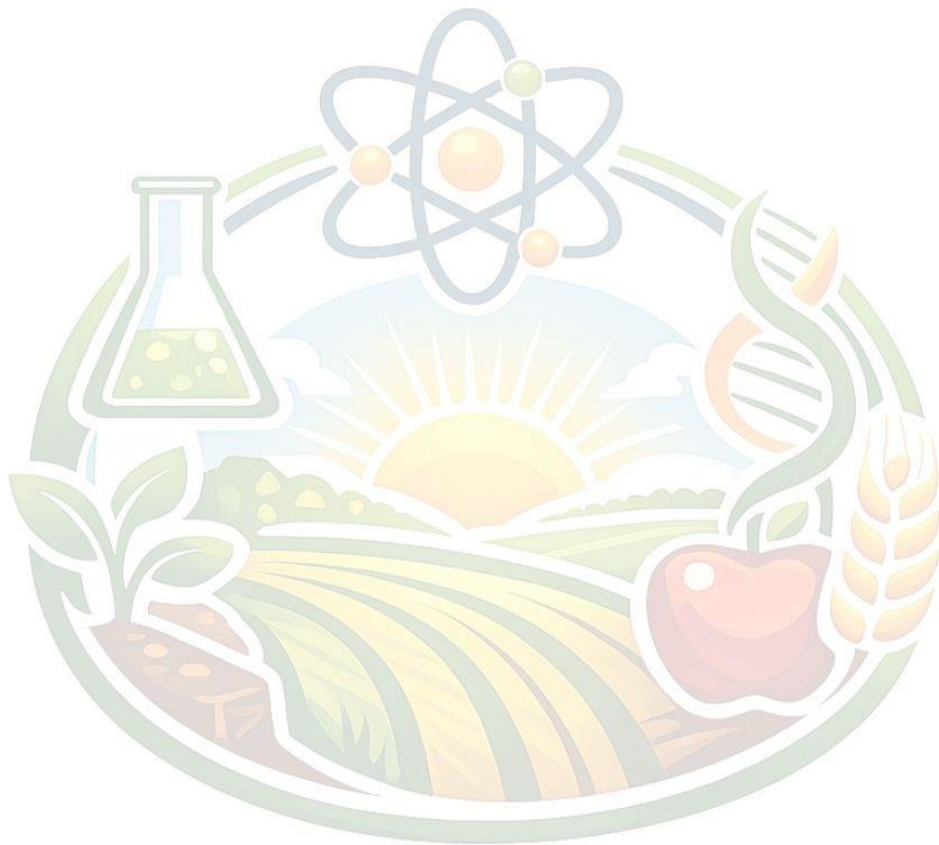
Despite its advantages, shuttle breeding also has limitations.

1. Requires access to multiple breeding locations.
2. Increases operational costs.
3. Requires careful coordination between locations.
4. Transportation of breeding materials can be expensive.
5. Environmental conditions may vary unpredictably.
6. Higher labor requirements.

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Comparative Assessment of Traditional Agromet Advisory Services and Satellite-Based Early Warning Systems for Smallholder Farmers

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Abstract

Climate and weather variability have major impacts on crop production and food security especially among smallholder farmers in rain-fed areas. Conventional agrometeorological advisory services provide farm-level recommendations based on ground observations, weather forecasts, agricultural experts and extension networks. Using rainfall estimates, vegetation indices, soil moisture and other remote sensing products, satellite-based early warning systems monitor agricultural risks over large areas. This paper compares both approaches in terms of spatial coverage, timeliness, accuracy, accessibility, technical requirements, farmer trust and usability. Satellite systems have broad coverage, and can monitor frequently and provide early warning of drought and crop stress. Traditional services can interpret the information locally, offer advice on specific crops and communicate directly with farmers. Evidence from India suggests that the two approaches are complementary (Rathore et al., 2025; Singh et al., 2023). Thus, integrating satellite data with ground observations and extension services may improve the reliability, timeliness and practical utility of climate information for smallholder farmers.

Keywords: Agrometeorology; Early Warning Systems; Satellite Remote Sensing; Food Security; Smallholder Farmers; Rain-fed Agriculture; Climate Risk Management.

Introduction

Rain-fed agriculture is highly sensitive to variations in rainfall, temperature changes, dry spells, floods, heat waves and other extreme weather events. These factors affect sowing, crop growth, pest and disease incidence, harvesting, productivity and income of the farm. Smallholder farmers are particularly vulnerable because they have limited options for irrigation, finance, technology and risk management. These risks can be mitigated by timely weather and climate information.

Agrometeorological Advisory Services (AAS) translate weather and climate information into advice that can be acted upon for sowing, irrigation, fertilizer use, pest control, harvesting and extreme weather response. In India, AAS have evolved from traditional weather-based advisories to digitally enabled and climate-informed decision support systems (Rathore et al., 2025; Singh et al., 2023).

Traditional services are primarily based on ground observations and forecasts, agricultural experts and extension networks. For large areas, agricultural conditions are monitored by systems based on satellite data such as rainfall estimates, vegetation indices and soil moisture information. These systems are particularly useful for drought and crop stress detection in regions where ground observations are scarce (Funk et al., 2015; Rembold et al., 2019).

Traditional Agrometeorological Advisory Services

Traditional AAS consists of observing or forecasting weather, interpreting its implications for agriculture, preparing advisories and communicating them to the farmers. Ground stations feed data on rainfall, temperature, humidity, wind and other weather variables. This information is used by agricultural experts to make recommendations for specific crops and locations (Rathore et al., 2025).

The main advantage of traditional services is human interpretation. For example, expected rainfall may mean fertilizer application is delayed, irrigation needs to be modified, drainage needs to be improved, or harvesting is advanced. The correct recommendation depends on the crop, growth stage, soil and conditions on the farm. Extension personnel can incorporate these factors and translate them into language that is understood locally.

Advisories can be provided through SMS, radio, television, mobile platforms, bulletins, farmer meetings and direct extension contact. Traditional systems, however, are often constrained by a scarcity of meteorological stations, delays in the dissemination of information, inadequate infrastructure, and a shortage of trained personnel. It can also be a challenge to reach remote farmers consistently (Singh et al., 2023).

Satellite-Based Early Warning Systems

Satellite-based systems use remote sensing to track rainfall, vegetation, soil moisture, temperature and other environmental conditions. Products like CHIRPS provide spatially distributed rainfall information useful for monitoring

precipitation variability and extremes (Funk et al., 2015). Other vegetation indices such as NDVI can be used to demonstrate changes in vegetation condition and crop stress while indicators of soil moisture can provide information on water availability.

The great advantage of satellite systems is the wide spatial coverage and frequent observations. They are able to monitor large agricultural areas and detect possible drought and crop stress even where ground stations are sparse. The ASAP system demonstrates how remote sensing and agroclimatic information can be used to detect agricultural production anomalies and food security hotspots (Rembold et al., 2019).

But small individual farms might not be accurately captured by the spatial resolution of satellite indicators. They also give indirect information. For example, a decline in NDVI may be indicative of crop stress but it cannot in itself distinguish between causes such as a shortfall of rainfall, pests, disease, late sowing or soil conditions. Satellite data must therefore be validated on the ground and technically interpreted.

Comparative Assessment

Traditional and satellite-based systems each have their strengths. Traditional services are good at local interpretation, crop-specific advice and direct contact with farmers. Satellite systems have strengths in wide-area monitoring, spatial targeting, and frequent observation. Satellite systems give earlier information on developing environmental anomalies and traditional services can use weather information to make practical farm decisions. Satellite products may, however, require local calibration and ground validation. Traditional services also rely on adequate meteorological stations, personnel and communications infrastructure.

Another major difference is ease of use for the farmer. Extension workers can convert traditional advisories into language that is familiar and answer questions of farmers. Technical satellite indicators like NDVI and soil moisture anomalies require interpretation before they can be used for farm decisions. So, technological accuracy by itself does not guaranty farmer adoption.

Integration of Both Approaches

Traditional and satellite-based systems should not be viewed as competing approaches, but as complementary to each other. Satellite systems can tell where a potential problem is developing; ground observations and extension personnel can identify the local cause and recommend appropriate action. For example, satellite data might indicate worsening vegetation conditions in a rain-fed area. Ground observations can determine if the decline is due to rainfall deficiency, pests, disease or other factors. Agricultural experts can then make appropriate recommendations and extension networks can relay the recommendations to farmers.

A hybrid framework can thus combine satellite monitoring, ground validation, agricultural interpretation and extension communication. This combination has the advantage of having the broad coverage of remote sensing combined with the local knowledge and farmer connection of the traditional advisory services (Singh et al., 2023; Rathore et al., 2025).

Future Research

In future, there is a need to validate satellite rainfall, vegetation and soil moisture products with ground observations and actual crop conditions. Research should also examine the lead time of different indicators and assess whether warnings are early enough for farmers to take preventive action.

The use of GIS, crop models, statistical methods and machine learning can improve risk detection and spatial targeting. Farmer perception, trust, accessibility and communication also need to be given more attention. An early warning is only useful if farmers get the information, understand it and use it in time.

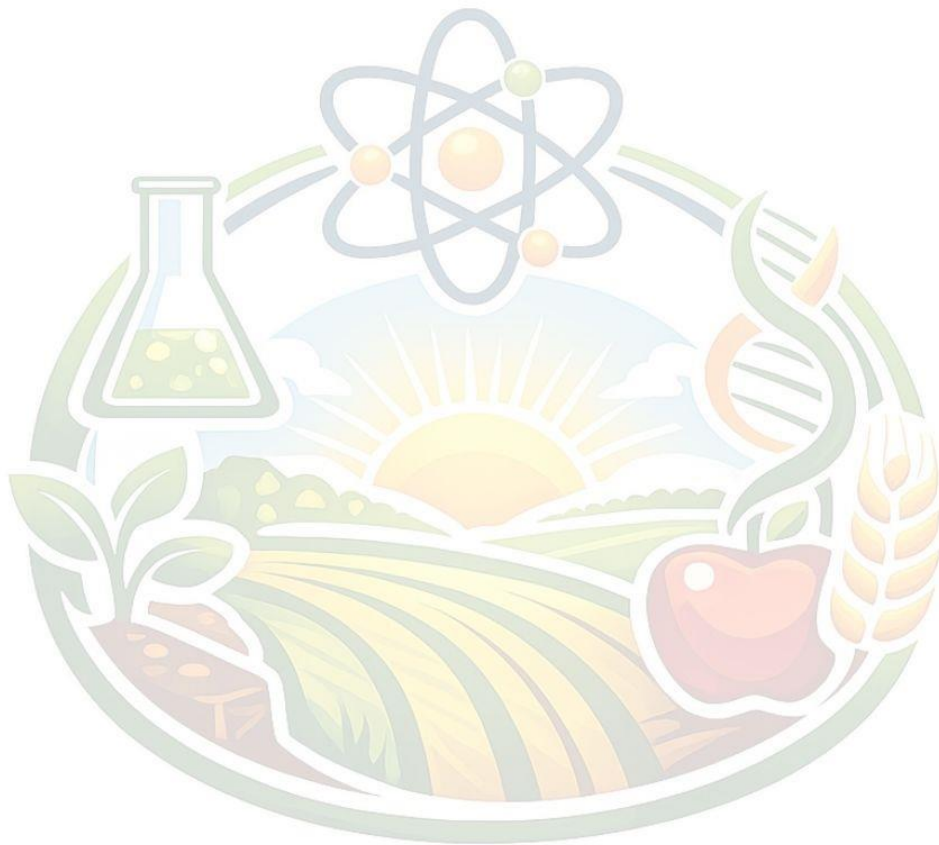
Conclusion

Complementary benefits are provided by traditional agrometeorological services and satellite-based early warning systems. Traditional services offer local interpretation, crop-specific recommendations and direct farmer communication, while satellite systems provide wide spatial coverage, frequent monitoring and early detection of agricultural stress (Funk et al., 2015; Rembold et al., 2019). The combination of both approaches can result in greater benefits for smallholder farmers. Satellite data can identify risk areas, ground observations can validate the signals, experts can interpret them and extension networks can disseminate practical advice. A hybrid system like this can improve the timeliness, reliability, accessibility, and utility of agrometeorological information and strengthen climate risk management among smallholder farmers in India (Rathore et al., 2025; Singh et al., 2023).

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Polyploidy as a Genetic Resource for Climate Resilient Crop Breeding

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Whole-genome duplication, the process by which an organism comes to possess more than two complete sets of chromosomes, has long been recognized as one of the most significant forces in plant evolution. The condition, known as polyploidy, is not a rare curiosity confined to a handful of species; it is estimated that nearly all flowering plants have undergone at least one round of genome duplication at some point in their evolutionary history. Among cultivated crops, the phenomenon is especially pronounced: bread wheat, cotton, potato, banana, sugarcane, and strawberry are all polyploid, carrying multiple copies of their genome inherited either from within a single species or from the merger of two or more distinct species. As the pressures of climate change intensify, researchers are increasingly examining polyploidy not merely as an evolutionary artifact, but as an active genetic resource that can be deliberately harnessed to breed crops capable of withstanding drought, heat, salinity, and other forms of environmental stress.

The renewed interest in this area reflects a broader recognition that conventional diploid breeding, while effective, draws on a comparatively narrow genetic and regulatory toolkit. Polyploid genomes, by contrast, offer redundancy, flexibility, and evolutionary novelty that diploid genomes generally lack. Understanding how these properties arise, and how they can be captured through breeding, has become a central question in efforts to secure the resilience of global food production.

Genetic Redundancy as a Buffer Against Stress

One of the most direct advantages conferred by polyploidy is genetic redundancy. Where a diploid plant carries only two copies of each gene, a polyploid plant may carry four, six, or more. This additional redundancy means that if one gene copy is damaged by mutation, environmental stress, or pathogen attack, the remaining copies can continue to perform the gene's function, allowing the plant to maintain normal growth and metabolism under conditions that might otherwise prove disruptive. This buffering effect is thought to be a central reason why many polyploid species, both wild and cultivated, exhibit broader ecological tolerances and are able to colonize a wider range of environments than their diploid relatives.

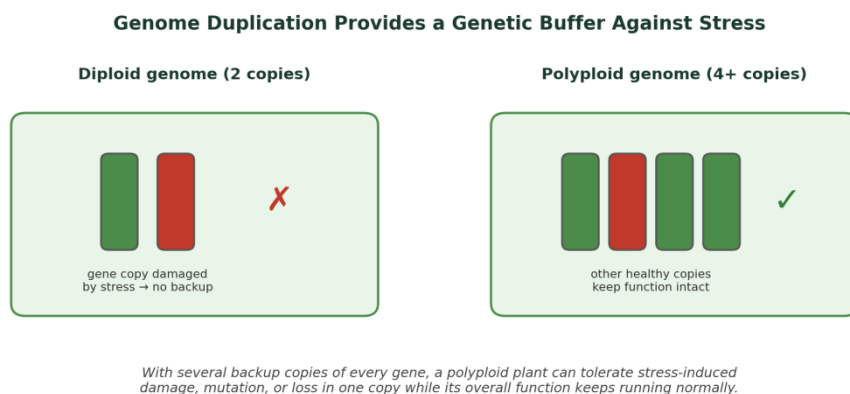


Figure 1. In a diploid genome, damage to a single gene copy has no backup. In a polyploid genome, additional copies of the same gene continue to function normally, buffering the plant against the effects of stress-induced damage.

Allopolyploidy and the Creation of Novel Genetic Combinations

A particularly consequential form of polyploidy, known as allopolyploidy, arises when two distinct species hybridize and their combined genome subsequently doubles, producing a new, stable, and fertile species that carries complete chromosome sets from both parental lineages. Bread wheat is among the most well-documented examples of this process: a diploid wild wheat relative first hybridized with a diploid wild goatgrass to produce tetraploid emmer wheat, which subsequently hybridized with a further wild goatgrass relative and underwent a second genome doubling to yield hexaploid bread wheat, carrying six complete sets of chromosomes drawn from three distinct ancestral genomes.

This layered evolutionary history is significant because it brought together, within a single species, distinct sets of genes and regulatory sequences that had evolved independently under different environmental pressures. The resulting genome possesses a considerably expanded capacity for adaptive regulation, since each of the merged subgenomes can respond somewhat independently to environmental cues while also compensating for one another. Researchers studying allopolyploid cotton have documented that subsequent to such genome mergers, extensive regulatory reprogramming occurs, involving structural genomic rearrangement, functional diversification of duplicated genes, and alterations to the epigenetic landscape, all of which contribute to the enhanced stress resilience frequently observed in allopolyploid crops.

How Hybridization and Genome Doubling Built Bread Wheat

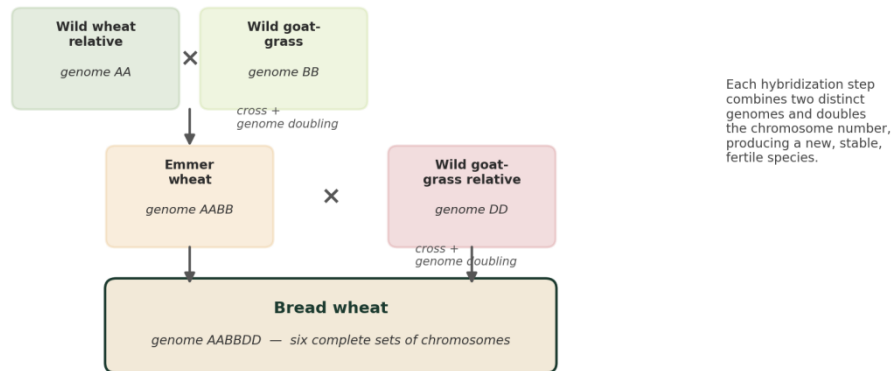
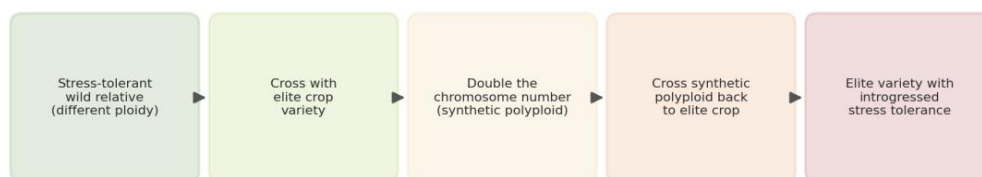


Figure 2. Bread wheat arose through two successive rounds of hybridization and genome doubling, combining genetic material from three distinct wild grass lineages into a single, stable hexaploid species.

Synthetic Polyploids as a Breeding Bridge

Beyond studying naturally occurring polyploids, breeders have developed methods for deliberately inducing polyploidy to move valuable traits between species that could not otherwise be crossed. When two species of differing ploidy are hybridized directly, the resulting offspring is frequently sterile, since mismatched chromosome sets cannot pair correctly during reproduction. By artificially doubling the chromosome number of such a hybrid, typically through chemical treatment during early development, breeders can restore fertility and create what is termed a synthetic polyploid. This synthetic polyploid can then serve as a fertile intermediary, or breeding bridge, permitting genes for drought tolerance, salinity tolerance, or heat tolerance present in a wild relative to be introduced into the gene pool of a cultivated elite variety through subsequent rounds of crossing.

Using a Synthetic Polyploid as a Breeding Bridge



The synthetic polyploid acts as a fertile "bridge" between two species that could not otherwise be crossed directly, allowing stress-tolerance genes to move into the elite crop's gene pool.

Figure 3. A synthetic polyploid, created by doubling the chromosome number of a wild-elite hybrid, restores fertility and provides a bridge through which stress-tolerance genes can be introgressed into an elite crop variety.

Phenotypic Plasticity and Environmental Adaptability

In addition to genetic redundancy, polyploid plants frequently display greater phenotypic plasticity, meaning that a single genotype is capable of producing a wider range of physical and physiological responses depending on the environmental conditions it encounters. This plasticity has been linked to variation in traits such as leaf anatomy,

stomatal size and density, and canopy architecture, all of which influence how efficiently a plant manages water loss and carbon uptake under drought or elevated temperature. Because these traits often differ measurably between diploid and polyploid individuals of the same species, researchers have proposed that manipulating ploidy level, whether through natural variation or induced polyploidization, represents a practical route toward improving a crop's physiological resilience to a changing climate.

Challenges of Breeding at Higher Ploidy Levels

Despite these advantages, breeding polyploid crops presents distinct technical challenges that do not arise, or arise less acutely, in diploid systems. Polyploid genomes do not always follow the simple inheritance patterns familiar from diploid genetics: autopolyploids exhibit polysomic inheritance, in which chromosomes from more than two homologous sets can pair and recombine during reproduction, while allopolyploids typically show disomic inheritance complicated by interactions between subgenomes. This complexity makes it considerably more difficult to track and fix a desired trait through successive breeding generations. Vegetatively propagated polyploid crops, including potato, banana, and sugarcane, face an additional obstacle, since their reliance on clonal propagation rather than seed limits the extent to which conventional crossing can be used to introduce new traits at all, increasing reliance on genome editing and transgenic approaches instead.

Nevertheless, the accelerating availability of high-quality reference genomes and pangenomes for polyploid crops and their wild relatives is steadily reducing these barriers. As researchers develop increasingly sophisticated tools for navigating polyploid genomes, breeding strategies once considered impractical, including precise editing of individual gene copies within a redundant set, are becoming achievable. Taken together, genetic redundancy, hybrid genomic novelty, synthetic polyploid bridging, and expanding technical capability position polyploidy as one of the more promising, if underexploited, avenues for building the climate-resilient crops that global food security will increasingly depend upon.

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Steel Waste to Soil Wealth: The Agricultural Potential of Linz-Donawitz Slag

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Abstract

Linz-Donawitz (LD) slag, a major by-product of steel production, is increasingly gaining attention as a potential agricultural resource. Rich in calcium, silicon and other beneficial elements, it can improve acidic soils, supply nutrients, enhance crop growth, immobilize toxic metals and potentially reduce greenhouse-gas emissions. However, concerns regarding heavy metals, over-liming, soluble salts and processing costs require careful management. With appropriate processing, soil-test-based application and monitoring, LD slag offers an opportunity to convert industrial waste into a valuable input for sustainable and circular agriculture.

Keywords: Agriculture; LD slag; Liming material; Soil amendment; Steel industry.

Introduction

Every tonne of steel India makes leaves behind a mountain of grey, glassy rock byproduct called steel slag. The largest single source of it comes from the Linz-Donawitz (LD) or basic oxygen furnace (BOF) steel making process of integrated steel plants. The steel slag generated through the LD process is called LD slag. For decades this by-product was simply dumped, occupying land and leaching into water bodies. Today, a growing agronomic research is turning that story around, LD slag is emerging as a low-cost liming agent, a silicon and calcium fertiliser, a tool against toxic-metal contamination, and reduces greenhouse-gas emissions from rice fields.

Synthetic Polyploids as a Breeding Bridge

Beyond studying naturally occurring polyploids, breeders have developed methods for deliberately inducing polyploidy to move valuable traits between species that could not otherwise be crossed. When two species of differing ploidy are hybridized directly, the resulting offspring is frequently sterile, since mismatched chromosome sets cannot pair correctly during reproduction. By artificially doubling the chromosome number of such a hybrid, typically through chemical treatment during early development, breeders can restore fertility and create what is termed a synthetic polyploid. This synthetic polyploid can then serve as a fertile intermediary, or breeding bridge, permitting genes for drought tolerance, salinity tolerance, or heat tolerance present in a wild relative to be introduced into the gene pool of a cultivated elite variety through subsequent rounds of crossing.

What is LD Slag?

The Linz-Donawitz process (named after the two Austrian towns where it was pioneered) is the oxygen-blowing technique used in basic oxygen furnaces to convert molten pig iron into steel. Lime (CaO) or dolomitic lime is charged into the furnace along with molten metal or scrap, and high-pressure oxygen is lanced in. The oxygen strips carbon and other impurities out of the iron, and these oxidised impurities combine with the lime to float as a liquid layer on top of the steel. Once the steel is tapped off, this residual liquid (furnace or tap slag, raker slag, and ladle slag, depending on where in the process it is skimmed) is cooled, crushed, and stockpiled (Chand et al., 2015). The schematic representation of the Basic-Oxygen Furnace/LD steelmaking process is shown in **Figure 1**.

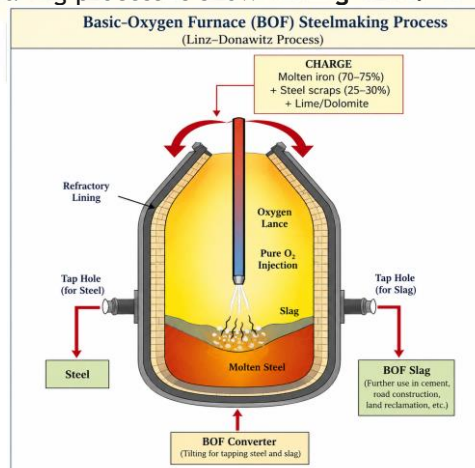


Figure 1. The Basic-Oxygen Furnace/LD steelmaking process (Source: modified from Yildirim & Prezzi, 2011)

Chemically, LD slag consists of calcium oxide, silicon dioxide, iron oxides, magnesium oxide, aluminium oxide, manganese oxide, and phosphorus pentoxide. The chemical composition of LD/BOF steel slag has shown in Table 1.

Table 1. Typical chemical composition of LD/BOF steel slag:

	CaO	SiO ₂	FeO & Fe ₂ O ₃	MgO	Al ₂ O ₃	MnO	P ₂ O ₅
LD/BOF slag (%)	45-60	10-15	24-28	3-13	1-5	2-6	1-4

Source: Singh et al. (2013)

Global crude steel production attained 1.85 billion tonnes and roughly 257.9 million tonnes of slag are generated in 2025 with the share of 62.8% being BOF slag (Harder, 2026). The mineral phases within it include dicalcium silicate, tricalcium silicate, calcium-iron-magnesium, and free lime. These phases govern how slag behaves once it is applied on a field.

The Indian Scenario

India's steel plants generate an estimated 150-180 kg of LD slag for every tonne of crude steel produced (Yadav et al., 2002). The steel slag production in the country is around 19 MT per annum. However, only around 25% of this slag is currently reused within India, compared with 70-100% recycling rates achieved in steel-producing nations such as Japan and Germany (Umadevi et al., 2010).

The remaining sits in storage yards, occupying land that could otherwise support cultivation and posing a long-recognised pollution risk. Recognising the potential, the Government of India formally notified that LD slag could be used as a soil conditioner once crushed, washed, and blended with rock phosphate. In India, Tata steel launched Growell, an enriched LD-slag-based soil conditioner which reported a yield increase of more than 25% in acidic soils (Chand et al., 2015).

Processing LD Slag for Agricultural Use

Raw slag straight from the furnace is unsuitable for direct field application. It must first be aged/weathered, crushed, and screened to remove tramp metal and to reduce the free-lime content that can otherwise cause structural instability. The powdered slag after processing is shown in Figure 2. For liming purposes, agronomic guidelines recommend that at least 90% of the material pass through a 20-mesh sieve (US standard). Compared with agricultural lime, slag is denser (bulk density 1.6-1.9 g/cm³ for slag and 1.4-1.5 g/cm³ for lime) and more reactive, so dosing is normally calibrated against a soil acid-buffer test rather than applied by rule of thumb.



Figure 2. The powdered slag after processing

Advantages of LD Slag Usage in Agriculture

1. Acidic soil reclamation: The presence of calcium and magnesium silicates in LD slag hydrolyse in soil water, releasing hydroxide ions that neutralise acidity much as agricultural lime does, while also releasing plant-available silicon. Field trials in northern Spain found that 7,500 kg of slag per hectare lifted pasture soil pH from 5.3 to 6.4, with an even larger response of a 41% pH increase in the following season at a lower dose of 3,000 kg per ha. Recommended application rates for Indian conditions generally fall between 1.5 and 5.0 tonnes per hectare depending on soil type and crop (Chand et al., 2015).

2. A source of plant nutrients: Beyond liming, slag supplies calcium, magnesium, silicon, phosphorus, iron and manganese nutrients that are often deficient in the same acidic, weathered soils that need liming in the first place. Because slag is low in nitrogen and potassium, studies suggest using it alongside conventional NPK fertilisers rather than as a stand-alone input.

3. Raising yields and strengthening crops: Silicate slag fertilisers have boosted submerged rice yields by up to 47.3% in some studies (Ali et al., 2009), largely because silicon deposited in cell walls makes plants more resistant to lodging, drought, salinity and fungal disease including brown spot. In a more recent Indian trial, combining LD slag (2 t/ha) with

biochar (1 t/ha) raised wheat leaf area, chlorophyll content and photosynthetic rate, delivering 25-27% higher yield than recommended dose of fertilizer alone (Pooja et al., 2024).

4. Taming toxic metals: Counter-intuitively, a material that itself contains trace heavy metals can reduce metal contamination risk elsewhere. Slag's silicates, iron oxides and hydroxide ions immobilise cadmium, arsenic, lead and chromium through adsorption, precipitation and ion exchange, making them less available for plant uptake. A study conducted in cadmium contaminated paddy soil shows that the slag application cut cadmium concentrations by 40% in rice roots and 38% in shoots (Liu et al., 2020) and in copper-contaminated sandy soil, phosphorus-spiked LD slag both raised soil pH and lowered foliar copper below toxic thresholds while still allowing normal bean growth.

5. Reducing greenhouse gas emissions: Because slag is rich in reactive iron, it favours iron-reducing bacteria that outcompete the methane-producing archaea in flooded rice soils. Field studies across Bangladesh, China, Japan, Indonesia and Korea report methane reductions of 0.6% to 56% depending on soil type, slag composition and dose, while silicate fertiliser under intermittent irrigation has cut nitrous oxide emissions by up to 99% in China. Slag-biochar combinations have also been shown to raise soil organic and microbial-biomass carbon, pointing to a secondary role in soil carbon storage (Mahadev et al., 2025).

Barriers of LD Slag Usage in Agriculture

1. Heavy metal load: Steel slag carries chromium, vanadium, nickel and lead at levels far higher than agricultural soils, reported at up to roughly 1,700 mg/kg chromium(III) in metallic slag fractions. Most of this remains bound within the slag matrix. The toxicity characteristic leaching procedure (TCLP) tests found chromium leachate concentrations of only 0.003-0.004 mg/L, and soils amended with up to 10 tonnes per acre showed only small, non-hazardous increases in extractable chromium (Chand et al., 2015). However, long-term, high-dose use warrants periodic soil and crop testing.

2. Over-liming: Slag's equilibrium pH of around 12.5 is far more alkaline than limestone pH of 8.25. Consequently, excessive application can push soils too alkaline, locking up phosphorus, iron, copper and zinc. The application rate should always be based on an acid-buffer soil test rather than a flat rate.

3. Soluble salts: The calcium and magnesium hydroxides in LD slag are considerably more water-soluble than limestone, giving fine and coarse slag electrical conductivities of roughly 2.5-3.7 dS/m in a study conducted in US which is within the tolerance of most crops (up to about 4 dS/m) at normal agronomic rates, but worth monitoring at the higher doses used in mine-land or landfill reclamation.

4. Economics and logistics: Slag is bulky, must be transported, crushed and screened, and currently commands a low market value relative to its processing cost. A challenge that includes wider adoption, alongside the need for clearer regulatory standards.

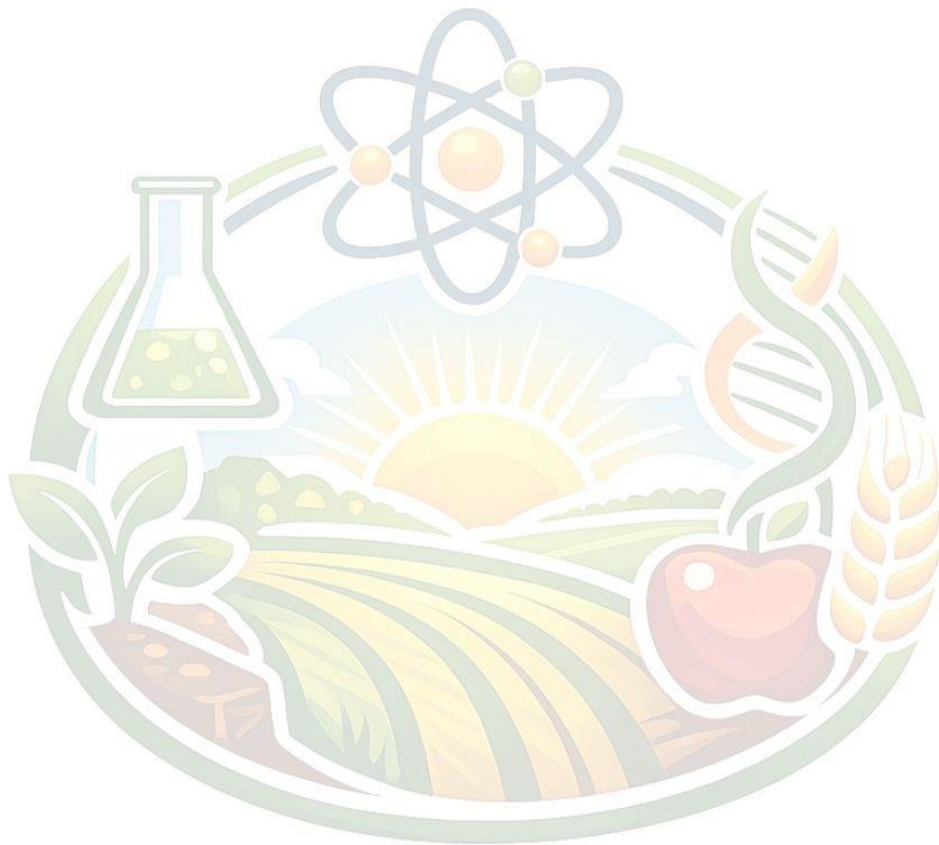
Conclusion

LD slag has considerable potential to transform an industrial by-product into a valuable agricultural resource. Its benefits in improving acidic soils, supplying nutrients, enhancing crop growth, immobilizing toxic metals and reducing greenhouse-gas emissions make it promising for sustainable agriculture. However, its safe use requires proper processing, soil-test-based application and monitoring of heavy metals and soil properties. Under Indian conditions, further multilocal field trials across diverse soil types, agro-climatic regions and cropping systems are needed to validate its agronomic effectiveness and safety. Studies involving multiple crops and long-term applications are also essential to determine crop-specific responses, appropriate application rates and possible cumulative effects. Such research will help establish reliable recommendations and regulatory guidelines for the wider adoption of LD slag in Indian agriculture.

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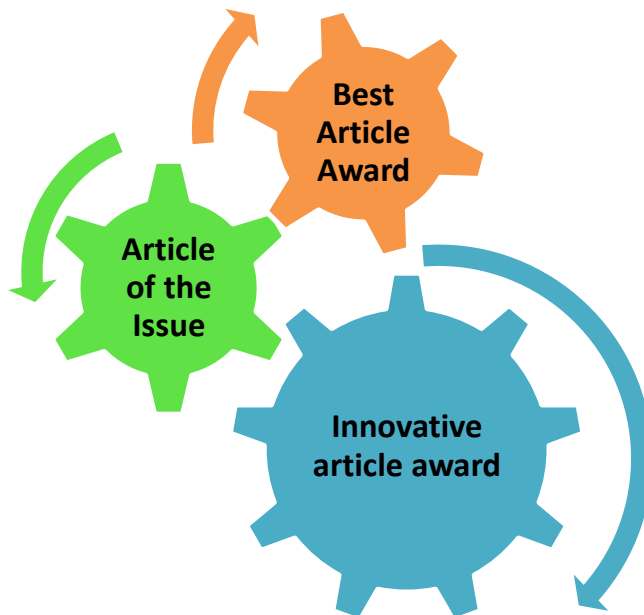
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