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AGRICULTURAL WASTE: FROM FARM WASTE TO BIOFUEL WEALTH

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Abstract

Agricultural waste is produced in bulk after the harvesting of crops like rice, groundnut, wheat, sugarcane, maize and cotton. Most of these agricultural wastes are used as fodder and compost but a significant amount is underutilized and is disposed of by open field burning that leads to environmental pollution and loss of resources which can be utilized. Simultaneously the energy demands are increasing everyday due to depletion of the fossil fuel reserves, increased emission of greenhouse gases that have led to the need of renewable and alternative sources of energy. Agricultural waste are rich lignocellulosic feedstocks that can be converted to biofuels like biohydrogen, bioethanol and biogas and other value added biochemicals by the biorefinery approach. The effective utilization of these agricultural waste addresses the challenge of waste management contributing to reduction in carbon emission, energy security, rural development and mitigation of climate change. New developments in the biomass conversion techniques in India have integrated with government policies and initiative for biofuels to speedup the development of industries that based on biomass. This article focuses on the characteristics of the agricultural waste and their potential for the production of biofuel, emerging technologies and their role in leading a circular bioeconomy.

Keywords: Agricultural waste, Bioethanol, Biomass, Bioenergy, Sustainability

Introduction

India is the richest country in terms of agricultural resources and currently produces 350 tonnes of agricultural waste. The largest portion of this waste is occupied by the solid waste like paddy, sugarcane bagasse, wheat husk and straw, groundnut shell, jute fibers, coconut husk, cotton stalk and waste from tea and oil production like oil seed cakes (Maji *et al*., 2020). The annual production and the chemical composition of these wastes are mentioned in the table 1. Different types of agricultural biomasses are being utilized in the production of first and second generation of biofuels as they are renewable in nature with high feasibility to be used as a precursor in these industries (Dai *et al*., 2020). The agricultural biomass gets converted into sugars by pretreatment and hydrolysis which are energy intensive processes resulting in high costs. Depending on their source of production the agricultural waste can be of four types: 1) Crop waste: barley, wheat, oats and rice straw, cotton stalk, 2) Industrial processing waste: sugarcane bagasse, rice husk, seed cakes, orange peels, rice bran, amla and apple pomace, 3) Livestock waste: animal fat, cattle manure and swine manure and 4) Food waste that comes from banana peels mango peels and seeds, cabbage. lettuce (Pattanaik *et al*., 2019).

Table 1: Chemical Composition and Annual Production of Agricultural Wastes

Agricultural Waste	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Annual Production (MT/Year)	Reference
Banana Leaves	26.1	17	25	233	Reddy and Yang 2015

Agricultural Waste	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Annual Production (MT/Year)	Reference
Corn Husk	31-39	34-41	2-14	64	Mendes *et al*., 2015
Rice Husk	32-47	19-27	5-24	10	Belal 2013
Bagasse	32-44	27-32	19-24	39	Hernández-Salas *et al*., 2009
Groundnut Shell	35.7	18.7	30.7	11.10	Raju *et al*., 2012

Underutilization of agricultural waste

India being agriculture centric country generates huge quantity of agricultural waste majorly from sugarcane, wheat, cotton, oilseeds, maize and rice. States like Rajasthan, Punjab, Uttar Pradesh and Haryana face problems in managing their agricultural waste due to huge cereal cultivation. Large amounts of bagasse and sugarcane waste is generated in sugarcane growing states like Karnataka, Uttar Pradesh and Maharashtra. Though all these agricultural waste hold enormous potential but they remain underutilized as open burning still takes place which is considered as a speedy method of clearing fields before the next cropping season. This open field burning releases huge quantities of carbon dioxide, nitrous oxide, particulate matter, methane and other pollutants into the atmosphere that leads to health hazard and smog formation during winters. In order to recognize the value of these agricultural waste Government of India has introduced several initiatives which are focused on the promotion of agricultural waste utilization for the generation of energy, biofuels production and production of biogas.

Biofuel Production

Bioethanol production

Bioethanol has become one of the most common fuel that has found a huge place by being blended with petrol. Unlike the first-generation fuels that were produced from sugar crops this fuel is made from agricultural waste which are lignocellulosic in nature means they have lignin, cellulose and hemicellulose. Production of bioethanol requires four main steps: Pretreatment which helps in the removal of lignin makes cellulose accessible and it can be done by physical, chemical, biological and physiochemical approaches, Hydrolysis leads to the breakdown of cellulose and hemicellulose into simpler sugars like xylose and glucose that can be fermented, Fermentation that uses the simpler sugar for the production of bioethanol with the help of *Saccharomyces cerevisiae* and *Zymomonas mobilis* and distillation which separates pure fuel grade bioethanol.

Biogas Production

Biogas is a mixture of gas produced by anaerobic digestion of agricultural waste by microorganisms. Anaerobic digestion is a biochemical process in which bacteria is used that breaks down organic matter in a oxygen free environment producing H_2, CH_4, CO_2 and some other gases and decomposed biomass which can be used as a fertilizer. During the process of production, the organic content of the agricultural waste is broken down to amino acids, sugar and alcohol by acid producing bacteria. The whole process consists of three major processes: Hydrolysis, Acid formation and Methane formation. In the process of hydrolysis organic molecules of proteins, fats and starch break down into simpler compounds by the enzyme produced by bacteria due to this it is also known as the polymer breakdown stage. The simpler compounds are fermented under anaerobic conditions in the acid formation stage that leads to the formation of different acids like acetic acid, butyric acid and propionic acid. The acetic acid produced is converted into methane and carbon dioxide by microbes named as methanogens which are obligate anaerobes and sensitive to environment changes. Methanogens use the products of the acid forming stage and convert them into methane, carbon dioxide and water. This whole process leads to the production of methane which is used as biogas in heating, cooking, electricity production and as compressed biogas.

Biohydrogen Production

Biohydrogen has come up as a clean renewable source of energy due to its high yield and environment friendly combustion as it produces water as a by-product. Agricultural waste has complex carbohydrates that can be converted into simpler sugars by pretreatment and hydrolysis and fermented by microbes to produce hydrogen through their biological routes like dark fermentation, microbial electrolysis and photo-fermentation. Amongst all the biological routes dark fermentation has attracted more attention due to its simplicity, potential to use wide range of agricultural biomass and reduced energy needs. Although there are issues faced with biomass recalcitrance, process optimization and lower hydrogen yields there are developments in the pretreatment technologies, microbial engineering and integrated biorefinery approaches that enhance the commercial feasibility of agriculture residue based biohydrogen production as it contributes to the reduction of greenhouse gas emission, waste valorization and development of circular bioeconomy approach.

India's Bioenergy Potential

India is focused on developing its bioenergy resources in order to provide affordable energy to reduce the imports of fossil fuel, reducing greenhouse gas emissions and improving air quality. Modern bioenergy accounts for 13% total energy consumption of India and is expected to increase by 45% till 2030. These long-term bioenergy ambitions require the use of new technologies and practices to collect and convert its huge agriculture residue production into biofuels. India is recognized as the fastest bioenergy market globally accounting for more than third of global bioenergy demand with the help of targets like 5% biodiesel blending by 2030, 5% compressed biogas blending by 2028, 20-30% bioethanol blending by 2026, 7% co-firing solid biomass in coal power plants by 2026 and 2% bio jet blending for internation flights by 2028.

There are four action areas which can diversify sustainable bioenergy production like phasing out traditional use of bioenergy to improve the modern access to energy, a detailed understanding of the biomass available and their utilization in the production of biofuels, co-ordination with the bioenergy initiatives and preparation of greenhouse gas based standards.

Indian Initiative for Biofuel Production from Agricultural Waste

The government of India has implemented several programs to enhance the biofuel adoption focusing on biodiesel, biogas and bioethanol. Some of the key policies are mentioned below:

National Bio-Energy Mission

The National Bio-Energy Mission has been enhanced by the Ministry of New and Renewable Energy supports biofuel producers in the country. This initiative focused on providing substantial financial aids and regulatory support for companies setting up production plants for biofuel production. Along with that the government is encouraging public private partnership in order to drive innovation and research in development of advanced biofuels.

Ethanol Blending Programme

The market of bioethanol in India is increasing due to accomplishment of the ethanol blending targets. Government of India was able to blend 20% bioethanol in 2025 significantly reducing the dependence on crude oil imports. The key updates of this programme are giving higher financial aids to sugar mills to produce bioethanol from maize and sugarcane, increasing financial assistance for second generation ethanol plants using agricultural waste, waiving off taxes and excise duty for companies dealing in ethanol production and distribution, and easy process of licensing and reducing the burdens of compliance from small scale bioethanol producers.

Biodiesel Production and Promotion

The production of biodiesel in India has been incentivized through different measures which are aimed at increasing the domestic production reducing dependence on fossil fuel imports. The government has introduced subsidized to setup biodiesel refineries using non-edible oil sources like Jatropha, mandating minimum blending of biodiesel in diesel fuels, granting financial assistance to companies that are working in the development of advanced biodiesel production systems from algae and waste to energy projects and finally strengthening the supply chain infrastructure like dedicated transport corridors and well-established storage facilities (Government Policies & Subsidies in 2025 for Biofuel Production in India).

Economic benefits and Challenges

The conversion of agricultural waste into biofuels offers several economic benefits like its helps farmers to generate additional incomes by selling agricultural waste after harvest which can enhance rural livelihoods and farm profitability instead of discarding and burning that waste. Biofuel industries create employment options in collection of agricultural waste their transportation, processing and marketing. These industries will also stimulate rural industrialization and development of infrastructure reducing dependance on fossil fuel imports and strengthening the national energy security thereby reducing expenditure on foreign exchange.

Despite the enormous potential and benefits the utilization of agricultural waste still faces some challenges that hinder their large-scale adoption for biofuel production as high costs are related to their collection and transportation, issues related to seasonal availability and storage, barriers in pretreatment and processes of conversion and constraint related to investment. Future research and efforts need to be focused on developing cost effective conversion technologies, use of genetic engineering for enhancing microbial strains used in the production of enzymes, adoption of advanced biorefineries and improved supply chains. To realize the full potential of agricultural waste converting them to biofuels needs help from government, public-private partnership and technological development that will foster the growth of this sector.

Conclusion

Agricultural waste is India's most abundant and underutilized renewable resources which should not be viewed as waste as they can serve as valuable feedstock for biofuel production. Their effective utilization can offer sustainable solution to the management of agricultural waste while producing renewable energy, rural development, energy security and environmental protection. The rapid growth seen in the India's biofuel industry coupled with the development conversion technologies providing an opportunity to transform agricultural waste into economic wealth. By adopting approaches of integrated biorefinery and strengthening government policies for support India can significantly convert farm waste into biofuel advancing towards sustainable circular bioeconomy.

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DIGITAL TRANSFORMATION IN FISHERIES RESOURCE MANAGEMENT: APPLICATIONS OF GIS, REMOTE SENSING, AND ARTIFICIAL INTELLIGENCE

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Abstract

The fisheries and aquaculture sectors are increasingly adopting digital technologies to improve resource management, productivity, and sustainability. Geographic Information Systems (GIS), Remote Sensing (RS), and Artificial Intelligence (AI) have emerged as important tools for modern fisheries management by enabling real-time monitoring, spatial analysis, predictive modeling, and data-driven decision-making. GIS facilitates habitat mapping, marine spatial planning, and aquaculture site selection, while remote sensing provides satellite-based information on sea surface temperature, chlorophyll concentration, and oceanographic conditions for identifying Potential Fishing Zones (PFZs) and monitoring marine ecosystems. Artificial Intelligence further enhances fisheries management through fish stock prediction, automated monitoring, disease diagnosis, and smart aquaculture systems. The integration of these technologies supports precision fisheries management, biodiversity conservation, climate resilience, and sustainable utilization of aquatic resources. Despite challenges related to infrastructure, technical expertise, and data accessibility, digital transformation offers significant opportunities for improving fisheries governance and ensuring long-term sustainability of the fisheries and aquaculture sectors.

Introduction

Fisheries and aquaculture play a crucial role in global food security, nutrition, employment generation, and economic development. According to the Food and Agriculture Organization (FAO), fisheries contribute significantly to the livelihoods of more than 600 million people worldwide and provide an important source of animal protein for billions of consumers (FAO, 2022). However, rapid population growth, overexploitation of fish stocks, climate change, habitat degradation, pollution, and illegal fishing activities have created serious challenges for sustainable fisheries resource management. Traditional fisheries management approaches often rely on manual surveys, limited datasets, and delayed decision-making processes, which are insufficient to address the increasing complexity of aquatic ecosystems. In recent years, digital transformation has emerged as a revolutionary approach for improving fisheries governance and resource management. Advanced technologies such as Geographic Information Systems (GIS), Remote Sensing (RS), Artificial Intelligence (AI), Internet of Things (IoT), and big data analytics are increasingly being integrated into fisheries and aquaculture sectors to support data-driven and real-time decision-making. These technologies facilitate accurate monitoring, forecasting, mapping, and assessment of fishery resources, thereby enhancing productivity and sustainability. Geographic Information Systems (GIS) have become valuable tools for spatial analysis and resource mapping in fisheries management. GIS enables the integration of environmental, biological, and geographical data for habitat suitability analysis, coastal zoning, fish distribution mapping, and aquaculture site selection (Meaden and Kapetsky, 1991). Similarly, remote sensing technologies provide satellite-derived information on sea surface temperature (SST), chlorophyll concentration, ocean currents, and coastal ecosystem dynamics, which are essential for identifying Potential Fishing Zones (PFZs) and monitoring marine environmental changes (Klemas, 2013). Artificial Intelligence (AI) and machine learning technologies are further transforming fisheries management through predictive analytics, automated fish species identification, disease diagnosis, stock assessment, and smart aquaculture systems. AI-driven tools can analyze large volumes of environmental and fisheries data with greater speed and accuracy, supporting sustainable harvesting practices and reducing operational risks (Allken *et al*., 2019). The integration of GIS, remote sensing, and AI technologies offers immense potential for precision fisheries management, ecosystem conservation, and climate-resilient aquaculture development. Therefore, the present article highlights the role of digital transformation technologies, particularly GIS, remote sensing, and AI, in modern fisheries resource management and discusses their applications, benefits, challenges, and future prospects for sustainable fisheries development.

Role of GIS and Remote Sensing in Fisheries Resource Management

Geographic Information Systems (GIS) and Remote Sensing (RS) technologies have revolutionized modern fisheries resource management by enabling efficient monitoring, assessment, and sustainable utilization of aquatic resources. These advanced geospatial technologies provide accurate spatial and environmental information that supports scientific decision-making, ecosystem monitoring, and fisheries planning. GIS is a computer-based analytical system used for capturing, storing, integrating, analyzing, and visualizing geographically referenced data (Meaden & Aguilar-Manjarrez, 2013). In fisheries management, GIS plays a crucial role in habitat mapping, aquaculture site selection, coastal resource assessment, and marine spatial planning. It integrates diverse datasets, including water quality parameters, bathymetry, climatic variables, fish distribution, and biodiversity information, into a single platform for comprehensive analysis. GIS-based models help identify suitable fish breeding, spawning, and nursery grounds by evaluating environmental factors such as temperature, salinity, dissolved oxygen, and substrate composition. Furthermore, GIS supports the management of coastal ecosystems such as mangroves, estuaries, wetlands, and coral reefs, which are essential for maintaining fisheries productivity and biodiversity (Kapetsky and Aguilar-Manjarrez, 2007).

Remote sensing complements GIS by providing large-scale and real-time environmental data through satellite and aerial observations. Satellite-derived information on Sea Surface Temperature (SST), chlorophyll-a concentration, ocean color, turbidity, and ocean currents is extensively utilized in fisheries resource assessment and marine ecosystem monitoring. One of the most important applications of remote sensing is the identification of Potential Fishing Zones (PFZs), where favorable environmental conditions promote high fish abundance. PFZ advisories generated using SST and chlorophyll data help fishers reduce fuel consumption, minimize search time, and improve catch efficiency (Solanki *et al*., 2005). In addition, remote sensing technologies are widely applied in monitoring harmful algal blooms (HABs), coastal pollution, sediment transport, habitat degradation, and climate change impacts on marine ecosystems. Satellite systems such as MODIS, Sentinel, Landsat, Oceansat, NOAA-AVHRR, and INSAT provide continuous oceanographic information essential for sustainable fisheries management. In India, the Indian National Centre for Ocean Information Services (INCOIS) effectively utilizes satellite-based remote sensing data to disseminate PFZ advisories and ocean state forecasts for supporting the fishing community. The integration of GIS and remote sensing has significantly enhanced precision fisheries management by enabling real-time monitoring, spatial analysis, and ecosystem-based management approaches (Table 1). These technologies contribute to sustainable harvesting practices, biodiversity conservation, climate-resilient fisheries development, and evidence-based policy formulation, thereby ensuring long-term sustainability of fisheries resources worldwide.

Table 1. Applications of GIS, Remote Sensing, and Artificial Intelligence in Fisheries Resource Management

Technology	Major Applications	Benefits in Fisheries Management
Geographic Information System (GIS)	Habitat mapping, aquaculture site selection, coastal resource assessment, marine spatial planning	Improved spatial analysis, sustainable resource utilization, ecosystem conservation
Remote Sensing (RS)	Potential Fishing Zone (PFZ) identification, sea surface temperature monitoring, chlorophyll analysis, harmful algal bloom detection	Real-time environmental monitoring, improved fishing efficiency, reduced fuel consumption
Artificial Intelligence (AI)	Fish stock prediction, disease diagnosis, automated feeding systems, fish species identification	Precision aquaculture, improved productivity, predictive decision-making
GIS + RS + AI Integration	Smart fisheries management, ecosystem monitoring, climate-resilient fisheries planning	Real-time monitoring, sustainable fisheries governance, enhanced policy formulation

Role of Artificial Intelligence in Fisheries Resource Management

Artificial Intelligence (AI) has emerged as a transformative technology in modern fisheries and aquaculture management by enabling intelligent data analysis, automation, and predictive decision-making. AI technologies, including machine learning, deep learning, computer vision, and neural networks, are increasingly being utilized to improve fisheries productivity, resource assessment, disease management, and environmental monitoring. The integration of AI into fisheries management supports precision aquaculture and promotes sustainable utilization of aquatic resources. One of the major applications of AI in fisheries is fish stock assessment and prediction. AI-based models can analyze large volumes of oceanographic, climatic, and fisheries data to estimate fish abundance, migration patterns, and seasonal distribution with high accuracy. Machine learning algorithms help identify trends in fish population dynamics and support sustainable harvesting strategies, thereby reducing the risk of overfishing and resource depletion (Allken *et al.*, 2019). AI is also widely applied in aquaculture systems for real-time monitoring and automation. Smart aquaculture technologies utilize AI-enabled sensors and IoT devices to continuously monitor water quality parameters such as temperature, pH, dissolved oxygen, salinity, and ammonia levels. These systems provide early warning signals and automated responses to maintain optimal culture conditions, improving fish health and production efficiency. AI-driven automatic feeding systems further optimize feed utilization, reduce feed wastage, and minimize operational costs.

Computer vision and deep learning technologies have significantly improved fish species identification, biomass estimation, and behavioral analysis. AI-powered underwater cameras and image recognition systems can automatically detect fish species, count fish populations, and monitor fish movement in natural and cultured environments. These technologies reduce manual labor and improve the accuracy of fisheries data collection. Additionally, AI-based diagnostic tools are increasingly used for early detection of fish diseases and stress conditions, enabling timely management interventions and reducing economic losses in aquaculture operations. Artificial Intelligence also contributes to fisheries surveillance and marine conservation. AI-supported satellite data analysis and vessel monitoring systems are used to detect Illegal, Unreported, and Unregulated (IUU) fishing activities. Predictive analytics and spatial modeling help identify high-risk fishing zones and support effective fisheries law enforcement. Furthermore, AI technologies assist in climate change studies by analyzing long-term environmental data and predicting the impacts of changing ocean conditions on fishery resources. The integration of AI with GIS, remote sensing, and big data analytics has accelerated the development of smart fisheries management systems. These technologies facilitate real-time monitoring, ecosystem-based management, and evidence-driven policymaking. Despite challenges related to data availability, technical expertise, and infrastructure requirements, AI has immense potential to enhance sustainability, productivity, and resilience in fisheries and aquaculture sectors worldwide.

Challenges and Future Perspectives

Despite the significant advancements in digital fisheries management, the adoption of GIS, Remote Sensing (RS), and Artificial Intelligence (AI) technologies faces several challenges. One of the major constraints is the high cost of infrastructure, satellite data processing systems, advanced sensors, and AI-based monitoring tools, which limits their accessibility, particularly in developing countries. Inadequate technical expertise, lack of trained personnel, and limited awareness among fishers and stakeholders further hinder the effective implementation of these technologies. Additionally, issues related to data availability, accuracy, interoperability, and real-time data sharing remain important challenges in fisheries resource management. Remote and coastal fishing communities often face poor internet connectivity and insufficient technological infrastructure, restricting the utilization of digital tools and smart fisheries systems. Furthermore, AI models require large, high-quality datasets for accurate predictions, while fisheries data are frequently fragmented and inconsistent. Concerns related to cybersecurity, data privacy, and policy regulations also need to be addressed for effective digital governance in fisheries sectors. Despite these limitations, the future of digital fisheries management is highly promising. Rapid advancements in AI, cloud computing, big data analytics, drones, autonomous underwater vehicles, and IoT-based smart monitoring systems are expected to enhance fisheries resource assessment and ecosystem management. The integration of GIS, remote sensing, and AI will support real-time monitoring, climate-resilient fisheries planning, precision aquaculture, and sustainable harvesting practices. Emerging technologies such as blockchain for seafood traceability and digital twin models for aquatic ecosystems may further revolutionize fisheries governance and resource sustainability. Therefore, increased investment in infrastructure, capacity building, interdisciplinary research, and policy support will be essential for achieving smart and sustainable fisheries management in the future.

Conclusion

Digital transformation has emerged as a powerful approach for improving fisheries resource management through the integration of Geographic Information Systems (GIS), Remote Sensing (RS), and Artificial Intelligence (AI). These advanced technologies provide accurate spatial, environmental, and predictive information that supports real-time monitoring, resource assessment, habitat mapping, and sustainable fisheries planning. GIS and remote sensing facilitate efficient ecosystem monitoring and identification of productive fishing zones, while AI enhances automation, predictive analytics, and precision aquaculture management. The combined application of these technologies contributes to sustainable harvesting practices, biodiversity conservation, climate-resilient fisheries management, and improved livelihoods of fishing communities. Although challenges such as high implementation costs, technical limitations, and data management issues persist, continuous technological advancements and increasing digital adoption are creating new opportunities for smart fisheries governance. Therefore, strengthening technological infrastructure, capacity building, and interdisciplinary collaboration will be essential for ensuring the long-term sustainability and resilience of global fisheries and aquaculture sectors.

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ANTIBIOTIC RESISTANCE IN PLANT PATHOGENIC BACTERIA: A GROWING CONCERN FOR INDIAN AGRICULTURE

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Introduction

Antimicrobial resistance (AMR) is widely recognized as a major challenge in human and animal health. However, its emergence in agricultural systems particularly among plant pathogenic bacteria is an equally serious but less appreciated concern. Bacterial diseases such as citrus canker, pomegranate blight, rice leaf blight, bacterial wilt, and fire blight are increasingly showing resistance to commonly used antibiotics. India is one of the world's largest agricultural producers, and the demand for effective disease management tools continues to increase. Antibiotics such as streptomycin and oxytetracycline have been used in several horticultural and field crops for managing bacterial diseases. However, growing evidence indicates that excessive and repeated use of these compounds can accelerate the emergence of resistant bacterial populations, thereby reduce their effectiveness and raise concerns regarding environmental and public health (Fig.1).

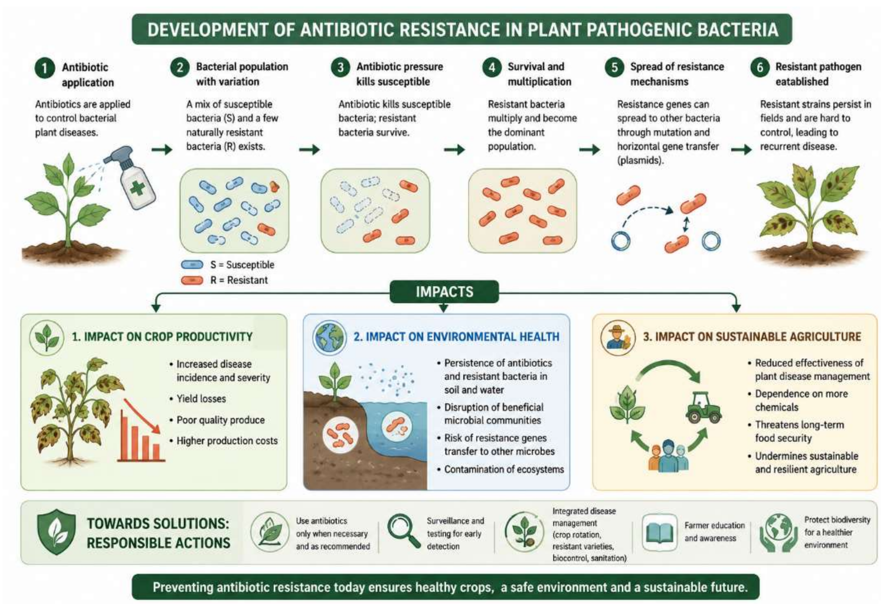

Fig. 1. Schematic illustration showing the development of antibiotic resistance in plant pathogenic bacteria and its impacts on crop productivity, environmental health, and sustainable agriculture in India.

Emerging Resistance in Major Pathogens

Recent studies indicate a clear shift in antibiotic sensitivity among important plant pathogens. Several important bacterial pathogens, including species of *Xanthomonas*, *Pseudomonas*, and *Erwinia*, have evolved the ability to survive antibiotic treatments. This resistance develops through genetic changes that enable the bacteria to tolerate or evade the effects of antibiotics. (Table 1; Fig.2). For example, *Xanthomonas campestris* causing black rot in crucifers and *X. axonopodis* pv.

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punicae in pomegranate have shown widespread resistance due to intensive antibiotic use. Similarly, *Pseudomonas syringae*, prevalent in temperate and hill regions, exhibits adaptive strategies such as biofilm formation and efflux systems, enabling survival under repeated antibiotic exposure. Although fire blight (*Erwinia amylovora*) is less widespread in India, resistant strains have also been reported.

Table 1. Major plant pathogenic bacteria and their resistance characteristics in India

Pathogen	Disease	Crop Affected	Resistance Mechanism
Xanthomonas campestris	Black rot	Crucifers	*strA, strB, rpsL* genes
X. oryzae pv.*oryzae*	Leaf blight	Rice	*adeF*, *FosI*, *vanY*
X. axonopodis pv. *punicae*	Bacterial blight	Pomegranate	Plasmid-mediated gene transfer
Erwinia amylovora	Fire blight	Apple, pear	Mutation and acquired resistance
Pseudomonas spp.	Leaf spots, blights	Various crops	Adaptive resistance mechanisms

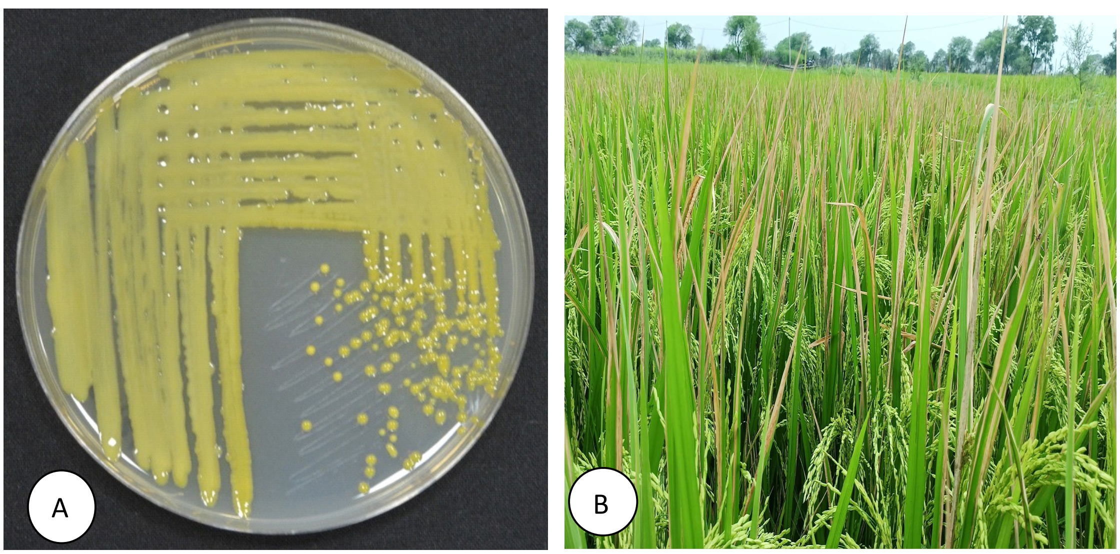

Fig.2: *Xanthomonas oryzae* pv. *oryzae*
(A) causing bacterial leaf blight in rice (B) in Chhattisgarh.

Xanthomonas campestris* pv. *campestris (Xcc)

The *Xcc* is responsible for the black rot of crucifers in India. In southern India, for example, the black rot pathogen has also been observed to have a high prevalence of streptomycin resistance in field strains of black rot crucifers. Molecular studies have detected strains bearing resistance markers including *strA*, *strB* and *rpsL*. The bacterial strains are also less susceptible to streptomycin in the majority of strains, even at doses previously shown to be relatively effective.

***Xanthomonas axonopodis* pv. *punicae* (*Xap*)**

India is the world leader in pomegranate production, and this pathogen (*Xap*) poses a serious threat in Maharashtra, which is contributing 60% pomegranate production. As mentioned, intensive and repeated use of streptomycin-based antibiotic formulations has also accelerated the development of resistance up to 1000 ppm. The genes which confer resistance are the *strA–strB* genes and the spontaneously mutated *rpsL* gene. Resistance is largely disseminated via plasmids, facilitating rapid transfer from one population of bacteria to another. Farmers frequently increase application rates, yielding diminishing returns and the high price of pomegranate production.

Erwinia amylovora

Fire blight is less common in temperate regions of India, like Himachal Pradesh, Jammu and Kashmir, Uttarakhand, etc. Local outbreaks have shown potent resistance to streptomycin, though streptomycin and oxytetracycline are largely used in the management of fire blight in apple, pear, quince, and other Rosaceae members. There are a few confirmed large-scale research reports on resistance in India. Resistance is conferred by genes *strA–strB* genes and the spontaneously mutated *rpsL* gene.

Pseudomonas syringae

Pseudomonas syringae, one of the bacterial plant pathogens widely known to infect India, has been found to colonize numerous crops and vegetables. It is an important pathogen found in regions with cool to moderate temperatures, high humidity and rainfall, such as parts of Himachal Pradesh, Uttarakhand, Jammu & Kashmir and southern hill ecosystems. In these agro-climatic zones, it results in the development of such diseases as bacterial leaf spot, blight and canker, causing loss of production and quality. One of the primary challenges in India is the emergence of antibiotic-resistant populations of *P. syringae* to the treatment, which occurs after multiple, and sometimes indiscriminate use of particular antibiotics, such as streptomycin (used at 100–200 ppm along with copper compounds) in the country. Field-observed and experimentally demonstrated are many strains that are now able to withstand these advised doses. Resistance is mainly linked to the *strA* and *strB* genes and mutations of the *rpsL* gene. Further, *P. syringae* strains of Indian agro-ecosystems employed adaptation strategies such as biofilm formation and efflux pump function so as to survive constant antibiotic exposure.

Drivers of Antibiotic Resistance

Several interconnected factors influence the development of resistance in plant pathogens, including indiscriminate and prophylactic use of antibiotics, inadequate regulation and easy availability, incorrect dosage and repeated applications, as well as environmental contamination of soil and water. These factors accelerate the selection and spread of resistant bacterial populations across agroecosystems.

Regulatory and Policy Framework

India has initiated measures under the National Action Plan on AMR (NAP-AMR 2.0) to address this issue. These include restricting antibiotic use to critical situations, promoting disease surveillance, and strengthening resistance monitoring systems. To ensure adherence and safety and to prevent misuse or overuse of antibiotics, regulatory bodies such as the Central Insecticides Board & Registration Committee (CIB&RC) and Directorate of Plant Protection, Quarantine and Storage (DPPQS) oversee the approval and use of agrochemicals, including antibiotics such as streptomycin, kasugamycin, validamycin and aureofungin. Despite policy interventions, challenges remain in ensuring compliance at the field level. The CIB & RC prescribes doses of streptomycin for various crops, but farmers are the target of no action and practice it on local approval or recommendation. This is especially concerning at this time.

What Farmers Can Do?

Farmers can play a vital role in slowing the spread of antibiotic resistance by adopting the following practices:

- Use antibiotics only when recommended by authorized agricultural experts.
- Follow recommended doses and application schedules.
- Avoid repeated applications of the same antibiotic.
- Adopt resistant crop varieties whenever available.
- Promote biological control agents and integrated disease management practices.
- Maintain field sanitation and remove infected plant material promptly.
- Monitor crops regularly for early disease detection and timely intervention.

Sustainable Alternatives and Future Strategies

With declining antibiotic efficacy, there is a growing emphasis on eco-friendly disease management approaches. Several ICAR institutes and agricultural universities are actively developing eco-friendly alternatives for bacterial disease management. These include microbial biocontrol agents, plant-derived antimicrobial compounds, bacteriophages, and disease forecasting systems. Such approaches can reduce dependence on antibiotics while ensuring sustainable crop protection.

Biological control using beneficial microbes like *Bacillus*, *Pseudomonas fluorescens*, and *Streptomyces* suppress pathogens through competition and natural antimicrobial compounds. Botanical formulations, including plant-based preparations (e.g., neem-based products, traditional formulations), offer safer alternatives without promoting resistance. Precision agriculture, with the aid of advanced tools such as sensors and AI-based systems, enables early disease detection and targeted interventions. In addition, bacteriophage therapy is emerging as a promising approach for managing bacterial diseases like rice leaf blight.

Rice-bactericides such as copper-based compounds, kasugamycin and validamycin, along with other immunomodulators for bacterial leaf blight in rice, and other bacterial diseases are suitable alternatives for the rice growers. Overall, the integrated disease management, combining cultural, biological, and chemical strategies, offers long-term sustainability.

Key Take Home Messages

- Antibiotic resistance is no longer limited to human and animal health; it is emerging as a serious challenge in crop production.
- Repeated and indiscriminate use of antibiotics can make plant disease-causing bacteria resistant to treatment.
- Resistant pathogens can increase crop losses and production costs.
- Integrated disease management, biological control agents, and botanical products offer sustainable alternatives.
- Responsible use of antibiotics is essential for safeguarding crop productivity and environmental health.

Conclusion

Antibiotic resistance in plant pathogenic bacteria is emerging as a significant challenge for Indian agriculture, with implications for crop productivity, environmental sustainability, and food security. While antibiotics have played an important role in managing bacterial diseases, their indiscriminate use has accelerated the emergence of resistant pathogen populations. Sustainable disease management strategies based on biological control, precision agriculture, integrated disease management, and responsible antibiotic stewardship must be promoted. A holistic One Health approach that recognizes the interconnectedness of plant, animal, human, and environmental health will be essential for safeguarding agricultural resilience and ensuring long-term food security.

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ANTI-NUTRIENTS: THE "SECRET VILLAINS" IN FORAGE CROPS

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Abstract

Anti-nutrients are naturally occurring chemical compounds in agricultural and forage crops such as sorghum, alfalfa and *Brassica* species. Common anti-nutrients include phytic acid, tannins, saponins and hydrogen cyanide, which can cause health problems in humans and animals when consumed in excessive amounts. These compounds act as plants' natural defense mechanisms, protecting them from overgrazing and pest attacks. Despite their harmful effects, many anti-nutrients have been commercially exploited for pharmaceutical medicines. Therefore, breeding crops for a balanced level of these secondary metabolites is a promising and advantageous strategy.

When Your Pasture Fights Back

Imagine feeding your animals with green forage, believing you are providing them with the best nutrition possible. But harmless leaves and stems have hidden chemical compound inside that seemingly work quietly against your animals' health and productivity. These are the anti-nutrients nature's own defence system that can turn a nutritious meal into a potential health hazard.

Plant secondary metabolites (PSMs) are naturally occurring compounds produced by plants that can have both negative and positive biological activity in farm animals. These "secret villains" are broadly categorized into seven main groups: glycosides, alkaloids, phenolic compounds, phytic acid, non-starch polysaccharides, lectins and enzyme inhibitors. Each category influences animal health and productivity through distinct mechanisms that can interfere with digestion, nutrient utilization and physiological functions.

The Usual Suspects: Major Anti-Nutrients in Forages

The Mineral Robber: Phytic Acid

Phytic acid is considered one of the most common anti-nutritional factors present in forage crops. Duraiswamy *et al*., (2023) reported that phytic acid functions as a natural antioxidant and strongly chelates essential positively charged minerals such as phosphorus, iron, and zinc, thereby limiting their absorption in animals. Monogastric animals, including pigs and poultry, are especially susceptible because their digestive systems lack sufficient phytase enzyme required to break down phytic acid. As a result, poor mineral utilization can lead to reduced growth, weakened immunity, and decreased overall productivity.

The Grass Toxin: Alkaloids from Epichloe Endophytes

One of the interesting stories in forage anti-nutrients involves the relationship between perennial ryegrass and its fungal partner, *Epichloe endophytes*. Caradus and Chapman (2025) explained the production of secondary metabolites that deter herbivory by both ruminants and insect pests. While this metabolite protects the plant, it can cause serious damage to grazing animals. The alkaloid lolitrem B, first identified by William Gallagher and colleagues in 1984, is responsible for causing "ryegrass staggers," a neurological disorder in grazing animals characterised by trembling, loss of coordination, and unsteady movement.

The Anti-Feeding Compounds: Tannins and Saponins

Tannins are polyphenolic compounds capable of binding and precipitating proteins. In animals consuming tannin-rich forages, these compounds interact with dietary proteins and digestive enzymes, thereby reducing their availability and nutritional utilisation. According to Duraiswamy *et al*., (2023) less iron absorption and intestinal damage can be caused due to tannins in forage. Saponins, another group of anti-nutrients that have soap-like properties, are found in forages like alfalfa which can cause digestive upset. Researchers reported that saponins can attach to intestinal cells, reduce nutrient absorption in the body and even cause breakdown of red blood cells in extreme cases.

The Gas Producers: Raffinose Family Oligosaccharides

Beans, legumes, and some grasses contain raffinose family oligosaccharides (RFOs). Humans and monogastric animals cannot digest these compounds. Instead, RFOs are fermented by microorganisms in the large intestine, producing carbon dioxide, hydrogen, and methane. This leads to problems like Bloating, flatulence and stomach discomfort that reduce feed intake and animal comfort.

The Adaptation Miracle: How Animals Fight Back

In nature the one that is quick to adapt will have more chance to survive. Despite these chemical defenses for anti-nutrients, nature has provided animals with the ability to adapt. Khajali and Rafiei (2024) highlighted a significant advancement in forage science, showing that farm animals can gradually adapt to anti-nutritional compounds through modifications in their gut microbiome. In ruminants such as cattle and sheep, the digestive system hosts billions of microorganisms capable of progressively detoxifying and neutralizing certain anti-nutrients over time. The gut microbiome of cattle can change according to the feed.

The Breeding Solution: Fighting Back with Science

If nature created these anti-nutrients for plant survival, perhaps science can undo some changes. Plant breeders have been working on this since long time. Duraiswamy *et al*., (2023) traced the history of anti-nutrient breeding to the 1960s, when McMichael (1960) identified the glandless genes *gl2* and *gl3* in cotton that regulate the toxic compound gossypol. In recent years, marker-assisted selection has emerged as an advanced breeding approach, enabling breeders to efficiently identify and select plants with reduced anti-nutrient content without relying on lengthy field evaluations and laboratory analyses.

For example, zero Kunitz trypsin inhibitor was developed through the introgression of a recessive gene into elite soybean cultivars. But the breakthrough has come from genetic modification. Rathore *et al*., (2020) developed ultra-low-gossypol cotton by specifically silencing the δ-cadinene synthase gene in seeds, while maintaining sufficient gossypol levels in leaves and stems to protect against insect pests. This "seed-specific" approach represents the holy grail of anti-nutrient reduction, removing the toxin only where it matters for animal feed while preserving the plant's natural defences.

The Hidden Benefits: Not All Anti-Nutrients Are Villains

Managing the anti-nutrients (villainous) in crops is challenging because they serve essential functions in plants. As Khajali and Rafiei (2024) pointed out, plant secondary metabolites can have beneficial properties that actually promote animal and human health. Phytic acid acts as a beneficial antioxidant in foods despite its miner binding properties. Researchers reported that dietary phytic acid can help in the control of colon cancer and other bowel diseases prevention through lipid peroxidation and oxidative spoilage. Several studies have demonstrated that saponins possess important bioactive properties, including anti-cancer, anti-inflammatory and cholesterol-reducing effects. Similarly, glucosinolates present in forage brassicas degrade into isothiocyanates, compounds known for their apoptotic and antiproliferative activity against cancer cells. Even gossypol, which is a toxin in cotton, has shown effective as a male contraceptive in pharmaceutical research. The challenge for forage plant breeders is to reduce these compounds below a critical level that makes forages safe, but not so much that beneficial properties are lost or worse that plants become susceptible to pests and diseases.

The Persistence Paradox: Why Modern Cultivars Sometimes Fail

The novel genotypes developed to eliminate animal toxins may have compromised plant survival. Because animals can overgraze pastures down to lower residuals, it reduces the plant's ability to regrow and survive, especially during drought combined with insect pressure.

Practical Solutions for Farmers Today

While scientists work on better cultivars, farmers can use processing methods for harvested forages to reduce anti-nutrients. There are several effective processing techniques:

Method	Anti-nutrients Targeted	Key Findings
Soaking	Phytic acid, Protease inhibitors, Lectins and Tannins	12-hr soak of pea seeds reduces phytate ~9%; 6-18 hr soak of pigeon peas reduces lectins 38-50%, tannins 13-25%, protease inhibitors 30%
Boiling	Lectins, Tannins and Protease inhibitors	Boiling pigeon peas for 80 min reduces protease inhibitors 70%, lectins 79%, tannins 69%
Fermentation	Tannins, Polyphenols Phytate, Trypsin inhibitors	Lactic acid bacteria fermentation significantly reduces tannins, polyphenols, phytate, and trypsin inhibitors
Sprouting	Phytic acid	10 days of sprouting reduces phytate in cereals by 37-81% across various grains and legumes
Soaking and Boiling	Lectins Tannins Protease inhibitors	Combined method eliminates 98-100% of lectins, tannins, and protease inhibitors in pigeon peas

The Future: Precision Editing for Better Forages

Major breakthroughs are taking place at the molecular level, where CRISPR/Cas9 technology enables precise editing of the plant genome. Through this technology, scientists can remove or reduce specific anti-nutrients by specific gene knock out. Duraiswamy *et al*., (2023) report successful applications of this technology in different crops. In soybean, knocking out galactinol synthase genes (*GmGoLS1A* and *GmGoLS1B*) reduced raffinose by 35% with no other negative effect on the plant. In cassava, targeted editing of the *CYP79D1* gene resulted in reduced levels of cyanide. Compared with conventional breeding methods, gene editing offers greater speed, accuracy, and efficiency in crop improvement.

Conclusion: A Balanced Perspective

Anti-nutrients in forage crops are neither villains nor heroes. They are complex chemical compounds that have evolved to protect plants from pests and over grazing. These chemicals affect animals in ways that range from mild annoying to severe toxicity that leads to death. The challenge for plant breeders and livestock producers is to find the balance spot for reduced anti-nutrients to protect animal health while preserving those that contribute to plant persistence and pest resistance.

As Caradus and Chapman (2025) concluded natural selection and plant breeding are acting oppositely. Natural selection conserves traits that favour plant survival, while plant breeders mainly seek to increase yield. The most successful forage varieties of the future will be those that balance productivity and persistence. Breeding programs and biotechnology tools are the main solutions for this (Khajali and Rafiei, 2024). Good farm management with appropriate processing methods helps farmers unlock the full nutritional potential of their forages while keeping the "secret villains" under control.

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SEEDS OF UNCERTAINTY: GEOPOLITICS, FERTILIZER ECONOMICS AND INDIA'S AGRICULTURAL RESILIENCE

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"The next battle for food security will be won or lost in geopolitics, energy, and equitable access to soil nutrients."

— Dr. M.S. Swaminathan
Father of the Green Revolution in India

Abstract

Fertilizer markets have emerged as a critical nexus of agricultural vulnerability and geopolitical risk. This article understands how converging global disruptions the Russia-Ukraine conflict, Red Sea shipping crises, and the 2026 Strait of Hormuz crisis have explained the structural fragilities in India's agricultural input supply chains. Drawing on data from FAO, IFA, World Bank, and government sources, the article helps to understand price transmission mechanisms, India's import dependency, fiscal implications, and strategic policy pathways for building long-term agricultural resilience.

Introduction

Contemporary agriculture is deeply embedded in the dynamics of global geopolitics. Fertilizers are the cornerstone of modern crop productivity and are among the agricultural inputs most susceptible to international disruptions. Data from the Food and Agriculture Organization indicate that fertilizer expenditure now constitutes 40–60 percent of variable production costs in South Asian cereal farming, rendering any price shock immediately consequential for smallholder incomes and national food security (FAO, 2023).

Between 2021 and 2023, three concurrent crises the Russia-Ukraine conflict, regional tensions in West Asia, and lingering post-pandemic supply chain dislocations collectively drove global fertilizer prices to multi-decade highs. The ensuing volatility has exposed structural vulnerabilities in import-dependent countries such as India, which sits at the demand end of tightly concentrated global supply chains. Most recently, the 2026 escalation of West Asian hostilities transformed previously theoretical risk scenarios into acute agricultural emergencies.

Global Fertilizer Markets Under Geopolitical Stress

Supply Concentration and Price Volatility

Global fertilizer production is concentrated in a few regions, making the sector more vulnerable to geopolitical risks. Russia and Belarus collectively account for approximately 40 percent of global potash exports, while Russia independently supplies around 22 percent of internationally traded ammonia and 14 percent of urea (IFA, 2023). China, responsible for roughly 30 percent of global phosphate exports, periodically curbs shipments to safeguard domestic availability, with immediate upward pressure on global prices.

The magnitude of price disruption was striking. As shown in Table 1, urea prices surged by 260 percent from pre-crisis baselines, while ammonium nitrate experienced the steepest relative increase at 290 percent (ScienceDirect, 2024). Natural gas which is the primary feedstock for nitrogen fertilizer synthesis saw European spot prices escalate from USD 5 per MMBtu in early 2021 to over USD 70 per MMBtu (Metric Million British Thermal Unit) by August 2022, triggering mass plant shutdowns across the continent (IEA, 2022).

Fertilizer	2020 (USD/MT)	Peak 2022 (USD/MT)	Change (%)	2024 (USD/MT)
Urea	250	900	+260%	340
DAP	310	950	+206%	540
MOP (Potash)	220	700	+218%	310
Ammonium Nitrate	200	780	+290%	370

Table 1: Global Fertilizer Price Movements (2020–2024) | Sources: World Bank; ScienceDirect, 2024

The 2026 Strait of Hormuz Crisis

The Strait of Hormuz which is a passage merely 34 kilometres wide, facilitates transit of approximately 20 percent of global seaborne petroleum trade and up to 30 percent of internationally traded fertilizers. The Persian Gulf accounts for an estimated 30–35 percent of global urea exports and 20–30 percent of ammonia exports; Qatar's QAFCO complex alone represents 14 percent of global urea trade (Kpler, 2025). India has been severely affected as approximately 75 percent of India's urea imports in 2024–25 originated from Gulf nations transiting through the Strait. Disruption to gas supply across Qatar, UAE, Kuwait, Bahrain, and Saudi Arabia directly compromised domestic urea manufacturing, with plants operating at barely 60 percent of installed capacity.

Globally, nearly one-third of fertilizer trade i.e. around 3–4 million tonnes per month was stalled. Middle East granular urea prices rose to over USD 590 per tonne within days, while several previously negotiated contracts were withdrawn, pushing buyers toward more volatile spot markets. By late March 2026, urea prices had surged nearly 50 percent since the onset of hostilities, with global fertilizer prices projected 15–20 percent higher in H1 2026 if the crisis persists (Down to Earth, 2026). Container freight rates tripled, and approximately four lakh tonnes of basmati rice were stranded at ports, imperilling India's USD 11.8 billion West Asian agricultural export relationship (Rural Voice, 2026).

India's Structural Dependency and Fiscal Exposure

Import Dependency by Nutrient

India is the world's second-largest fertilizer consumer, using around 56 million metric tonnes of nutrients each year across 170 million hectares of cultivated land (DAC&FW, 2023). Despite considerable domestic urea manufacturing, dependence on imports for phosphate and potash is structurally deep-rooted, as shown in Table 2.

Nutrient	Consumption (MT/yr)	Domestic Prod. (MT)	Import Share	Key Suppliers
Urea (N)	Approx. 34 million	Approx.25 million	Approx.26%	Russia, China, Qatar
DAP (P)	Approx.11 million	Approx. 4 million	Approx.64%	Morocco, Jordan, China
MOP (K)	Approx.5 million	Negligible	Approx.100%	Russia, Belarus, Canada

Table 2. India's Fertilizer Import Dependency by Nutrient, Sources: FAI Annual Report 2023; DAC&FW

Complete potash import dependency represents India's most acute structural vulnerability. Key supplier nations Russia and Belarus are simultaneously subject to international sanctions, complicating payment and logistics arrangements (Down To Earth, 2024).

The Fiscal Dimension: Subsidy Burden

To shield farmers from price volatility, India's fertilizer subsidy outlay escalated from INR 1.27 lakh crore in 2021–22 to INR 2.25 lakh crore in 2022–23 a 77 percent annual increase before moderating to approximately INR 1.89 lakh crore in 2023–24 as international prices stabilised (Union Budget Documents, 2024). Urea accounts for over 70 percent of total subsidy expenditure, creating skewed incentives that encourage nitrogen over-application while phosphate and potash remain relatively underused. Geopolitical disruptions compound this through higher crude oil prices, which simultaneously raise transportation, irrigation energy, and pesticide costs across the entire agricultural value chain (ORF, 2024).

Geopolitical Transmission Channels and Policy Responses

Five Transmission Pathways

A ten percent rise in European gas prices has historically led to a 6–8 percent increase in urea production costs (IFPRI, 2023).

Freight and Insurance Escalation: Red Sea shipping attacks added 10–14 days to key trade lanes, inflating freight costs by an estimated 150–200 percent (UNCTAD, 2024).

Currency Depreciation: The Rupee's move from INR 73 to INR 83–84 per USD between 2021 and 2023 independently added roughly 15 percent to import costs in domestic currency terms.

Export Restrictions: Thirteen countries-imposed fertilizer export controls between 2021 and 2023, reducing market-available supply and intensifying price spikes (FAO, 2022).

Speculative Hoarding: Price uncertainty prompts precautionary procurement by distributors and governments, generating artificial demand surges that amplify underlying supply shocks.

Government of India Policy Responses

India's policy architecture spans price stabilisation, supply diversification, and demand efficiency. Urea retail prices have been fixed at INR 242 per 45-kg bag since 2012, with manufacturers compensated through subsidy transfers. Bilateral government-to-government procurement agreements have been established with Jordan, Senegal, Oman, and Turkmenistan. Buffer stocks covering 30–45 days of consumption are maintained at major ports.

The Nano Urea programme with annual production capacity of 220 million bottles by 2023–24, reduces logistics weight by 99 percent relative to conventional packaging (IFFCO, 2024). The PM PRANAM scheme incentivises states to achieve measurable reductions in chemical fertilizer consumption.

International Best Practices

Precision Agriculture (US, Netherlands): Variable-rate application guided by remote sensing reduces average fertilizer use by 15–20 percent without yield loss (FAO, 2023).

Integrated Nutrient Management (Brazil): Combining organic, biological, and mineral inputs reduced synthetic fertilizer dependency by 20–30 percent while sustaining yields (CropLife, 2023).

Phosphorus Recovery from Waste Streams (EU, Netherlands): Commercial-scale recovery from sewage sludge meets approximately 10 percent of domestic phosphate requirements. India generates over 72,000 MT of sewage sludge daily.

Green Ammonia (Australia, Japan): Renewable hydrogen-based ammonia synthesis projected to reach cost parity with conventional production by 2030–2035 (BloombergNEF, 2024).

Strategic Pathways and the Role of Financial Institutions

Multi-Horizon Roadmap

Short Term (1–3 years): can expand strategic reserves to 60-day coverage; diversify procurement to politically stable African, Central Asian, and Oceanian suppliers; accelerate FPO-based digital input procurement platforms.

Medium Term (3–7 years): we can scale domestic phosphate mining from deposits in Rajasthan and Madhya Pradesh; build biofertilizer manufacturing capacity; establish state-level soil carbon baseline databases.

Long Term (7–15 years): we can develop green ammonia capacity leveraging India's renewable energy resources; establish circular nutrient recovery from urban and agricultural waste; create an India-led multilateral fertilizer security pact with food-importing developing nations.

Banking and Financial Institutions as Enablers

When geopolitical shocks destabilise fertilizer markets, the crisis ultimately arrives at the farm gate as a financing problem where banks and financial institutions can intervene decisively:

Pre-season agricultural input credit: can help farmers purchase inputs in advance and reduce the impact of sudden price increases during the peak farming season. Connecting working capital support with soil health data and advance input planning can help farmers manage costs more efficiently.

Supply Chain Finance: Receivables financing for fertilizer distributors and FPO networks reduces working capital bottlenecks, preventing upstream disruptions from cascading downstream.

Sustainability-Linked Lending: Directing capital toward biofertilizer manufacturers, precision agriculture platforms, and domestic mineral processing ventures structurally reduces import exposure.

Commodity Price Hedging: Helping farm enterprises and Farmer Producer Organisations access financial tools that protect them from sudden price changes.

Conclusion

The evidence is unequivocal: fertilizer markets are no longer insulated from geopolitical disruption, and India's agricultural economy bears disproportionate risk. With potash import dependency at 100 percent, a fertilizer subsidy bill capable of swinging by INR 1 lakh crore within a single fiscal year, and over 600 million livelihoods connected to agriculture, the stakes are high. At the same time, this analysis also highlights possible ways to address these challenges. India has the potential to build a strong and more resilient agricultural system over the coming decade. The country is steadily expanding its renewable energy capacity, which could support large-scale green ammonia production. It also has a strong base in soil science and agronomic research that can help improve nutrient use efficiency. Alongside this, India's growing digital infrastructure can deliver precision farming guidance to millions of farm households. Institutions such as banks, cooperatives, Farmer Producer Organizations (FPOs), and state agriculture departments can play an important role in bringing these capabilities together and ensuring they reach farmers effectively. Turning these vulnerabilities into an opportunity for agricultural modernisation is now an important challenge as well as a major opportunity for policymakers, financial institutions, and the farming community.

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SMART FARMING WITH DRONE SENSORS

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Abstract

Drone based Smart farming is an emerging approach in precision agriculture that integrates unmanned aerial vehicles (UAVs), advanced sensors, artificial intelligence (AI), remote sensing, and Internet of Things (IoT) technologies to improve agricultural productivity and resource management. Traditional farming practices often rely on manual field inspection and conventional management methods, which can be time-consuming, labour-intensive, and less efficient. In contrast, drone-based smart farming enables rapid, accurate, and real-time monitoring of crops, soil, irrigation, and environmental conditions. Agricultural drones equipped with sensors collect valuable field data for crop health assessment, disease detection, water stress analysis, nutrient management, and precision mapping. The collected data is processed using advanced analytical software and AI-based algorithms to generate actionable information for farmers. Furthermore, integration with IoT platforms and decision support systems enhances farm automation and data-driven decision-making. This article discusses the key components, sensor technologies, working principles, data processing techniques, and agricultural applications of drone-based smart farming systems. The study highlights the significant role of drone sensor technology in promoting sustainable, intelligent, and efficient agricultural practices for modern farming systems.

Keywords*:* Precision Farming; Drone in Agriculture; Sensors; Smart Farming,

Introduction

Smart farming with drone sensors is an advanced and innovative method of agriculture that combines modern technologies such as drones, artificial intelligence, sensors, GPS, remote sensing, and data analytics to improve farming practices and increase agricultural productivity. Traditional farming methods often depend on manual labour, visual inspection, and general field management techniques, which may consume more time, labor, and resources. However, with the introduction of precision agriculture, farmers can now monitor and manage their farms more accurately and efficiently. Drone technology has become one of the most important tools in smart farming because it allows farmers to collect real-time information about crops, soil, irrigation, and field conditions from the air. Drones equipped with advanced sensors help farmers make better decisions, reduce production costs, save water and fertilizers, and improve crop quality and yield.

In smart farming, different types of sensors are attached to drones to perform specific agricultural tasks. RGB sensors are commonly used to capture normal color images of fields and crops. These images help farmers inspect crop growth, identify damaged plants, and monitor overall field conditions. Multispectral sensors capture light reflected from crops at different wavelengths, allowing farmers to analyse plant health, chlorophyll levels, and nutrient conditions. This helps in detecting crop stress, diseases, and pest attacks at an early stage before major damage occurs. Thermal sensors measure temperature differences in crops and soil, which helps farmers identify water stress, irrigation problems, and unhealthy plants. Another highly advanced technology used in smart farming is LiDAR (Light Detection and Ranging) sensors. LiDAR sensors use laser pulses to create accurate 3D maps of farmland, crop height, terrain structure, and drainage patterns. These maps help in land surveying, soil analysis, crop planning, and precision irrigation management.

Key components

1. **The Aerial Hardware (UAV)**
   - **Flight System:** Comprises motors, rotors, and lightweight composite frames designed for stability, wind resistance, and endurance over large acreages.
   - **Energy System:** Typically, high-capacity lithium-polymer (LiPo) batteries that power the drone for specific flight durations before automatic return-to-home.
   - **Autonomous Flight Controller:** Integrates with GPS and onboard sensors to maintain precise altitude, speed, and pre-programmed flight paths
2. **Sensor Payloads**
   - **RGB Cameras:** Standard high-resolution optical cameras used for visual inspections, 3D field mapping, and generating true-color orthomosaic maps.
   - **Multispectral Sensors:** Capture specific bands of light (like Near-Infrared). They are foundational for calculating indices like the Normalized Difference Vegetation Index (NDVI) to accurately gauge plant health, stress, and chlorophyll levels.
   - **Hyperspectral Sensors:** Capture hundreds of narrow, contiguous light bands to detect early-stage crop diseases, specific nutrient deficiencies, and chemical compositions.
   - **Thermal Sensors:** Detect infrared radiation and measure temperature variations. They are primarily used for precision irrigation management to spot dry, stressed, or overwatered zones.
   - **LiDAR:** Uses laser pulses to generate high-precision 3D elevation models of the terrain and canopy, aiding in land levelling and drainage planning.
3. **Data Processing & Analytical Software**
   - **Photogrammetry & Mapping Software:** Stitches raw aerial images and sensor data together to create actionable 2D maps and 3D terrain models.
   - **AI Analytics Platforms:** Process multispectral and thermal data using machine learning to identify pest infestations, estimate crop yields, and monitor weed encroachment.
   - **IoT Integration:** Connects drone-captured data with ground-based weather stations and soil sensors to create a comprehensive digital twin of the farm.
4. **Precision Application Systems**
   - **Smart Spraying Systems:** Interchangeable payloads featuring precision nozzles, flow meters, and liquid tanks. They enable variable rate applications (VRA) for applying pesticides, bio-fertilizers, and water only where needed, substantially reducing chemical waste

Working Principle

Smart farming with drone sensors is an advanced agricultural technology that integrates drones, sensors, GPS, artificial intelligence (AI), Internet of Things (IoT), and data analytics to improve farming efficiency and productivity. In this system, drones fly over agricultural fields and collect real-time information about crops, soil, water, and environmental conditions. The collected data is analyzed to support precision farming decisions such as irrigation scheduling, fertilizer application, pest control, and crop monitoring. The complete working principle can be understood through the following stages.

1. **Flight Planning and Mission Setup:** Flight planning is the first and most important step in drone-based smart farming. Before the drone begins operation, a predefined flight mission is created using specialized mission-planning software installed on a computer or mobile device. Modern agricultural drones use GPS and autopilot systems for automatic navigation. The GPS receiver continuously communicates with satellites to determine the exact location of the drone. Based on the programmed coordinates, the drone follows a systematic path over the field. Proper flight planning ensures:
    - Uniform data collection
    - High-quality mapping
    - Reduced flight time
    - Better sensor accuracy
2. **Data Collection Using Drone Sensors:** The core principle of smart farming lies in sensor-based data acquisition. Agricultural drones are equipped with various sensors that detect physical and biological properties of crops and soil. Different sensors operate on different scientific principles. These sensors collect reflected light, thermal radiation, distance measurements, and environmental data from the field.

Table 1: Common Drone Sensors Used in Smart Farming

Sensor Type	Working Principle	Agricultural Application
RGB Camera	Captures normal color images	Crop monitoring and mapping
Multispectral Sensor	Captures specific wavelength bands	Plant health analysis
Thermal Sensor	Detects heat emitted from crops/soil	Water stress and disease detection
LiDAR Sensor	Uses laser pulses for distance measurement	3D field mapping and canopy analysis
Hyperspectral Sensor	Captures hundreds of spectral bands	Nutrient deficiency and disease identification
GPS Sensor	Determines precise location coordinates	Precision navigation and mapping

3. **Data Processing and Analysis:** Raw drone data alone is not useful until processed into meaningful information. Advanced software and AI algorithms analyse the collected images and sensor outputs. The main processing steps include:
    A. **Image Stitching:** Multiple overlapping images are combined to form a single high-resolution orthomosaic map of the field.
    B. **Vegetation Index Calculation:** Vegetation indices are mathematical combinations of spectral bands used to evaluate crop health.

$$GNDVI = \frac{NIR - Green}{NIR + Green}$$

C. **Artificial Intelligence Analysis:** AI and machine learning algorithms detect patterns in drone imagery.

4. **Decision Support System (DSS):** A Decision Support System converts processed data into actionable farming recommendations. Based on drone analysis, DSS may suggest:
   - Variable fertilizer application
   - Irrigation scheduling
   - Pest control measures
   - Crop protection strategies

Conclusion

Smart farming with drone sensors combines UAV technology, remote sensing, GPS, AI, and IoT to modernize agricultural operations. Drone sensors collect accurate field information, which is processed into actionable insights for precision farming. This technology enables efficient resource utilization, early stress detection, reduced production cost, and higher agricultural productivity. As agriculture moves toward automation and digitalization, drone-based smart farming is becoming an essential tool for sustainable and intelligent farming systems. The system supports precision spraying, variable rate application, and efficient irrigation management, thereby reducing chemical wastage, production costs, and environmental impact.

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ECO-FRIENDLY CROP PROTECTION: THE BIOCONTROL POWER OF *Trichoderma* and *Bacillus*

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Abstract

Recent advancements in agricultural technologies have significantly enhanced production capabilities, yet certain contemporary practices pose environmental challenges. A pressing issue in modern farming is to boost yields while maintaining ecological integrity, underscoring the urgent need for sustainable solutions. Among the various biocontrol agents utilized in agriculture, *Trichoderma* and *Bacillus* species are prominent choices for managing a range of plant pathogens. Recent research indicates that these organisms serve not only as biocontrol agents but also promote plant resistance, growth, and overall development, leading to increased crop yields. Their antagonistic mechanisms include mycoparasitism, the production of antibiotics, nutrient competition, and the induction of systemic resistance in plants. Consequently, the incorporation of *Trichoderma* and *Bacillus* into agricultural practices presents a promising pathway toward the advancement of sustainable agriculture.

Key words: *Trichoderma, Bacillus*, Sustainable agriculture

Introduction

The rapidly increasing global population has intensified the demand for higher agricultural productivity and improved food quality. To meet these demands, farmers often rely heavily on chemical pesticides and fungicides, which pose serious threats to environmental sustainability, soil health, biodiversity, and human well-being. In this context, microbial-based biopesticides, particularly those derived from *Trichoderma* and *Bacillus* species, have emerged as efficient and eco-friendly alternatives for disease management in agricultural systems. *Trichoderma* species primarily exert their biocontrol effects through mechanisms such as mycoparasitism, competition for nutrients and space, and the production of antimicrobial metabolites. In contrast, *Bacillus* species employ multiple strategies including secretion of lipopeptides, production of lytic enzymes and siderophores, and activation of induced systemic resistance (ISR) in plants. Owing to their multifunctional roles in disease suppression and plant growth promotion, these microorganisms are increasingly being incorporated into sustainable crop management practices. This article highlights the major mechanisms and agricultural applications of *Trichoderma* and *Bacillus* as potent biocontrol agents.

Trichoderma and *Bacillus* in Agriculture

Microbial inoculants have gained considerable importance in modern agriculture because of their environmentally safe and sustainable nature. These beneficial microorganisms improve nutrient availability, enhance soil fertility, stimulate plant growth, and protect crops against various pathogens. Among them, fungal species belonging to the genus *Trichoderma* and bacterial species of *Bacillus* have received special attention due to their remarkable biocontrol potential.

Trichoderma is a filamentous fungus commonly found in soil and rhizosphere ecosystems. It efficiently colonizes plant roots and produces several bioactive metabolites with strong antimicrobial properties. These fungi enhance plant growth, improve nutrient uptake, and suppress numerous soil-borne pathogens. Species of *Trichoderma* are particularly effective against fungal pathogens such as *Fusarium oxysporum*, *Botrytis cinerea*, *Rhizoctonia solani*, and *Alternaria alternata*. In addition, they are also known for their ability to degrade harmful environmental contaminants and contribute to soil health restoration.

Similarly, *Bacillus* species play a significant role in improving crop productivity and soil fertility while acting as efficient biocontrol agents. These Gram-positive, spore-forming aerobic bacteria produce a wide range of bioactive compounds that promote plant growth and suppress phytopathogens. *Bacillus subtilis*, one of the most extensively studied species, exhibits strong antifungal activity through metabolites such as surfactin, iturin, and fengycin. Besides disease suppression, *Bacillus* species also function as biofertilizers and biostimulants by enhancing nutrient uptake and producing phytohormones that support plant development.

Mechanisms of Action of Biocontrol Agents

1. *Trichoderma* spp.

a) Mycoparasitism

Trichoderma species employ a dual mechanism to attack and degrade the cell walls of pathogenic fungi through enzymatic hydrolysis and production of secondary metabolites. They secrete extracellular enzymes such as chitinases, glucanases, and proteases that break down the structural components of fungal cell walls. Simultaneously, they produce bioactive compounds including peptaibols and gliotoxins, which weaken pathogen integrity and facilitate penetration and colonization by *Trichoderma* (Mukherjee *et al*., 2022).

b) Competition for Nutrients and Ecological Niches

Trichoderma species effectively compete with pathogens for essential resources such as nutrients, space, water, and oxygen in the rhizosphere. Their rapid growth and efficient root colonization enable them to establish a protective barrier around plant roots, thereby preventing the establishment and proliferation of pathogenic microorganisms.

c) Antibiosis and Plant Growth Promotion

Trichoderma produces a diverse range of secondary metabolites with antimicrobial properties that inhibit the growth of plant pathogens. These metabolites include peptaibols, polyketides, pyrones, and terpenes. In addition, *Trichoderma* synthesizes growth-promoting substances such as auxins, cytokinins, and gibberellins that enhance plant growth and development. It also activates induced systemic resistance (ISR), strengthening the plant's innate defence mechanisms against pathogen attack.

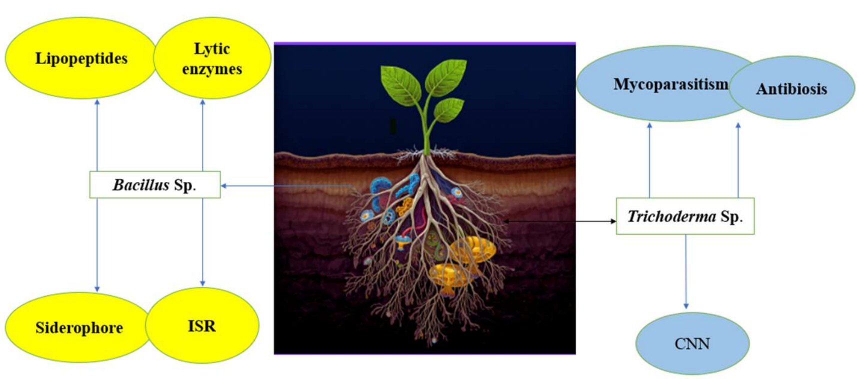

Figure: Beneficial traits of *Trichoderma* and *Bacillus* as biocontrol agents

2. *Bacillus* spp.

a) Production of Lipopeptides

Lipopeptides produced by *Bacillus* species are crucial for plant protection and growth promotion (Saiyam *et al*., 2024). These compounds exhibit strong antifungal activity against several plant pathogens including *Monilinia fructicola*, *Fusarium* spp., *Botrytis cinerea*, *Alternaria* spp., and *Colletotrichum gloeosporioides*. Furthermore, lipopeptides stimulate systemic resistance in plants and facilitate biofilm formation, thereby improving microbial colonization and antagonistic activity in the rhizosphere.

b) Production of Lytic Enzymes

Bacillus species synthesize various hydrolytic enzymes such as chitinases, β-glucanases, cellulases, and proteases, which play an important role in pathogen suppression. These enzymes degrade the structural components of pathogen cell walls, ultimately causing lysis and destruction of pathogenic organisms.

c) Production of Siderophores

Bacillus species are known for their ability to produce siderophores—low molecular weight compounds that efficiently chelate ferric iron (Fe^{3+}). By sequestering iron from the surrounding environment, these bacteria limit iron availability to phytopathogens, thereby suppressing their growth and enhancing competitive survival in the rhizosphere.

d) Induced Systemic Resistance (ISR)

The interaction between *Bacillus* species and plants activates a cascade of biochemical and molecular responses involving signaling pathways associated with jasmonic acid (JA), salicylic acid (SA), and ethylene (ET). Important ISR elicitors produced by *Bacillus* include cyclic lipopeptides (CLPs), N-alkylated benzylamine derivatives (NABD), and pyoverdines (Pršić & Ongena, 2020). These molecules strengthen plant immunity and enhance resistance against a broad spectrum of pathogens without exerting direct antimicrobial activity.

Table: Success of *Trichoderma* and *Bacillus* as Biocontrol Agents

Crop	Pathogen	Strain	Mechanism of Action	Reference
Potato (*Solanum tuberosum*)	*Fusarium* sp.	*B. subtilis*	Antagonism	Karačić *et al*., (2024)
Maize (*Zea mays*)	*Cephalosporium maydis*	*B. subtilis*	Siderophore production	Karačić *et al*. (2024)
Rice (*Oryza sativa*)	*Rhizoctonia solani*	*B. subtilis*	Biocontrol and antagonism	Karačić *et al*., (2024)
Soybean (*Glycine max*)	*Phytophthora sojae*	*B. subtilis*, *B. amyloliquefaciens*	Biocontrol activity	Karačić *et al*., (2024)
Tomato (*Solanum lycopersicum*)	*Botrytis cinerea*, *Cladosporium fulvum*	*B. subtilis*	Biocontrol activity	Karačić *et al*., (2024)
Tomato (*Solanum lycopersicum*)	*Fusarium* sp.	*T. asperellum*	Growth inhibition and hydrolytic	Yao *et al*., (2023); Kour & Kaur (2022)

Crop	Pathogen	Strain	Mechanism of Action	Reference
			enzyme production	
Maize (*Zea mays*)	*Spodoptera frugiperda*	*T. atroviride*	Hydrolytic enzyme production	Yao *et al*., (2023)
Onion (*Allium cepa*)	*Fusarium* sp.	*T. harzianum*	Growth inhibition	Kour & Kaur (2022)
Melon (*Cucumis melo*)	*F. oxysporum*, *F. solani*	*T. asperellum*	Antagonism	Yao *et al*., (2023)
Groundnut (*Arachis hypogaea*)	*Sclerotium rolfsii*	*T. virens*	Hydrolytic enzyme production	Yao *et al*., (2023)

Conclusion

Biocontrol agents such as *Trichoderma* and *Bacillus* species represent promising and sustainable alternatives to chemical pesticides in modern agriculture. These beneficial microorganisms not only suppress plant pathogens but also improve soil fertility, stimulate plant growth, and enhance crop productivity. Their diverse mechanisms—including antibiosis, mycoparasitism, lytic enzyme production, siderophore secretion, and induction of systemic resistance—make them highly effective tools for environmentally friendly crop protection. A comprehensive understanding of their mechanisms, formulation strategies, field performance, and environmental interactions is essential for maximizing their effectiveness under diverse agricultural conditions. The integration of microbial biocontrol agents into crop management practices can significantly reduce dependence on synthetic agrochemicals and contribute toward sustainable and climate-resilient agriculture.

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CARBON CREDIT POTENTIAL OF BIO-CHAR APPLICATION IN INDIAN AGRICULTURE

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Abstract

The transition toward "Green Agriculture" in India necessitates a strategic shift from yield-centric practices to sustainable waste management and soil restoration. Indian agriculture is currently a leading contributor to global greenhouse gas (GHG) emissions, driven largely by enteric fermentation and the open-field burning of approximately 92 million tonnes of surplus crop residue. This practice not only triggers severe air quality crises but also destroys vital soil microorganisms and organic matter. This paper explores the potential of bio-char a carbon-dense, stable material produced through the pyrolysis of organic waste—as a transformative solution to these challenges. By converting surplus biomass into bio-char, farmers can effectively "lock" carbon into a chemically stable form that remains in the soil for centuries. This process prevents the release of over 141 million tonnes of CO_2 and other high-GWP gases like methane (CH_4) And nitrous oxide (N_2O) associated with traditional disposal. Beyond climate mitigation, bio-char acts as a permanent soil amendment, enhancing water retention, nutrient density, and overall crop resilience. Crucially, this technology introduces a robust economic incentive through the generation of carbon credits. By quantifying the sequestered carbon, Indian farmers can access a new stream of sustainable revenue, offsetting the costs of labour and technology. Ultimately, bio-char application creates a circular economy that addresses the triple bottom line: mitigating environmental pollution, restoring soil health, and providing financial empowerment to the agricultural community, positioning India as a global leader in carbon sequestration.

Introduction

The primary objective of modern agricultural science has undergone a fundamental shift. In previous decades, the focus was almost entirely on maximizing yields through intensive chemical inputs. Today, however, the industry's main target is the development of sustainable farming systems that prioritize a reduction in synthetic pesticides and a significant decrease in environmental pollution. As the global community moves toward "Green Agriculture," the management of organic waste and the restoration of soil health have become the most critical pillars of this transformation.

One of the most persistent and damaging challenges in traditional farming is the disposal of surplus biomass. Each harvest season, massive quantities of crop residues, manure, and forestry waste are generated. Historically, the most common disposal method has been open-field burning. While this is a low-cost solution for the farmer, the environmental price is staggering. Open burning releases vast amounts of particulate matter and greenhouse gases into the atmosphere, contributing to localized air pollution and global climate change. Furthermore, this practice is destructive to the land itself; the intense heat kills beneficial soil microorganisms and destroys organic matter, leading to a steady decrease in soil quality, fertility, and water retention. To resolve this ecological crisis, we must rethink the lifecycle of agricultural waste. Instead of viewing surplus biomass as a by-product to be destroyed, we can treat it as a feedstock for bio-char production. Bio-char is a carbon-dense material created through pyrolysis the thermal decomposition of organic matter in a closed container with little to no oxygen. Unlike open burning, which releases carbon into the air, pyrolysis captures it. By converting wood, leaves, or manure into bio-char, we prevent the creation of smoke and pollutants, effectively eliminating the environmental hazards associated with waste disposal.

The true value of bio-char, however, lies in its application back into the Earth. When bio-char is integrated into agricultural land, it acts as a permanent soil amendment. Because of its highly porous structure, it enhances the soil's carbon content, improves nutrient density, and boosts the soil's ability to hold water during droughts. Unlike raw organic matter, which decomposes quickly, the carbon in bio-char is chemically stable and can remain in the soil for hundreds or even thousands of years. This process transforms the farm from a source of emissions into a massive carbon sink.

Beyond the environmental and agronomic benefits, this system introduces a powerful economic incentive: carbon credits. As industries worldwide seek to offset their carbon footprints, the documented sequestration of carbon through bio-char application becomes a tradable commodity. By quantifying the amount of carbon "locked" into the ground, farmers can generate carbon credits, providing a new stream of sustainable revenue. This creates a circular economy where waste is eliminated, soil is restored, and the farmer is financially rewarded for environmental stewardship. Ultimately, the adoption of bio-char represents a triple-win for modern agriculture: it cleans the air, heals the land, and strengthens the agricultural economy.

Methodology

1. Biomass Availability

India generates approximately 500 million tonnes of agricultural residue annually, with about 92 million tonnes of surplus biomass, primarily from rice, wheat, and sugarcane, available for bio-char production. This surplus is concentrated in states like Uttar Pradesh, Punjab, and Maharashtra, offering a significant, untapped feedstock that can be utilized without threatening food or fodder security.

Table-1: Total Biomass Available in India (In Thousand Tonnes):

States	Wheat	Rice	Maize	Sugarcane	Total Crops
Andaman & Nicobar	--	19.7	1	0.1	20.8
Andhra Pradesh	0.1	14407	4248	394	19049.1
Arunachal Pradesh	14.2	322	--	2.1	338.3
Assam	43.6	7768	212.5	56.5	8080.6
Bihar	10096	11571.6	7289	646.6	29603.2
Chandigarh	4.6	0.1	0.1	--	4.8
Chhattisgarh	268	10962	599.5	3.9	11833.4
Dadra & Nagar Haveli, and Daman &Diu	0.6	41.5	0.2	2.6	44.9
Goa	--	157.5	--	2	159.5

States	Wheat	Rice	Maize	Sugarcane	Total Crops
Gujarat	4904.8	2785.1	1659	555.9	9904.8
Haryana	20024.4	5985.5	57.5	371.7	26439.1
Himachal Pradesh	922.3	166.5	1459	2	2549.8
Jammu & Kashmir	1040.2	865.9	1221.2	--	3127.3
Jharkhand	340.4	3479.3	753.3	--	4573
Karnataka	311.7	4413	9381	1630.5	15736.2
Kerala	--	739.3	0.1	0.6	740
Madhya Pradesh	31555.6	5131.5	5316.4	187.8	42191.3
Maharashtra	3048.1	4456	6231.7	3433.8	17169.6
Manipur	10	803.9	135.5	17.1	966.5
Meghalaya	1.6	455.1	95.4	--	552.1
Mizoram	--	92.6	22.1	2.4	117.1
Nagaland	9.1	684	319.3	21.3	1033.7
Odisha	0.4	11110.3	332.4	1.9	11445
Puducherry	--	76	--	10.1	86.1
Punjab	30925.8	18921.5	1013.1	366.2	51226.6
Rajasthan	20609.2	636.7	3315.4	25.5	24586.8
Sikkim	0.7	29.6	157.3	--	187.6
Tamil Nadu	--	18154.3	10620.2	1027.5	29802
Telangana	23.9	10835.7	7834.7	183.7	18878
Tripura	0.6	1345.8	21.5	2.2	1370.1
Uttar Pradesh	65194.1	23005.1	3571.3	8561.7	100332.2
Uttarakhand	1639.4	977.4	91.4	295.8	3004
West Bengal	1348.7	24139.1	3780.2	81.5	29349.5
Total	192338.9	184538.8	69739.4	17887.1	464504.2

Table-2: Total Surplus Biomass (In Thousand Tonnes):

States	Rice	Wheat	Maize	Sugarcane	Total
Andaman & Nicobar	3.3	--	0.2	--	3.50
Andhra Pradesh	2571	--	2389	394	5354
Arunachal Pradesh	14	2.8	20.2	0.5	37.50
Assam	650.58	8.71	42.5	14.12	715.91
Bihar	1106.7	2019.2	1860.6	570.6	5557.10
Chandigarh	0.1	0.9	--	--	1.00
Chhattisgarh	2189.5	53.6	86.9	1	2331
Dadra & Nagar Haveli, and Daman &Diu	7.06	0.11	0.45	0.66	8.28
Goa	26.78	--	--	0.51	27.29
Gujarat	111.4	981	116.1	155.7	1364.20
Haryana	3002.7	2002.4	11.5	92.9	5109.50
Himachal Pradesh	28.3	184.5	291.8	0.5	505.10
Jammu & Kashmir	147.2	208	244.2	--	599.40
Jharkhand	347.9	68.1	346.5	--	762.50
Karnataka	750.2	62.3	1876.2	1524.5	4213.20

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States	Rice	Wheat	Maize	Sugarcane	Total
Kerala	175.9	--	--	0.1	176.00
Madhya Pradesh	1940.8	6311.1	2152.3	46.9	10451.10
Maharashtra	43.1	609.6	38.9	858.4	1550.00
Manipur	352.1	2	27.1	2.3	383.50
Meghalaya	25.7	0.3	19.1	--	45.10
Mizoram	11.3	--	4.4	0.6	16.30
Nagaland	203.5	1.8	63.9	5.3	274.50
Odisha	2007.3	0.1	66.5	0.5	2074.40
Puducherry	12.9	--	--	2.5	15.40
Punjab	18786.3	3092.6	202.6	91.5	22173.00
Rajasthan	108.2	4121.8	25.3	6.4	4261.70
Sikkim	0.2	0.1	31.5	--	31.80
Tamil Nadu	3086.2	--	2124	256.9	5467.10
Telangana	1368.7	4.8	2350.4	45.9	3769.80
Tripura	228.8	0.1	4.3	0.5	233.70
Uttar Pradesh	1035.2	13038.8	35.7	2211.8	16321.50
Uttarakhand	158.3	327.9	18.3	73.9	578.40
West Bengal	1225.2	269.7	756	20.4	2271.30
Total	41726.9	33372.5	15206.7	6379.1	96685.20

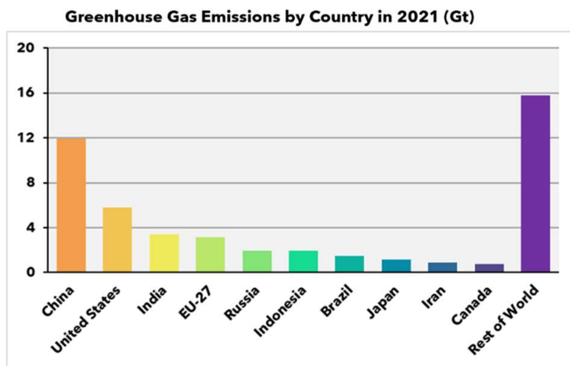
*Source: https://nibe.res.in/english/index.php

2. Background

Indian agriculture is the third-highest contributor of GHGs in the world, as shown in the provided figure for 2021. Agriculture predominantly contributes to the emission of high global warming potential (GWP) gases which are rich in methane (CH_4) and nitrous oxide(N_2O) mainly coming from enteric fermentation, synthetic fertilizer usage, and rice cultivation.

The disproportionate emission of powerful GHGs such as N_2O and CH_4 from intensive agriculture is a major concern for realizing sustainable GHG emission targets. On the other hand, CH_4 has a short half-life (12 years) in the atmosphere in comparison to N_2O and other major GWP contributors. Thus, it makes CH_4 an ideal target molecule for rapidly balancing out the carbon footprint from Indian agriculture. However, the increase in population and food habit changes (preference for animal protein) due to enhanced purchasing power will be the major accelerators of offsetting the environmental footprint of the agricultural sector in India.

Sources of agricultural emissions include CO_2 from liming and urea application, CH_4 from rice cultivation, and burning crop residues, which produces CH_4 and N_2O.



Source: Climate Watch Historical GHG Emissions (1990-2020). 2023.

The potential for bio-char in India is rooted in the country's massive agricultural output, which produces approximately 500 million tonnes of crop residue annually. Currently, a staggering 92 million tonnes of this biomass primarily from rice, wheat, and sugarcane is burned openly in fields. This practice is driven by economic pressures and the narrow time window between harvest and sowing seasons. By converting this surplus waste into bio-char through pyrolysis instead of burning it, India could pivot from being a major source of regional air pollution to a global leader in carbon sequestration. Makavana *et al.* (2020) to analysed the quality of bio-char for various applications is discussed along with different quality parameters.

Environmentally, the shift to bio-char would address a critical air quality crisis. The provided data shows that burning nearly 100 million tonnes of residue releases over 141 million tonnes of CO_2 and massive amounts of particulate matter, which in areas like Delhi can be 17 times higher than industrial or vehicular emissions. Bio-char technology traps this carbon in a stable, solid form, preventing it from entering the atmosphere. This process not only mitigates global warming but also preserves the essential nitrogen and organic carbon that are currently lost to the flames, thereby protecting long-term soil fertility and biodiversity.

From an economic and "Carbon Credit" perspective, bio-char offers a dual-income stream for Indian farmers. Beyond the traditional sale of food grains, farmers could generate tradable carbon credits by documenting the amount of carbon "locked" into the soil. This provides the financial incentive needed to overcome the labour shortages and high costs that currently make burning the only viable option for many. Furthermore, the application of bio-char back into the fields improves water retention and nutrient efficiency, leading to higher crop yields and more resilient agricultural systems in the face of climate change.

Conclusion

Bio-char offers a transformative "triple-win" for Indian agriculture by addressing environmental, agronomic, and economic challenges through a scalable, low-cost strategy. By replacing the destructive practice of open-field burning with controlled pyrolysis, India can reduce life-cycle emissions by up to 72% and mitigate severe air quality crises while sequestering carbon for centuries in a stable, solid form. Beyond climate mitigation, bio-char serves as a permanent soil amendment that restores land health by enhancing nutrient retention and water use efficiency, ultimately boosting crop resilience. Economically, the system introduces a vital dual-income stream for farmers, who can generate tradable carbon credits estimated to reach break-even viability at 25 USD per tCO_2 providing the financial incentive necessary to transition toward sustainable, "Green Agriculture".

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CARRAGEENAN FILM INCORPORATED WITH HERBAL EXTRACTS FOR ACTIVE SEAFOOD PACKAGING: RECENT ADVANCES AND APPLICATIONS

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Abstract

The growing environmental concerns associated with synthetic plastic packaging and increasing consumer demand for natural food preservation methods have accelerated research on biodegradable active packaging systems. Carrageenan-based films incorporated with herbal extracts have emerged as promising eco-friendly packaging materials for seafood preservation. Carrageenan, a sulfated polysaccharide extracted from red seaweeds, possesses excellent film-forming and gelation properties suitable for food packaging applications. Herbal extracts rich in phenolic compounds, flavonoids, and essential oils exhibit strong antimicrobial and antioxidant activities that enhance the functional properties of carrageenan films. These bioactive films effectively retard microbial growth, lipid oxidation, and quality deterioration in seafood products during storage. This article reviews the properties, preparation methods, mechanisms, applications, advantages, recent developments, and future prospects of carrageenan films incorporated with herbal extracts in active seafood packaging systems.

Keywords: Carrageenan film, Herbal extracts, Active packaging, Seafood preservation Biodegradable packaging, Antimicrobial film, Antioxidant packaging

Introduction

Seafood products are highly susceptible to spoilage due to microbial contamination, enzymatic activity, and lipid oxidation. Conventional plastic packaging materials provide physical protection; however, they contribute significantly to environmental pollution due to their non-biodegradable nature. Consequently, biodegradable and active packaging materials have gained substantial attention in the seafood processing industry. Carrageenan, a natural polysaccharide obtained from red seaweeds such as Kappaphycus alvarezii and Eucheuma, has emerged as an important biodegradable film-forming material because of its excellent mechanical strength, transparency, flexibility, and biocompatibility. However, pure carrageenan films possess limited antimicrobial and antioxidant activities.

To overcome these limitations, researchers have incorporated herbal extracts into carrageenan films to develop active packaging systems capable of extending seafood shelf life and improving product safety. Herbal extracts derived from plants such as turmeric, clove, neem, oregano, rosemary, green tea, and ginger contain bioactive compounds with strong preservative effects. These natural additives enhance the antimicrobial, antioxidant, and functional properties of carrageenan films while maintaining biodegradability and food safety.

Carrageenan as a Biopolymer for Seafood Packaging

Carrageenan is a sulfated galactan extracted from red seaweeds and widely used in food and pharmaceutical industries. Based on sulfate content and molecular structure, carrageenan is classified into:

- Kappa-carrageenan
- Iota-carrageenan
- Lambda-carrageenan

Among these, kappa-carrageenan is most commonly used in film preparation because of its strong gel-forming properties.

Properties of Carrageenan Films

- Excellent film-forming ability
- Biodegradable and edible
- Good oxygen barrier properties
- High transparency
- Non-toxic and biocompatible
- Flexible and heat stable

These properties make carrageenan highly suitable for seafood packaging applications.

Herbal Extracts Used in Carrageenan Films

Various herbal extracts are incorporated into carrageenan films to improve preservation efficiency.

Herbal Extract	Major Bioactive Compounds	Functional Properties
Turmeric	Curcumin	Antioxidant, antimicrobial
Clove	Eugenol	Antibacterial, antifungal
Neem	Azadirachtin	Antimicrobial
Ginger	Gingerol	Antioxidant
Rosemary	Rosmarinic acid	Antioxidant
Oregano	Carvacrol	Strong antimicrobial
Green tea	Catechins	Antioxidant

These bioactive compounds inhibit microbial growth and lipid oxidation in seafood products.

Preparation of Carrageenan-Herbal Films

The preparation of carrageenan films generally involves:

1. Dissolution of carrageenan in distilled water
2. Heating and stirring to form a uniform solution
3. Addition of plasticizers such as glycerol
4. Incorporation of herbal extracts
5. Casting and drying of films

The resulting films are biodegradable, flexible, and bioactive.

Mechanism of Preservation

Antimicrobial Action

Herbal extracts disrupt microbial cell membranes, inhibit enzyme activity, and interfere with microbial metabolism, thereby reducing bacterial and fungal growth in seafood products.

Antioxidant Action

Phenolic compounds present in herbal extracts scavenge free radicals and retard lipid oxidation, thereby preserving seafood flavor, texture, and color.

Applications in Seafood Preservation

Carrageenan films incorporated with herbal extracts are extensively used for packaging:

- Fish fillets

- Shrimp
- Dried fish
- Smoked seafood
- Frozen fish products

Effects on Seafood Quality

These films help:

- Reduce microbial load
- Lower lipid oxidation
- Maintain texture and color
- Improve sensory quality
- Extend shelf life

Recent Advances

Nanocomposite Carrageenan Films

Researchers have incorporated nanoparticles such as:

- Zinc oxide nanoparticles
- Silver nanoparticles
- Nano-cellulose

to improve:

- Mechanical strength
- Water resistance
- Antimicrobial activity

Intelligent Packaging Systems

Carrageenan films integrated with natural pigments can function as freshness indicators by changing color in response to seafood spoilage.

Advantages of Carrageenan-Herbal Packaging

Environmental Advantages

- Biodegradable
- Eco-friendly
- Reduces plastic pollution

Functional Advantages

- Active preservation
- Improved shelf life
- Natural antimicrobial activity
- Consumer safety enhancement

Economic Advantages

- Renewable raw materials
- Potential commercial scalability

Limitations

Despite several advantages, some limitations remain:

- Poor moisture resistance
- Lower mechanical strength compared to plastics
- Higher production cost

- Sensitivity to humidity

Further modifications and composite technologies are needed to improve industrial applicability.

Future Perspectives

Future research should focus on:

- Development of multifunctional smart packaging systems
- Integration of biosensors and freshness indicators
- Commercial-scale production methods
- Use of marine-derived natural preservatives
- Improvement of water resistance and mechanical durability

Carrageenan-herbal films have tremendous potential to replace conventional plastic packaging in seafood industries and contribute to sustainable food systems.

Conclusion

Carrageenan films incorporated with herbal extracts represent an innovative and sustainable approach for active seafood packaging. The combination of biodegradable seaweed-derived polymers with natural antimicrobial and antioxidant compounds offers an eco-friendly alternative to synthetic plastic packaging materials. These active films effectively enhance seafood quality, safety, and shelf life by reducing microbial spoilage and lipid oxidation. Although challenges related to moisture sensitivity and production cost remain, ongoing advancements in biopolymer technology and active packaging systems are expected to accelerate commercial applications. Therefore, carrageenan-herbal extract films hold significant promise for the future development of sustainable seafood preservation technologies.

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HOW CLIMATE CHANGE INFLUENCES PHOTOSYNTHESIS AND CROP YIELD

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Abstract

Climate change is emerging as a major threat to global agriculture by altering environmental conditions essential for crop growth. Rising temperatures, irregular rainfall patterns, droughts, floods, and increasing atmospheric carbon dioxide (CO_2) levels significantly influence photosynthesis, the primary process responsible for plant growth and yield formation. Elevated temperatures can reduce photosynthetic efficiency through increased photorespiration and chlorophyll degradation, while drought and flooding restrict carbon assimilation and nutrient uptake. Although higher CO_2 levels may enhance photosynthesis in some crops, the benefits are often offset by heat stress, water scarcity, and nutrient limitations. These combined effects reduce crop productivity and threaten global food security. Adoption of climate-resilient crop varieties, efficient water management, improved soil health practices, and digital agricultural technologies can help farmers adapt to changing climatic conditions and sustain crop production in the future.

Keywords: Climate change, Photosynthesis, Crop yield, Drought stress, Elevated CO_2, Climate-smart agriculture

Introduction

Agriculture is highly dependent on favorable climatic conditions. However, climate change is disrupting crop production worldwide through rising temperatures, erratic rainfall, prolonged droughts, flooding, and frequent extreme weather events. Among plant processes, photosynthesis is particularly sensitive to environmental changes because it drives the production of carbohydrates that support plant growth and yield. Any factor that affects photosynthesis ultimately influences crop productivity. Understanding these relationships is essential for developing sustainable and climate-resilient agricultural systems.

Photosynthesis: The Engine of Crop Production

Photosynthesis is the process by which green plants convert sunlight, water, and carbon dioxide into sugars and oxygen. Chlorophyll pigments in leaves capture solar energy and transform it into chemical energy, which supports plant growth, flowering, fruit development, and grain filling. Since crop yield depends largely on the efficiency of photosynthesis, environmental stresses caused by climate change can have serious consequences for agricultural productivity.

Rising Temperatures and Photosynthesis

One of the most evident effects of climate change is increasing global temperature.

Reduced Enzyme Efficiency

Photosynthesis relies on enzymes such as RuBisCO. Excessive temperatures reduce enzyme efficiency and increase photorespiration, a process that wastes energy and decreases carbohydrate production.

Chlorophyll Damage
Heat stress can degrade chlorophyll pigments and damage chloroplast structures, reducing the plant's ability to capture sunlight effectively. Symptoms often include leaf yellowing and reduced crop vigor.

Impact on Reproduction
High temperatures during flowering can reduce pollen viability, fertilization, and grain filling. Crops such as rice, wheat, and maize are particularly vulnerable, resulting in lower yields.

Elevated Carbon Dioxide: A Double-Edged Sword
Increasing atmospheric CO_2 levels can stimulate photosynthesis, especially in C_3 crops such as rice, wheat, soybean, and cotton. This phenomenon is known as the CO_2 fertilization effect. However, the benefits are often limited by simultaneous stresses such as drought, heat, and nutrient deficiencies. Elevated CO_2 may also reduce the protein, zinc, and iron content of grains, affecting nutritional quality.

Drought Stress and Crop Productivity
Climate change is increasing the frequency of droughts in many agricultural regions.

Stomatal Closure
Under water deficit conditions, plants close their stomata to reduce water loss. This also restricts CO_2 entry into leaves, reducing photosynthesis.

Reduced Leaf Growth
Drought limits cell expansion and leaf development, decreasing the surface area available for light interception.

Oxidative Damage
Water stress often triggers the production of reactive oxygen species (ROS), which damage chloroplasts, proteins, and cell membranes, further reducing photosynthetic efficiency.

Effects of Flooding and Waterlogging
Excess rainfall and flooding are becoming more common under changing climatic conditions. Flooded soils contain limited oxygen, restricting root respiration and nutrient uptake. Consequently, plants experience chlorophyll degradation, poor growth, and reduced photosynthetic activity. Waterlogging can cause substantial yield losses in maize, soybean, pulses, and several horticultural crops, particularly when flooding occurs during sensitive growth stages.

Extreme Weather Events
Climate change has increased the frequency of heat waves, cyclones, heavy rainfall, and prolonged dry spells.
These events can cause

- Leaf scorching and tissue damage, Lodging in cereal crops, Flower and fruit drop, Poor pollination, Increased pest and disease outbreak. Repeated exposure to such stresses significantly reduces crop productivity and farm profitability.

Impact on Major Crops
Rice
Rice is highly sensitive to heat stress during flowering. High temperatures can increase spikelet sterility and reduce grain filling, leading to lower yields.

Wheat

Rising temperatures shorten the grain-filling period and reduce grain weight, affecting overall productivity.

Maize

Combined heat and drought stress during tasseling and silking stages severely affect pollination and kernel development.

Horticultural Crops

Fruit and vegetable crops experience reduced flowering, fruit set, quality, and shelf life under temperature fluctuations and water stress.

Implications for Food Security

Global food demand is increasing rapidly due to population growth. At the same time, climate change is reducing photosynthetic efficiency and crop productivity. Without effective adaptation measures, climate-induced yield losses may lead to food shortages, higher food prices, and nutritional insecurity, especially in developing countries.

Adaptation Strategies for Farmers

Several practical approaches can help reduce climate-related crop losses:

Climate-Resilient Varieties

- Heat-tolerant crops
- Drought-tolerant cultivars
- Flood-tolerant varieties

Efficient Water Management

- Drip irrigation
- Mulching
- Rainwater harvesting
- Precision irrigation

Improved Soil Health

- Addition of organic matter
- Conservation agriculture
- Improved nutrient management

Protected Cultivation

- Greenhouses
- Shade nets
- Polyhouses

Digital Agriculture

- Weather forecasting tools
- Remote sensing
- Smart irrigation systems
- Artificial intelligence-based decision support

Future Prospects

Researchers are exploring innovative solutions such as improving photosynthetic efficiency, gene editing technologies, climate-smart agriculture, beneficial microorganisms, and AI-assisted crop management. These advancements can help sustain agricultural productivity under future climate scenarios.

Conclusion

Climate change is significantly influencing photosynthesis and crop productivity through rising temperatures, drought, flooding, elevated CO_2 levels, and extreme weather events. Since photosynthesis forms the foundation of crop growth and yield, disruptions in this process directly threaten food security and farmer livelihoods. Adopting climate-smart agricultural practices, resilient crop varieties, efficient water management, and digital technologies will be essential to minimize climate risks and ensure sustainable agricultural production in the coming decades.

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CLIMATE SMART AGRICULTURE FOR SUSTAINABLE RURAL LIVELIHOODS

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Agriculture remains the primary source of livelihood for nearly 2.5 billion people worldwide and is central to food security, poverty alleviation and rural development (FAO, 2023). Globally, a large proportion of poor households live in rural areas and depend directly or indirectly on agriculture for their livelihoods. In India, agriculture and allied sectors contribute about 18 per cent to the Gross Value Added (GVA) and provide employment to nearly 46 per cent of the workforce (Government of India, 2024). In Assam, agriculture remains the principal occupation and a major source of employment and income. Out of the state's geographical area of about 7.8 million hectares, nearly 4.0 million hectares are under cultivation. Rice is the dominant crop, followed by rapeseed-mustard, tea, potato, banana, arecanut and various vegetables. Despite its importance, agriculture in Assam faces several challenges, including recurrent floods, low irrigation coverage, land degradation, limited adoption of improved technologies and increasing climate variability. These challenges highlight the need for innovative and sustainable agricultural approaches that can improve productivity, strengthen resilience and support sustainable rural livelihoods. Recent studies emphasize that climate-smart innovations can play a crucial role in building climate-resilient livelihood systems. Such innovations contribute not only to climate action (SDG 13) but also to poverty reduction (SDG 1) and food security (SDG 2) (Zewdu *et al.,* 2025).

Climate Change and Agricultural Livelihoods

Climate change is widely recognized as one of the most serious threats to global agriculture and food security. The Intergovernmental Panel on Climate Change (IPCC) reports that global surface temperature has already increased by approximately 1.1°C above pre-industrial levels, resulting in more frequent and intense extreme weather events such as floods, droughts, heat waves and cyclones (IPCC, 2023). Agriculture is particularly vulnerable because crop growth, livestock productivity, water availability and pest dynamics are directly influenced by climatic conditions.

In India, where agriculture remains a major source of employment and food security, climate change poses significant risks to sustainable agricultural development. Studies suggest that for every 1°C increase in global temperature, yields of major cereal crops may decline significantly unless appropriate adaptation measures are implemented (Porter *et al*., 2014). The challenge is particularly severe in Assam, where frequent floods, erratic rainfall, waterlogging, rising temperatures and increasing incidences of pests and diseases continue to affect agricultural productivity and rural livelihoods. These growing climate-related risks highlight the urgent need for climate-smart agricultural practices that can improve productivity, strengthen resilience and ensure long-term food security.

Climate-Smart Agriculture: A Sustainable Approach

Climate-Smart Agriculture (CSA) is an approach that aims to sustainably increase agricultural productivity and incomes, strengthen resilience and adaptation to climate change and reduce greenhouse gas emissions wherever possible (FAO, 2013; Lipper *et al.,* 2014). Rather than being a single technology, CSA integrates appropriate technologies, management practices, policies and institutional support according to local agro-ecological and socio-economic conditions.

By combining traditional knowledge with modern scientific innovations, CSA promotes productive, resilient and environmentally sustainable farming systems. Its three core objectives are enhancing productivity, strengthening adaptation and resilience and contributing to climate change mitigation.

Climate-Resilient Crops and Diversification

The adoption of climate-resilient crop varieties is a key component of CSA. Such varieties help farmers cope with droughts, floods, heat stress and emerging pest and disease threats. In Assam, flood-tolerant rice varieties such as Ranjit Sub-1, Bahadur Sub-1, Swarna Sub-1 and Bina Dhan-11 have demonstrated superior performance under submergence conditions by maintaining higher survival rates and yield stability during flood events. Likewise, drought-tolerant rice varieties such as CR Dhan 801, CR Dhan 802 and AAU TTB Dhan 45 have shown promising adaptability to moisture-stress conditions, particularly in rainfed and drought-prone areas of the region. Crop diversification through mixed cropping, intercropping and crop rotation further enhances resilience by reducing production risks and improving resource-use efficiency. Diversified farming systems also improve soil fertility, reduce pest incidence and contribute to stable farm income (Pretty *et al*., 2018; Altieri *et al*., 2015).

Climate-Smart Soil Management

Healthy soil forms the foundation of sustainable and climate-resilient agriculture (Lal, 2015). Climate-smart soil management focuses on improving soil fertility and maintaining long-term productivity through practices such as organic farming, composting, green manuring, crop residue incorporation and the use of biofertilizers.

Integrated Nutrient Management (INM), which combines organic and inorganic nutrient sources, helps maintain soil fertility and improve nutrient-use efficiency. The application of farmyard manure, vermicompost and biochar improves soil structure, nutrient availability, moisture retention and soil organic carbon content.

Conservation agriculture practices such as minimum tillage, residue retention, cover cropping, and crop rotation further improve soil health by reducing erosion, conserving moisture and enhancing carbon sequestration (FAO, 2021; Lal, 2015). Together, these practices strengthen resilience to droughts and floods while supporting sustainable agricultural production.

Efficient Water Management

Efficient water management is a key component of Climate-Smart Agriculture (CSA), especially in regions facing water scarcity, erratic rainfall and drought due to climate change. Since agriculture accounts for nearly 70% of global freshwater withdrawals (FAO, 2023), improving water-use efficiency is essential for enhancing resilience and sustaining crop production. Climate-smart water management includes rainwater harvesting through farm ponds and community water-storage structures to capture excess rainfall for use during dry periods. Micro-irrigation technologies such as drip and sprinkler irrigation improve water-use efficiency by delivering water directly to the root zone and reducing water losses.

In rice-based systems, water-saving practices such as Alternate Wetting and Drying (AWD), System of Rice Intensification (SRI) and Direct-Seeded Rice (DSR) help conserve water without reducing productivity. AWD can reduce irrigation water use by 15–30% and lower methane emissions compared to continuous flooding (Bouman *et al*., 2007; Lampayan *et al.,* 2015). SRI enhances water productivity through improved root growth and nutrient uptake, while DSR reduces water and labour requirements by eliminating puddling and transplanting. Together, these practices improve resource-use efficiency, strengthen resilience to water stress and support sustainable agricultural production under changing climatic conditions.

Climate-Smart Pest and Disease Management

Climate change is altering the distribution, intensity and epidemiology of insect pests and diseases through rising temperatures, changing rainfall patterns, increased humidity and extreme weather events (IPCC, 2023; Bebber *et al*., 2013). Consequently, pests such as stem borers, leaf folders, fall armyworm (*Spodoptera frugiperda*), swarming caterpillar (*Spodoptera mauritia*), aphids and fruit and shoot borers, as well as diseases including rice blast, brown spot, sheath blight, bacterial leaf blight and potato late blight, are becoming more frequent and severe, causing significant yield losses.

Climate-Smart Agriculture promotes Integrated Pest Management (IPM) and Integrated Disease Management (IDM) through resistant varieties, crop rotation, timely sowing, field sanitation, balanced nutrient management, habitat management and need-based pesticide use (Pretty & Bharucha, 2015). Biological control agents such as *Trichoderma viride*, *Pseudomonas fluorescens*, *Beauveria bassiana* and *Metarhizium anisopliae* provide eco-friendly management of pests and diseases. Additional measures include pheromone, sticky and light traps, bird perches and conservation of natural enemies such as predators and parasitoids. The integration of weather-based pest forewarning systems, regular surveillance and climate-informed advisory services further improves pest and disease management. Together, these climate-smart approaches reduce production costs, delay pesticide resistance, conserve biodiversity, protect ecosystem services and enhance agricultural resilience to climate-related risks (Pretty & Bharucha, 2015; Altieri *et al*., 2015).

Integrated Farming Systems and Agroforestry

Integrated Farming Systems (IFS) are a key component of Climate-Smart Agriculture, integrating crops, livestock, fisheries, horticulture and agroforestry to enhance productivity, profitability, resilience and environmental sustainability (Mahapatra *et al*., 2018). By promoting resource recycling through crop residues, by-products and livestock waste, IFS improves nutrient-use efficiency, soil health and reduces dependence on external inputs. It also diversifies income sources, generates year-round employment and strengthens livelihood security. In flood-prone areas, rice–fish farming systems provide additional income, improve nutritional security through animal protein, and enhance pest control and nutrient cycling. Similarly, crop diversification with fruits, vegetables, spices, plantation crops and other high-value enterprises increases profitability, reduces production risks and improves nutrition, making farming systems more resilient to climatic shocks.

Agroforestry, which integrates trees with crops and/or livestock, offers multiple benefits including improved soil fertility, biodiversity conservation, microclimate regulation, reduced soil erosion and greater resilience to climate variability. It also contributes significantly to climate change mitigation through carbon sequestration, with agroforestry systems storing about 2–9 Mg C ha^{-1} $year^{-1}$ (Jose, 2009). Together, IFS and agroforestry support sustainable, climate-resilient and economically viable agricultural development.

Climate Information Services and Digital Agriculture

Climate information services and digital technologies are becoming increasingly important in strengthening agricultural resilience. Accurate weather forecasts and agro-advisory services help farmers make informed decisions regarding sowing, irrigation, fertilizer application and pest management.

Mobile-based advisory services provide real-time information on weather, crop management, and market prices. Technologies such as remote sensing, Geographic Information Systems (GIS), drones and precision agriculture tools enable efficient monitoring of crop health, soil moisture and nutrient status. Early warning systems for floods, droughts, cyclones and pest outbreaks help farmers take timely preventive measures and minimize losses (World Bank, 2021; FAO, 2022).

Conclusion

Climate-Smart Agriculture offers a practical and holistic pathway for achieving sustainable rural livelihoods in the face of increasing climate variability and environmental challenges. By integrating climate-resilient crop varieties, efficient water and nutrient management, conservation agriculture, integrated farming systems, agroforestry and climate-informed decision-making, CSA enhances agricultural productivity while strengthening resilience and environmental sustainability.

For climate-vulnerable regions such as Assam and Northeast India, the widespread adoption of climate-smart practices can improve food security, diversify income opportunities, reduce climate-related risks and support long-term rural development. Continued investment in research, extension services, policy support and technological innovation will be essential for realizing the full potential of Climate-Smart Agriculture in the years ahead.

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FROM CROP CUTTING EXPERIMENTS TO SATELLITES: THE NEW FACE OF CROP YIELD ESTIMATION

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Introduction: Why Yield Estimation Matters?

A crop yield estimate may look like a simple number, but it carries enormous consequences. It tells governments how much food is likely to enter the market, helps procurement agencies prepare for arrivals, guides traders and processors, and determines the scale of compensation under crop insurance. For farmers, the difference between an accurate and a delayed yield estimate can be the difference between timely relief and avoidable financial stress.

For decades, India has relied heavily on Crop Cutting Experiments (CCEs), a statistically designed field method in which selected plots are harvested and weighed to estimate yield for a crop and area. CCEs remain scientifically valuable because they observe the crop in the field and provide ground truth. However, agriculture has changed. Holdings are fragmented, weather is more erratic, crop calendars are shifting, and insurance programmes require rapid, transparent and spatially consistent estimates. The question is therefore not whether CCEs should disappear; it is how they can be strengthened with satellites, mobile applications and modern statistical models.

The policy shift is already visible. Under the Pradhan Mantri Fasal Bima Yojana (PMFBY), the Government of India has introduced YES-TECH—Yield Estimation System Based on Technology—from Kharif 2023 for paddy and wheat, with soybean added from Kharif 2024. Official releases state that 30% weightage is mandatorily assigned to YES-TECH-derived yield for eligible crops, while technology is also being used for CCE planning, crop area estimation, loss assessment and insurance settlement (Government of India, Ministry of Agriculture & Farmers Welfare [MoAFW], 2024, 2025a).

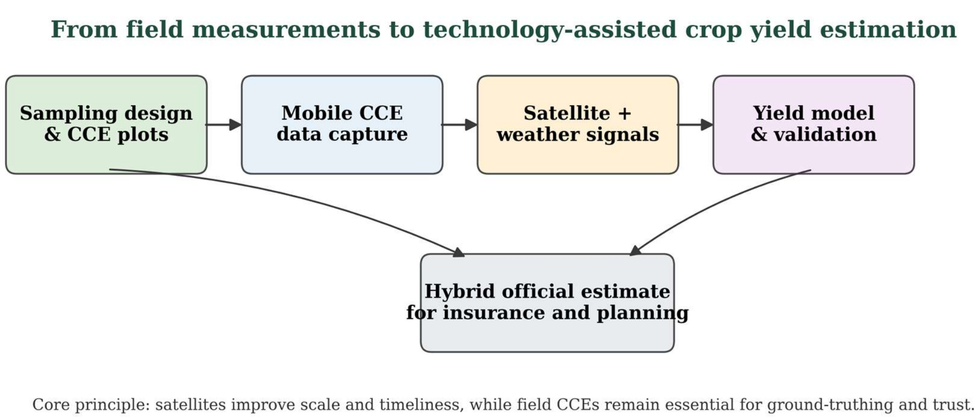

Figure 1. Conceptual workflow showing how field CCEs, mobile data capture, satellite/weather signals and statistical validation can be combined into a hybrid crop yield estimation system.

What CCEs Do Well—and Where They Struggle

The statistical strength of a CCE lies in probability sampling. Instead of measuring every field, a carefully selected sample of plots is harvested, and the resulting yield is expanded to represent a larger area. This is the same logic that makes sample surveys powerful: if the sample is representative and the measurement is reliable, the estimate can be both economical and scientifically defensible.

Yet CCEs face practical constraints. They are labour-intensive, time-sensitive and vulnerable to reporting delays. A harvested plot must be correctly located, cut at the right stage, weighed accurately and uploaded without manipulation. In a large country with diverse crops and agro-climatic zones, the operational burden becomes substantial. Moreover, localised weather shocks may create yield variability that a small number of sample plots cannot fully capture. This is where satellite-based indicators add value: they observe large areas repeatedly and provide objective signals on crop vigour, water stress, vegetation condition and spatial heterogeneity.

Remote sensing does not directly "see yield" in the way a field worker weighs grain. It measures reflectance, canopy condition, moisture and crop growth proxies such as vegetation indices. Statistical and machine-learning models then relate those signals to observed yield. Reviews of remote-sensing yield estimation show that optical data, radar data, weather variables and crop-growth models are increasingly being combined, but they also emphasize the continuing need for field data to calibrate and validate predictions (Basso *et al*., 2013; Muruganantham *et al*., 2022; Narimani *et al*., 2026).

Table 1. From Conventional CCEs to Hybrid Technology-Assisted Yield Estimation

Component	Conventional CCE system	Technology-assisted system	Best hybrid use
Primary evidence	Harvested sample plots and weighed produce	Satellite imagery, weather, crop masks and mobile records	Use CCE as ground truth and satellite data for spatial scale
Statistical logic	Probability sampling and expansion from plot to area	Prediction model trained on historical yield and remote-sensing features	Combine design-based and model-based inference
Strength	Direct field measurement; farmer-visible and auditable	Timely, scalable and spatially consistent	Improves transparency while reducing exclusive dependence on manual measurement
Main risk	Delay, inadequate sample size, operational errors	Cloud cover, model transferability, weak ground-truth data	Independent validation and transparent error reporting
Policy use	Official yield estimates and insurance assessment	Early warning, crop monitoring, loss assessment and yield dispute support	Faster, better documented estimates for planning and PMFBY

YES-TECH: The Statistical Bridge

YES-TECH should be understood as a bridge between field statistics and Earth observation. Government releases describe it as a system for gradually migrating toward remote-sensing-based yield estimation under PMFBY, after pilot studies and technical consultations through institutions including the Mahalanobis National Crop Forecast Centre. The system is intended to make yield estimation more systematic, timely, objective and transparent (MoAFW, 2024, 2025a).

In simple statistical terms, a hybrid yield estimate can be written as:

$Y^* = wCCE \times YCCE + wTECH \times YTECH$, where $wCCE + wTECH = 1$

Here, Y* is the blended yield estimate, YCCE is the estimate from conventional/statutory field measurement, and YTECH is the model-based technology estimate. In the current YES-TECH framework described by official releases, the technology component receives 30% mandatory weightage for specified crops. The logic is important: the model is not allowed to float without field evidence, and the field estimate is not left alone when spatial technology can improve timeliness and consistency.

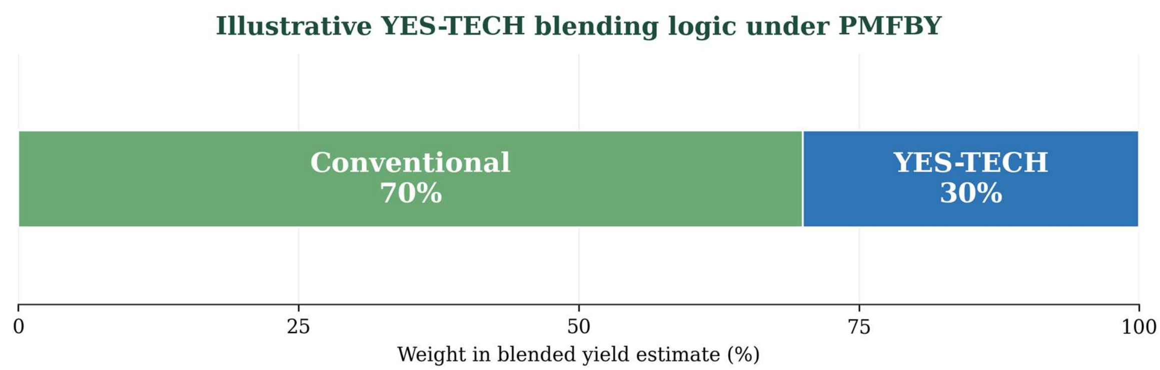

Figure 2. Official releases indicate 30% mandatory weightage to YES-TECH-derived yield for eligible crops; the bar is presented as an explanatory visual of the blended-estimate logic, not as a replacement for the detailed YES-TECH manual.

Digital Crop Survey and Krishi-DSS: Strengthening The Denominator

Yield is only one part of production. Production is calculated as area multiplied by yield. If crop area is wrong, even a good yield estimate may produce a poor production estimate. This is why Digital Crop Survey (DCS) and Krishi-DSS are central to the new architecture. The DCS system collects crop-sown details through a mobile interface and is intended to provide accurate, real-time crop area information for every agricultural plot (MoAFW, 2025b). Krishi-DSS integrates geospatial and non-geospatial data, including satellite, weather, soil, crop signatures, reservoirs, groundwater and government scheme information, and offers crop maps, soil maps, automated yield estimation models and drought/flood monitoring tools (MoAFW, 2025c).

This shift changes the statistical problem. Earlier, the main question was: “How many CCEs are enough to estimate yield?” The new question is broader: “How can plot-level crop area, satellite-derived crop condition, weather anomalies and field measurements be fused into a reliable, auditable estimate?” That requires not only data science but also survey discipline: sampling frames, metadata, validation plots, quality checks, model documentation and uncertainty intervals.

Table 2. Practical validation dashboard for technology-assisted crop yield estimation

Validation item	Suggested metric/check	Interpretation	Why it matters
Prediction error	RMSE, MAE, MAPE	Difference between model yield and observed CCE yield	Shows whether the model is accurate enough for operational use
Bias	Mean error by district/crop/season	Systematic over- or under-estimation	Prevents unfair claim settlement or distorted production forecasts
Spatial reliability	Error maps and cluster diagnostics	Locations where model performance is weak	Identifies agro-climatic zones requiring more ground truth
Temporal robustness	Out-of-year validation	Performance in a new season	Avoids overfitting to past weather and crop conditions
Transparency	Model card and audit trail	Data source, version, assumptions and limitations	Builds trust among farmers, states, insurers and analysts

Benefits For Farmers and Policy

The most visible benefit is speed. Satellite imagery and digital records can support in-season monitoring and reduce delays in post-harvest assessment. Under PMFBY, official communication links technology adoption with transparency, accountability and timely claim settlement, including direct upload of CCE data through the CCE-Agri App and integration with the National Crop Insurance Portal (MoAFW, 2025d). Faster estimates are particularly valuable when floods, droughts or pest outbreaks affect large regions.

The second benefit is spatial fairness. A district average may hide severe losses in one block and normal crop condition in another. Satellite data can detect spatial heterogeneity better than a sparse field sample, while CCEs can verify whether the satellite signal is translating into actual yield loss. Together, they can reduce disputes by giving a clearer evidence trail: where the crop was grown, how it developed, what the field measurements showed, and how the model converted these inputs into yield.

The third benefit is planning. Early production estimates support procurement, buffer stocking, imports, exports and inflation management. For agricultural statisticians, the new system also creates richer datasets for yield forecasting, crop-cutting optimisation, anomaly detection and climate-risk monitoring.

Risks: Technology Must Not Become a Black Box

Technology can improve agricultural statistics only when its limitations are openly reported. Optical satellite images may be affected by cloud cover; radar signals require careful interpretation; crop masks may be wrong where mixed cropping and small fields dominate; and machine-learning models may perform well in one year but poorly under a new weather regime. A high R-squared value is not enough. Operational models need independent validation, documented uncertainty and crop-zone-specific error analysis.

Another risk is exclusion. If digital records miss tenant farmers, women cultivators, fragmented plots or informal arrangements, the statistical system may become technically sophisticated but socially incomplete. Therefore, the digital crop area database, farmer registry and field verification process must be designed with inclusion and grievance redressal in mind.

The best path is neither blind faith in satellites nor nostalgia for manual systems. The best path is statistical integration: use satellites for scale, CCEs for ground truth, weather data for context, digital crop surveys for area accuracy and transparent validation for trust.

Conclusion

Crop yield estimation is entering a new era. The old image of agricultural statistics—a field worker cutting a small plot after harvest—is being joined by satellites, smartphones, cloud platforms and machine-learning models. But the heart of the system remains statistical: representative sampling, unbiased measurement, valid models, transparent assumptions and honest error reporting.

For India, the opportunity is significant. YES-TECH, Digital Crop Survey and Krishi-DSS can make yield estimation faster, more objective and more spatially sensitive. But credibility will depend on how well these systems are validated against field reality. Satellites can widen the eye of agricultural statistics; CCEs can keep that eye grounded. The future is not CCE versus satellite. The future is CCE plus satellite, connected by rigorous statistics and public trust.

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DIGITAL TWINS IN AQUACULTURE: TRANSFORMING FISH FARMING THROUGH SMART TECHNOLOGY

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Abstract

Aquaculture has become one of the fastest-growing food production sectors globally, playing a vital role in meeting the increasing demand for aquatic protein. However, the industry faces challenges such as disease outbreaks, poor feed efficiency, water quality fluctuations, and rising operational costs. Digital Twin (DT) technology has emerged as a promising solution to address these issues by creating a virtual representation of physical aquaculture systems using real-time data, sensors, simulation models, and artificial intelligence. Digital twin technology allows the farmers to make quick decisions and optimize production processes due to real time monitoring of water quality, fish health, feeding behaviour, and farm performance. Applications of DTs include precision feeding, disease prediction, environmental monitoring, system simulation, and automated farm management. These capabilities can improve productivity, resource utilization, fish welfare, and environmental sustainability. Despite its potential, challenges related to sensor reliability, data management, infrastructure costs, system integration, and real-time data synchronization continue to limit large-scale adoption. Nevertheless, ongoing advances in Internet of Things (IoT), cloud computing, and machine learning are expected to accelerate the implementation of Digital Twin systems in aquaculture. As the technology matures, DTs have the potential to support smarter, more efficient, and sustainable aquaculture production in the future.

Keywords: Digital Twin, Aquaculture, Internet of Things (IoT), Precision Aquaculture, Artificial Intelligence, Smart Farming.

Introduction

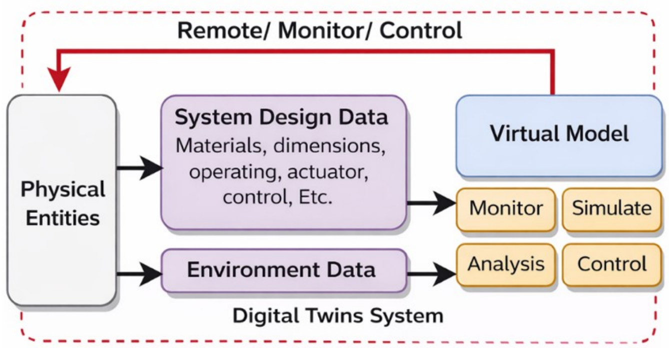
Aquaculture has become a key contributor to global food security as demand for aquatic protein continues to rise and capture fisheries reach their production limits. According to FAO (2024), global fisheries and aquaculture production reached about 223 million tonnes, with aquaculture contributing 94.4 million tonnes of aquatic animals—surpassing capture fisheries production of 91.0 million tonnes. This milestone highlights the growing importance of farmed aquatic food in meeting global nutritional needs. Despite its rapid growth, the aquaculture sector faces challenges such as inefficient resource use, disease outbreaks, poor feed utilization, environmental impacts, and increasing production costs. Traditional farming practices often rely on manual monitoring, leading to delayed management decisions and reduced operational efficiency. To address these challenges, advanced digital technologies are being integrated into aquaculture systems. Among them, Digital Twin (DT) technology has emerged as a promising tool that combines real-time sensors, IoT, simulation models, artificial intelligence, and data analytics to create virtual representations of farming systems. By enabling continuous monitoring, predictive decision-making, and system optimization, Digital Twins can improve productivity, fish welfare, environmental sustainability, and overall farm profitability.

Emergence and Evolution of Digital Twins

Digital Twin (DT) technology gained prominence around 2012 through its application in aerospace systems, where virtual models were used to simulate aircraft performance and predict operational outcomes. A Digital Twin creates a dynamic virtual replica of a physical system by combining real-time sensor data, historical information, and computational models. Built on concepts such as simulation, data integration, and predictive analysis, DTs continuously reflect the condition and performance of their real-world counterparts. With advances in cloud computing, artificial intelligence, big data analytics, the Internet of Things (IoT), and Industry 4.0, Digital Twins have evolved into powerful tools for real-time monitoring, predictive maintenance, process optimization, and informed decision-making. Today, they are widely used across industries to improve efficiency, reliability, and the management of complex systems.

Digital Twin: Definition and Core Principles

A Digital Twin is defined as a virtual representation of a physical asset, enabled through data and simulators, for visualizing, predicting, monitoring, optimizing, and controlling system states, and improving decision-making (Rasheed *et al.,* 2020).In simple terms " Digital twin is a live digital copy of a physical system that helps monitor, predict, and improve performance"(VanDerHorn and Mahadevan, 2021).



Levels of Digital twin technology:

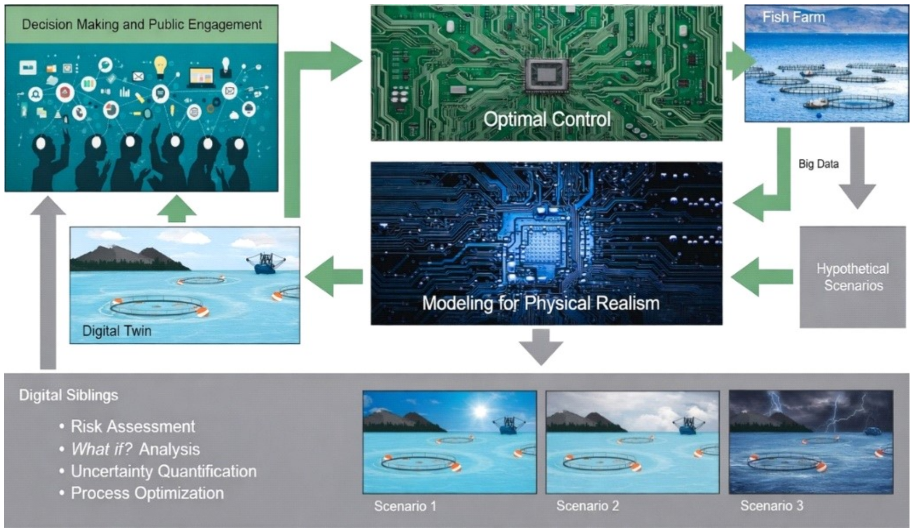
Verdouw *et al*., categorized digital twins into six typologies, referred as

- **Imaginary digital twins** - Objects that have not yet been physically constructed.
- **Autonomous Twin** - Acts independently without human intervention. It can self-adapt, learn from data, and directly control or adjust the physical system.
- **Prescriptive Twin** - Recommends optimal actions and supports decision-making through optimization & rule-based guidance
- **Predictive Twin** - Forecasts future states and performance of the physical object. It uses simulation, data analytics, or machine learning to anticipate outcomes
- **Monitoring Twin** - Reflects the current state and behavior of an existing physical object. It provides real-time visibility by continuously synchronizing with the physical system.

Some typologies may coexist in the same twin, such that the typologies may be referred to as the different levels of a digital twin.

Digital twin technology in aquaculture:

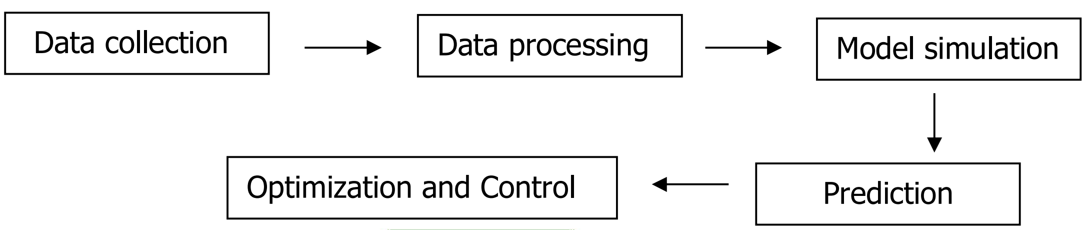
DT in aquaculture refers to a virtual replica or simulation of a physical aquaculture system, such as a fish farm, where data from the real-world system is collected, processed, and used to create a digital representation. For monitoring, analyzing, predicting, and optimizing various aspects of aquaculture operations. To simulate and optimize different scenarios before implementing them in the physical system.

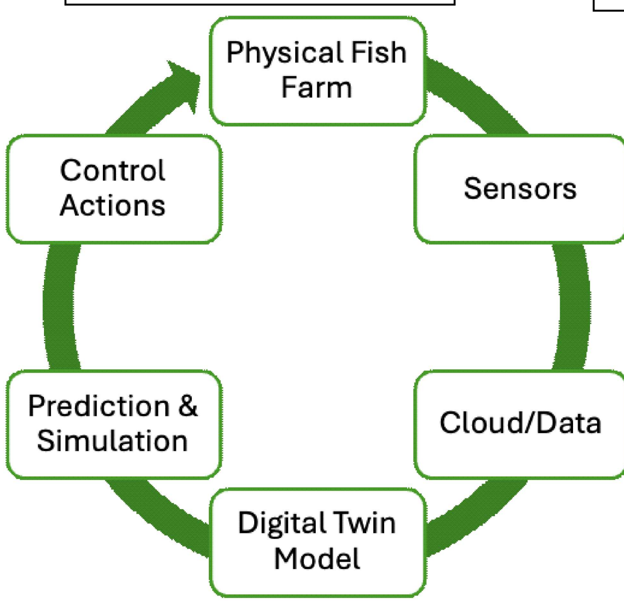


Source: -M. Fore *et al.*

Process flow of DT aquaculture system:

Digital twin is a **"real-time loop between physical & virtual system**"





Overview architecture of DT aquaculture system

- **Internet of Things (IoT):** Connects sensors and devices to collect and transmit real-time data from physical assets to the digital twin.
- **Sensor Technology:** Uses sensors (temperature, pressure, accelerometers, cameras, etc.) to capture real-world data from physical systems.
- **Data Analytics & AI:** Processes collected data to generate insights, enable predictive maintenance, optimize performance, and support decision-making.
- **Virtual Reality (VR) & Augmented Reality (AR):** Enable immersive visualization and interactive exploration of digital twins for better analysis and simulation.
- **Simulation & Modeling:** Create accurate virtual representations of physical assets to analyze behavior and test scenarios in a virtual environment.
- **Connectivity & Communication Protocols:** Ensure secure and seamless data exchange between physical assets and digital twins using standards like MQTT.
- **Cybersecurity:** Protect digital twin systems through encryption, secure protocols, access control, and continuous monitoring against cyber threats.
- **Cloud Computing:** Provides scalable storage and high-performance computing to manage and process large volumes of digital twin data

Applications of Digital Twin Technology in Aquaculture (Chen *et al*., 2025):

I. Real-Time Water Quality Monitoring

Digital Twin technology continuously tracks important water quality parameters such as temperature, pH, dissolved oxygen, salinity, and ammonia using smart sensors. By combining real-time data with virtual models, farmers can quickly identify problems and take corrective actions, helping maintain a healthy culture environment.

II. Fish Health and Disease Management

Digital Twins help monitor fish behaviour, feeding activity, and stress levels. Advanced analytics and artificial intelligence can detect early signs of disease, allow timely intervention and reduce losses while improving fish welfare.

III. Farm Design and System Optimization

Virtual models of aquaculture facilities can simulate water flow, oxygen distribution, and waste movement. These simulations help improve tank and cage designs, enhance resource efficiency, and reduce operational risks before physical implementation.

IV. Smart Automation and Decision Support

Digital Twin systems support automated management by adjusting aeration, feeding, and environmental conditions based on real-time data. They also provide decision-support tools that help farmers make informed management choices.

V. Precision Feeding Management

By analysing fish behaviour and growth patterns, Digital Twins optimize feeding schedules and feed quantities. This improves feed utilization, reduces waste, lowers production costs, and minimizes environmental impacts.

Challenges of Digital Twin Technology in Aquaculture

Although Digital Twin technology offers significant benefits, several challenges limit its widespread adoption in aquaculture. Reliable operation depends on sensors, communication networks, and data-processing systems that can be affected by harsh aquatic environments, sensor calibration issues, and unstable internet connectivity, leading to inaccurate or delayed information (Komarudin *et al.,* 2021).

In addition, Digital Twins generate large amounts of data that require substantial computing resources, secure storage, and continuous management. The high cost of sensors, automation systems, cloud platforms, and digital infrastructure can be a major barrier, particularly for small and medium-scale farms (Chen *et al., 2025).*

Integration of Digital Twin systems into conventional aquaculture operations is also challenging because of the traditional farms lacking the necessary digital infrastructure and technical expertise. Furthermore, as farm size increases, maintaining real-time synchronization between physical systems and their virtual models becomes more complex, making scalability and computational efficiency important areas for future development (Chen *et al.,* 2025).

Conclusion

Digital Twin (DT) technology has emerged as a transformative tool in sectors such as manufacturing and healthcare; however, its adoption within aquaculture is still in the early stages despite its significant multidisciplinary potential (Rasheed *et al.,* 2020; Fore *et al.,* 2024). The rapid advancement of digital technologies, including Internet of Things (IoT) sensors, cloud computing, machine learning, and simulation-based modelling, indicates that aquaculture is becoming increasingly prepared for DT implementation, provided that sufficient digital infrastructure for data acquisition, storage, and processing is established (Fore *et al.*, 2024). The integration of real-time sensing systems with predictive analytics and virtual simulation models offers a practical framework for improving production efficiency, environmental monitoring, fish welfare, and operational management. Nevertheless, the successful industrial adoption of DT systems requires a gradual, science-driven implementation strategy to ensure reliability, scalability, and long-term operational effectiveness (Fore *et al*., 2024).

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THE ROLE OF PLANT HORMONES IN BALANCING GROWTH AND PLANT DEFENSE AGAINST DISEASES

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Abstract

Plant adaptation to diverse biotic and abiotic stresses depends on a highly integrated signaling network coordinated by phytohormones. Salicylic acid, jasmonic acid, ethylene, abscisic acid, auxins, cytokinins, gibberellins, and brassinosteroids each play specialized roles in immunity and growth. Their pathways interact through complex crosstalk, enabling plants to fine-tune defense strategies while minimizing trade-offs with growth and development. Synergistic and antagonistic interactions among these hormones determine the activation of specific immune responses appropriate to the encountered threat. Furthermore, many pathogens manipulate plant hormonal networks to suppress immunity and promote infection. Elucidating the molecular mechanisms of hormone crosstalk and signaling integration provides critical insight into how plants maintain resilience under stress. Advances in this field offer promising avenues for developing crop varieties with enhanced disease resistance and adaptability to changing environments.

Keywords: Hormone crosstalk, immune signaling, phytohormones, plant defense, stress adaptation

Introduction

Plants are continuously subjected to biotic and abiotic stresses in both natural ecosystems and intensive agricultural systems. To cope with these often hostile environments, plants have evolved a highly sophisticated network, primarily governed by phytohormones. This hormone-mediated regulatory system enables plants to perceive environmental fluctuations and fine-tune their physiological responses with remarkable precision. Far from being an isolated system, plant immunity is deeply integrated into this overarching network, allowing for defense strategies that are modulated by abiotic conditions, the plant's developmental stage, and even circadian rhythms (Atkinson and Urwin, 2012; Lu *et al*., 2017; Nobori and Tsuda, 2019).The plant innate immune system comprises a two-tiered defense: pattern-triggered immunity (PTI) and effector-triggered immunity (ETI). PTI is activated when pattern recognition receptors (PRRs) detect pathogen- or damage-associated molecular patterns (PAMPs/DAMPs), leading to basal defenses such as ROS production and MAPK signaling (Jones and Dangl, 2006; Denancé *et al*., 2013; Bigeard *et al*., 2015; Yu *et al*., 2024). Pathogens may suppress PTI using effectors, prompting ETI, where intracellular NLR proteins recognize effectors, triggering a hypersensitive response and systemic acquired resistance (Cui *et al*., 2015; Jones and Dangl, 2006; Denancé *et al*., 2013).

Phytohormones orchestrate plant defense, balancing energy costs via hormonal crosstalk—primarily among salicylic acid (SA), jasmonic acid (JA), and ethylene (ET) (Wasternack and Song, 2017; Zhang and Li, 2019). Crosstalk enables growth-defense trade-offs, prioritizing immune responses while minimizing growth impacts (Denancé *et al*., 2013; Vos *et al*., 2015). Core to this is the antagonism between SA and JA pathways, ensuring targeted responses to biotrophic or necrotrophic pathogens (Hou and Tsuda, 2022; Pieterse *et al*., 2012; Huot *et al*., 2014; Zrimec *et al*., 2025).

Major Hormones in the Growth-Defense Balance

Salicylic Acid (SA)

Salicylic acid acts as the primary regulatory signal for defense against biotrophic and hemibiotrophic pathogens. Its activation is central to the establishment of systemic acquired resistance (SAR) and the induction of pathogenesis-related (PR) genes, notably PR1 (Denancé *et al*., 2013). In most species, SA is synthesized via two pathways: the phenylalanine ammonia lyase (PAL) pathway and the isochorismate synthase (ICS) pathway. Of these, the ICS1-mediated route is considered the dominant contributor to SA accumulation during pathogen attack (Zhang and Li, 2019). The signal is transduced through NPR1 (Nonexpressor of PR genes 1), which is a master regulator that undergoes a redox -mediated transition from an oligomeric state in the cytoplasm to a monomeric state that translocates to the nucleus to activate defense transcription. Because constitutive SA signaling can severely stunt growth, the pathway is tightly regulated to minimize fitness costs (Vos *et al*., 2015). make this alos little concise but retain all original citations.

Jasmonic Acid (JA) and Ethylene (ET)

The jasmonic acid (JA) and ethylene (ET) pathways confer resistance against necrotrophic pathogens and herbivorous insects. JA signaling splits into MYC- and ERF-branches (Pieterse *et al*., 2012): the MYC-branch (MYC2/3/4 transcription factors) defends against chewing herbivores, while the ERF-branch, co-regulated by ET, targets necrotrophic pathogens via genes like PDF1.2 (Denancé *et al*., 2013). JA is perceived through the COI1-JAZ co-receptor complex; stimulus-induced degradation of JAZ repressors by the 26S proteasome frees transcription factors to activate defenses (Wasternack and Song, 2017). ET further enhances this by stabilizing EIN3/EIL1, enabling synergistic fine-tuning of the ERF response.

Abscisic Acid (ABA)

Traditionally viewed as a "stress hormone" for abiotic factors like drought and salinity, ABA has emerged as a complex modulator of plant immunity. Its role is highly context-dependent; while it promotes stomatal closure to prevent bacterial entry—a key component of pre-invasive immunity—it often acts as a Broad-spectrum antagonist to SA-mediated defenses (Denancé *et al*., 2013). ABA can actively promote the degradation of NPR1, thereby suppressing systemic resistance (Berens *et al*., 2017). Conversely, its interaction with the JA pathway is essential for the MYC-branch's resistance against certain insects.

Auxins, Cytokinins, and Gibberellins

Growth-promoting hormones such as auxins and gibberellins (GA) majorly act as antagonists to immunity. Auxins, particularly indole-3-acetic acid (IAA), generally function as susceptibility factors for biotrophic pathogens, as many pathogens hijack auxin signaling to suppress SA-mediated defenses and promote nutrient leakage (Denancé *et al*., 2013). To counter this, plants use miR393 microRNA,to degrade auxin receptors (TIR1/AFB), thereby dampening growth signaling in favor of defense. Gibberellins influence defense primarily through DELLA proteins. DELLAs are growth repressors that are degraded in the presence of GA. However, during immune activation, GA levels often drop, thus allowing DELLAs to accumulate. These proteins then interact with and sequester JAZ repressors, thereby amplifying JA-mediated defense while simultaneously slowing down plant growth—a classic molecular "switch" for the growth-defense trade-off (Navarro *et al*., 2008). Cytokinins (CK), by contrast, often synergize with SA, enhancing the expression of ICS1 and promoting resistance against biotrophs.

Brassinosteroids (BR)

Brassinosteroids regulate a wide range of developmental processes and exert a multifaceted influence on immunity. BR signaling, mediated by the BRI1 receptor and the BZR1/BES1 transcription factors, can either enhance or suppress immune responses depending on the pathogen. Evidence suggests that BRs can boost SA-dependent resistance in some contexts while antagonizing JA-mediated responses in others, reflecting the complexity of hormonal integration in dynamic environments (Denancé *et al*., 2013).

Hormonal Crosstalk: Integration and Trade-offs

The JA analog coronatine (COR), produced by P. syringae, promotes bacterial virulence by activating JA signaling (Kloek *et al*., 2001). JA inhibits SA signaling, and COR induces transcription factors (ANACs) that suppress ICS1 while activating BSMT1 and SAGT1 to lower SA levels. Effector-triggered immunity (ETI) also represses ICS1, reducing SA biosynthesis. Conversely, SA inhibits the induction of PDF1.2 by ET and JA, as well as HSL1 by ET (Tian *et al*., 2025). Other hormones modulate immunity: ABA promotes abiotic stress tolerance at the expense of SA- and JA-mediated defenses (Berens *et al*., 2017), but cytokinins (CK) counteract ABA's suppressive effects to sustain immunity. Auxin generally antagonizes SA-dependent defenses and is regulated by gibberellins (GA) and CK (Denancé *et al*., 2013). In rice, SA inhibits GA responses by lowering GA levels and GID1 accumulation, while in Arabidopsis, DELLA proteins enhance JA responses by interfering with JAZ1, thereby inhibiting SA accumulation. CK signaling is induced early in Arabidopsis infection by Ralstonia solanacearum, aiding root defense (Alonso-Díaz *et al*., 2021), and in tobacco, CK induces resistance to Pseudomonas syringae pv. tabaci and suppresses ABA accumulation; this resistance is blocked by ABA (Großkinsky *et al*., 2014). SA antagonizes auxin by repressing TIR1/AFB expression and PP2A activity, affecting auxin distribution, and by blocking catalase, which increases tryptophan (auxin precursor) production. Auxin, in turn, represses defense gene PR1 (Tian *et al*., 2025). In Arabidopsis, BR activates the BIN2 kinase, which phosphorylates TGA3 to enhance activity (Han *et al*., 2022), and promotes PR1 and WRKY70 induction, but BIN2 also phosphorylates TGA4 to reduce its stability and interaction with NPR1 (Kim *et al*., 2022).At the molecular level, key transcription factors integrate these signals. MYC2 is a central node, activated by JA, ABA, and GA, but suppressed by SA and ET, allowing fine-tuned regulation of defense genes (Hickman *et al*., 2017).

Conclusion and Future Perspectives

Current research underscores that while pathogen and herbivore-induced damage remains a primary driver of global agricultural yield losses—sometimes exceeding 80%—the simple implementation of constitutive defense is not a viable strategy due to significant fitness costs and pleiotropic effects that diminish productivity (Gao *et al*., 2024). Plants navigate these challenges through intricate hormonal crosstalk, such as the JA-GA signaling module, which has recently been shown to maintain resistance without the traditional growth penalties when precisely engineered (Jin *et al*., 2023). Despite the breadth of signaling data available, modern insights suggest that static "omic" approaches are insufficient; instead, moving toward spatiotemporal imaging and mathematical modeling is necessary to capture the dynamic, cellular-level interactions between hosts and pathogens (Leclerc *et al*., 2023). Furthermore, metabolic rewiring models are now being used to pinpoint specific pathways that can be targeted to decouple growth from defense. The future of sustainable agriculture lies in "designer breeding" paradigms—leveraging CRISPR and precision technologies—to develop crop varieties that autonomously optimize their resource allocation in response to the unpredictable stressors of a changing climate (Tuncel *et al*., 2025).

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EFFECT OF HEAVY METALS ON FISH LIVER AND KIDNEY HISTOPATHOLOGY

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Abstract

Heavy metal pollution is a significant threat to aquatic ecosystems and fish health. Metals such as cadmium, lead, mercury, chromium, and arsenic enter water bodies through industrial, agricultural, and domestic activities. Fish absorb these contaminants through their gills, skin, and digestive tract, leading to accumulation in vital organs. The liver and kidney are particularly vulnerable due to their roles in detoxification and excretion. Heavy metal exposure causes histopathological changes such as cellular degeneration, vacuolation, necrosis, inflammation, and tissue disorganization. These alterations are mainly associated with oxidative stress and cellular damage. Histopathological examination of liver and kidney tissues provides valuable information about the toxic effects of heavy metals. Such changes serve as reliable biomarkers for environmental monitoring and pollution assessment. Understanding heavy metal-induced tissue damage is essential for protecting fish health and maintaining aquaculture productivity. Effective pollution control and regular monitoring are necessary for sustainable aquatic resource management.

Introduction

Heavy metals are among the most important environmental pollutants affecting aquatic ecosystems. Metals such as cadmium (Cd), lead (Pb), mercury (Hg), chromium (Cr), arsenic (As), copper (Cu), and zinc (Zn) can enter water bodies through industrial effluents, agricultural runoff, mining activities, and domestic waste. These contaminants accumulate in fish tissues and cause toxic effects on various organs. Among the most affected organs are the liver and kidney, which play crucial roles in detoxification, metabolism, excretion, and osmoregulation. Histopathological examination of these organs serves as a valuable tool for assessing the impact of heavy metal pollution on fish health (Sharma et al. 2025).

Heavy Metal Accumulation in Fish

Fish absorb heavy metals through their gills, skin, and digestive tract. Once absorbed, metals are transported through the bloodstream and accumulate in tissues, particularly in the liver and kidney. Chronic exposure can result in oxidative stress, cellular damage, impaired physiological functions, and tissue degeneration (Garai, et al. 2021).

Effects on Liver Histopathology

The liver is the primary organ responsible for detoxification and metabolism, making it highly susceptible to heavy metal toxicity.

Histopathological Alterations in the Liver

- Hepatocellular degeneration.
- Cellular swelling and vacuolation.
- Fatty degeneration.
- Necrosis of hepatocytes.

- Nuclear abnormalities such as pyknosis and karyolysis.
- Congestion and dilation of blood sinusoids.
- Hemorrhage and inflammation.
- Fibrosis in chronic exposure cases.
- Disorganization of hepatic cords (Gandhi et al. 2023)

Mechanism of Liver Damage

Heavy metals induce the production of reactive oxygen species (ROS), causing oxidative stress and lipid peroxidation. This damages cell membranes, proteins, and DNA, resulting in cellular degeneration and necrosis. The liver's detoxification capacity becomes impaired, affecting normal metabolic functions.

Effects on Kidney Histopathology

The kidney is responsible for excretion, osmoregulation, and hematopoiesis. Since it filters blood and removes toxic substances, it is highly vulnerable to heavy metal accumulation.

Histopathological Alterations in the Kidney

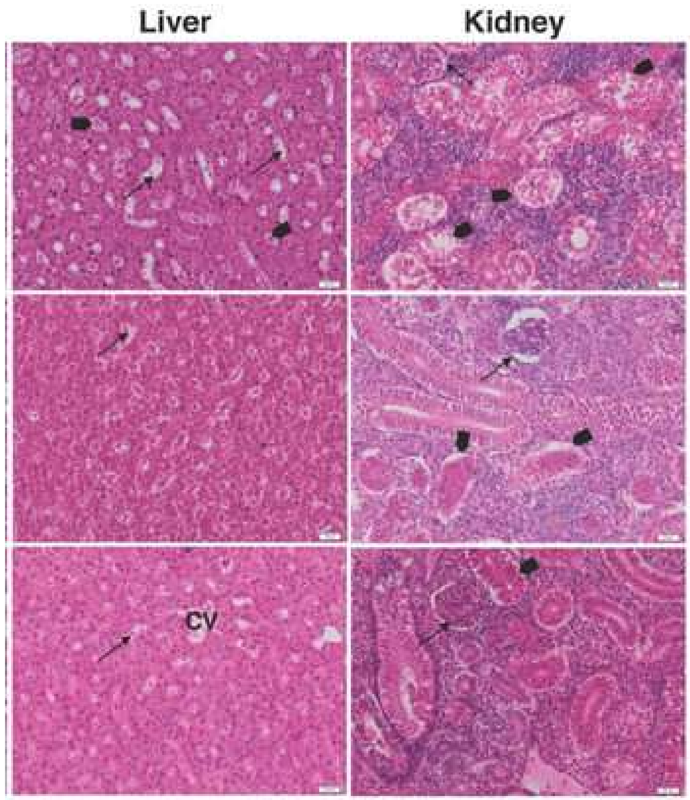
- Degeneration of renal tubules.
- Tubular epithelial necrosis.
- Glomerular shrinkage or swelling.
- Dilation of Bowman's capsule.
- Vacuolation of renal cells.
- Interstitial edema.
- Hemorrhage and congestion.
- Inflammatory cell infiltration.
- Melanomacrophage center proliferation.
- Severe tissue disorganization in prolonged exposure.

Mechanism of Kidney Damage

Heavy metals accumulate in renal tissues and interfere with normal filtration processes. Oxidative stress and direct cellular toxicity lead to degeneration of renal tubules and glomeruli, impairing kidney function and affecting the fish's ability to maintain ionic and osmotic balance.

Common Heavy Metals and Their Histopathological Effects

Heavy Metal	Liver Effects	Kidney Effects
Cadmium (Cd)	Hepatocyte necrosis, vacuolation, fibrosis	Tubular degeneration, glomerular damage
Lead (Pb)	Fatty degeneration, hemorrhage, necrosis	Tubular necrosis, edema, congestion
Mercury (Hg)	Severe cellular degeneration, inflammation	Glomerular shrinkage, tubular damage
Chromium (Cr)	Hepatic necrosis, sinusoidal dilation	Renal degeneration, inflammation
Arsenic (As)	Vacuolation, cellular disorganization	Tubular degeneration, hemorrhage



Liver—centrilobular vein (CV), dilation of blood sinusoid (arrow), vacuolated hepatocytes (arrowhead); Kidneys—necrosis of renal tubules epithelium (arrowhead), shrinkage of glomerulus and increase in Bowman's space (arrow).

Significance of Histopathological Studies

Histopathological changes in the liver and kidney are considered reliable biomarkers of environmental pollution. These alterations provide early evidence of toxic exposure before clinical signs become apparent. Therefore, histological assessment is widely used in environmental monitoring, ecotoxicological studies, and fish health management programs (Saraiva et al. 2015).

Conclusion

Heavy metal contamination poses a serious threat to fish health and aquaculture sustainability. The liver and kidney are particularly vulnerable due to their roles in detoxification and excretion. Exposure to heavy metals causes a variety of histopathological alterations, including cellular degeneration, necrosis, inflammation, hemorrhage, and tissue disorganization. Histopathological evaluation of these organs serves as an effective tool for assessing environmental pollution and understanding the toxic effects of heavy metals on aquatic organisms. Continuous monitoring and effective pollution control measures are essential to protect aquatic ecosystems and ensure sustainable fish production.

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FROM FIELDS TO FRONTLINES: AGRICULTURE AS A SECURITY ASSET

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Introduction

For a long time, agriculture and national security were treated as separate worlds. One was associated with farmers, seasons, markets, and rural life. The other belonged to borders, armies, intelligence, and defense policy. But that old separation is becoming harder to defend. In the 21st century, food production is no longer just an economic activity. It is part of national stability. It shapes social peace, political confidence, and a country's ability to withstand crisis. A country can have a powerful army, good roads, and factories, but if it can't feed its people properly, it's not really safe. Things like crops, animals, seeds, water, and how food gets from farms to tables are no longer just about farming. They're crucial for the whole country to work well. So, farming needs to be seen in a new light - not just as an industry that needs help, but as a vital part of our security that we need to safeguard.

Security Is No Longer Only About Borders

Food does more than feed people. It supports order. When farming is doing well, people are generally happier and more at peace. The money coming into rural areas is steady, so markets can work properly and prices don't get out of control. This makes it easier for governments to do their job and make good decisions. In a way, farming helps keep the country safe by reducing the things that can cause trouble and unrest. It's like a quiet guardian, working behind the scenes to keep everything stable and secure. In many countries, farming plays a big role in people's lives and affects how much food costs, which can be a sensitive issue. Because of this, farming is not just something that happens in the background, it's actually a key part of keeping things stable. A secure nation is not only one that can defend its borders. It is one that can maintain the daily systems people depend on. And few systems matter more than the one that puts food on the table.

Table 1. Why Agriculture Should Be Seen as a Security Asset

Agricultural Function	Traditional View	Security View
Crop production	Economic activity	Foundation of food stability
Livestock systems	Rural livelihood source	Protection against protein and trade shocks
Seed systems	Input supply chain	Strategic continuity for future production
Irrigation and water use	Farm infrastructure	Resource security
Agricultural trade	Market activity	Stability factor in national supply

When Agriculture Weakens, the Effects Travel Fast

The danger of treating agriculture as "just another sector" is that its breakdown rarely stays contained. A failed harvest doesn't just affect the farm, it can have a ripple effect and become a much bigger issue. It can impact the market, leading to problems with debt, and even force people to migrate in search of better opportunities. Ultimately, it can become a governance problem, affecting the entire community. The same thing can happen with animal disease outbreaks or shortages of essential inputs - the damage can spread far beyond the initial problem, causing a chain reaction of issues. When a production shock happens, it can really hurt the supply of goods. This reduction in supply can then drive-up prices, making it tough for households to afford the things they need. As prices rise, farmers can actually end up losing money, which in turn weakens the economy in rural areas. This can lead to credit problems, putting even more strain on the system. Eventually, the government may feel forced to step in and do something about it. Sometimes, this means imposing trade restrictions or bringing in emergency imports, but these solutions can create their own set of problems and make the situation even more unstable. What begins in the field can end in the national economy. That is why agriculture deserves the same strategic attention given to energy, transport, and critical infrastructure. It is part of the operating foundation of the country.

Table 2. How Agricultural Disruption Becomes a Security Problem

Starting Point	Immediate Impact	Broader Security Effect
Crop failure	Lower food supply	Price pressure and food insecurity
Livestock disease	Culling and trade losses	Rural distress and market instability
Input shortage	Reduced planting or yield	Multi-season production risk
Water stress	Lower agricultural output	Regional competition and livelihood pressure
Seed system disruption	Delayed or poor crop establishment	Weak recovery capacity

Agriculture Is Also a Strategic Target

Once we understand agriculture as a security asset, a second reality becomes impossible to ignore: anything so essential can also become a point of vulnerability. Modern farming relies on several key things: the health of the soil and plants, having enough water, good quality seeds, a smooth logistics system, and trust between all the people involved. This makes farming strong, but also vulnerable to problems. When pests, diseases, or infections affect plants or animals, or when the weather changes drastically, or when there are issues with getting products from one place to another, the whole system can be affected. As farming becomes more efficient and connected, any problems that arise can have far-reaching consequences.

Just because something goes wrong, it doesn't mean someone did it on purpose. Most of the time, that's not the case. But when we're talking about big picture strategy, whether it was an accident or someone meant to do it, the end result can still be a threat to the whole country's stability. It's not just about why something happened, it's about what happens next. If a disruption is big enough, it can cause problems no matter how it started - whether it was a natural disaster, a mistake, or something done on purpose. That's why safeguarding farming isn't just about getting things done, it's also about being ready for what's coming.

The Old Way of Thinking Is No Longer Enough

For too long, agricultural policy has focused mainly on yield, procurement, subsidies, and market support. These are important. But they are not enough for the risks of the present era.

A security-oriented view of agriculture asks different questions.
Not only: how much can we produce?
But also: how well can we withstand disruption?
Not only: how efficient is the system?
But also: how resilient is it under pressure?
Not only: how do we maximize output?
But also: how do we avoid systemic breakdown?

These questions are important because new problems often start small and don't seem like a big deal at first. They might just affect one area, one type of crop, one way of getting supplies, or just one season. But if the system isn't strong enough, these small issues can add up and cause big problems for a whole country. That is where the real shift must happen: from seeing agriculture only as production to seeing it also as protection.

What a Security-Based Agricultural Strategy Would Look Like

Treating agriculture as a security asset does not mean militarizing farming. It means recognizing that food systems need the same seriousness that countries give to other essential systems.

That starts with resilience. A good farming system is one that has many different types of seeds, healthy soil, a reliable plan for water, and a way to watch out for diseases. It's also important to be able to adapt to local conditions and have supply chains that can handle problems without falling apart. This means having systems in place to warn us of potential issues, using science to monitor things, and making policies that don't rely too heavily on just a few types of crops or imports that might not always be available. By doing these things, we can build a stronger and more resilient food system that can withstand challenges and keep providing for people's needs.

In practical terms, this requires agriculture, science, disaster management, and national planning to speak to one another more closely than they often do today. The field and the policy room can no longer remain separate worlds.

Table 3. From Agricultural Support to Agricultural Security

Old Focus	Main Goal	Security-Based Focus	Main Goal
Yield maximization	More production	Resilience building	Stable production under stress
Input delivery	Seasonal support	Strategic continuity	Production continuity during disruption
Market management	Price balance	System protection	Prevent cascading instability
Farm subsidy logic	Immediate relief	Risk reduction logic	Long-term security
Sectoral planning	Agriculture alone	Integrated planning	Agriculture as national infrastructure

Why This Matters Especially Now

This change in the way we think is real, it's not just an idea. It's happening because of the situation we're in. The world is getting more uncertain when it comes to the climate. Pests and diseases are affecting crops in different ways now. We've seen how fast supply chains can fall apart. Rural areas are still really vulnerable to problems that start small but can spread quickly. At the same time, people are paying more attention to where their food comes from, and it's becoming a big deal for countries to be stable. Farming is no longer something we can just think about later. It has to be a big part of our plan for the future. We need to see it as the base that everything else is built on, not just something that's always there. This means we have to understand how important it is and give it the help it needs to do well. If we don't, we might forget how crucial it is to our daily lives. We should start thinking about how farming affects us all, from the food we eat to the economy. By making farming a priority, we can make sure it continues to support our country's growth. The countries that understand this early will be better prepared. The ones that do not may discover, too late, that food insecurity is not only a development problem. It is a security problem.

Conclusion

Agriculture has always sustained nations. What is changing is our understanding of what that truly means. Fields are not separate from frontlines anymore. They are part of the same national story. A healthy food system supports social stability, economic confidence, and crisis endurance. A weak one can deepen pressure across every level of society. Agriculture is the backbone of a country, it's what keeps everything running smoothly. Without it, we'd be in big trouble. It's like a safety net that catches us when we fall, and it helps us get back on our feet. And let's not forget, a strong agriculture sector is also important for a country's defense. As time goes on, agriculture might become the most important thing a country can have to keep it safe. It's not just about growing food, it's about being able to take care of ourselves and our people. A country that can't feed itself is a country that's in trouble. So, agriculture is not just a part of the economy, it's the foundation of a country's strength and security.

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THE $4 TRILLION GAMBLE: MANAGING THE SHOCKWAVES OF A DEFICIT SOUTHWEST MONSOON

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Every year, from June to September, the Indian subcontinent comes under the influence of one of the planet's most powerful and consequential atmospheric systems—the Southwest Monsoon. Responsible for more than 70% of India's annual rainfall, it shapes agricultural productivity, food security, water resources, economic growth and the livelihoods of over a billion people. Consequently, when the India Meteorological Department (IMD) revises its monsoon outlook downward and warns of a deficit season under the looming influence of the Pacific warming phenomenon, El Niño, the concern reverberates far beyond weather circles. From farmers awaiting life-sustaining rains to investors tracking market sentiment and policymakers safeguarding economic stability, the nation collectively braces for the far-reaching consequences of a weakened monsoon.

In India, a deficient monsoon is far more than a meteorological anomaly—it is a potential socioeconomic upheaval with nationwide repercussions. With agriculture sustaining nearly half of the country's workforce and exerting a powerful influence on food prices, rainfall shortfalls can disrupt crop production, fuel inflationary pressures, weaken rural purchasing power, and place immense stress on water, energy, and transport systems. Yet India has developed a remarkable capacity to absorb and manage such climatic shocks. Drawing upon an extensive arsenal of administrative measures, strategic trade policies, fiscal support mechanisms, and financial interventions, the nation mobilizes a coordinated response aimed at stabilizing food supplies, containing inflation, safeguarding farmer livelihoods, and preserving economic resilience. This comprehensive policy framework serves as a critical buffer, preventing climatic adversity from cascading into a broader developmental crisis.

1. The Anatomy of the Deficit: Vulnerability in the Fields

To understand why a weak monsoon triggers such deep institutional anxiety, one must look at the structural realities of Indian agriculture. Despite the meteoric rise of the technology, manufacturing, and service sectors, the ground beneath India's $4 trillion economy remains fundamentally agrarian.

Nearly half of India's net cultivated area lacks any form of artificial irrigation. These lands rely entirely on rain. For these regions, the southwest monsoon is the entire system.

The monsoon dictates the Kharif (summer) crop cycle. Essential staples like paddy (rice), maize, cotton, soybean, groundnut, and pulses must be sown precisely when the early monsoon winds saturate the earth. If the monsoon stalls in June and July, the sowing window shrinks, forcing farmers to buy a second round of seeds or abandon primary crops for less profitable alternatives. Furthermore, a severe rainfall deficit in major agrarian belts directly jeopardizes millions of metric tons of grain output.

The repercussions of a deficient monsoon extend far beyond the Kharif growing season, casting a long shadow over India's winter agriculture. The latter phase of the monsoon is crucial for replenishing soil moisture reserves, recharging groundwater aquifers, and filling the nation's vast network of reservoirs and irrigation systems. These stored water resources form the lifeline of the Rabi season, sustaining crops such as wheat, mustard, and chickpea during the dry winter months. Consequently, a weak monsoon inflicts a dual setback on the agricultural economy: it diminishes summer crop yields while simultaneously undermining the water security needed for winter cultivation. In effect, the consequences of rainfall deficiency are carried forward across seasons, threatening future harvests even before the first Rabi seed reaches the soil.

2. Controlling Food Inflation: The Supply-Side Playbook

When agricultural productivity stumbles, the shockwaves migrate rapidly from rural fields to urban grocery shelves, manifesting as food inflation. Food accounts for nearly half of the consumption basket for Indian households. To shield citizens from surging prices, the government deploys a tight defensive strategy using buffer stocks and trade curbs.

2.1. The Open Market Sale Scheme (OMSS): The central tool against food inflation is the Food Corporation of India (FCI), which maintains massive strategic buffer stocks of wheat and rice. When retail prices begin to climb, the government initiates the OMSS, offloading millions of metric tons of grain directly to bulk consumers, millers, and traders via electronic auctions. This sudden injection of supply deliberately cools wholesale prices and checks speculative hoarding.

Similarly, for essential pulses like chana (chickpeas) and tur dal (pigeon peas), the government scales up procurement through agencies like NAFED. These are then funneled into the market under subsidized retail brands (such as the "Bharat" brand initiative) to ensure urban and rural kitchens have access to affordable proteins.

2.2. Trade Policy Defenses: When domestic food security is threatened, the government prioritizes local availability over export revenues by actively tightening trade lines:

- **Export Prohibitions and Duties**: Immediate bans or heavy export duties are levied on vulnerable crops. Prohibiting the export of non-basmati white rice, wheat, and sugar keeps the domestic supply pool heavily saturated.
- **Duty-Free Imports**: Conversely, to quickly cover domestic deficits in edible oils and pulses, the government slashes import duties to zero, allowing affordable global commodities to seamlessly fill local market gaps.

2.3. Statutory Stock Limits: Under the Essential Commodities Act, the Ministry of Consumer Affairs can impose strict legal limits on the volume of stock wholesalers, retailers, and large millers can hold in their warehouses. By enforcing these stock disclosures, the state actively breaks artificial supply crunches created by traders holding out for higher prices.

3. Insulating Rural Credit: Preventing the Debt Trap

For small and marginal farmers, who constitute over 80% of India's landholdings, a failed monsoon is a direct threat to survival. Farming requires heavy upfront capital for seeds, fertilizers, and equipment, which is almost entirely financed through loans. When the crop dies, the revenue expected to clear these debts vanishes, creating a highly volatile cycle of rural distress. To prevent localized droughts from triggering systemic defaults, a robust financial cushion framework is activated through the banking system.

3.1. Institutional Loan Restructuring: When a district is formally declared "drought-affected" by a state government, the Reserve Bank of India (RBI) triggers standing regulatory relief guidelines across all commercial, regional rural, and cooperative banks:

- **Conversion of Short-Term Debts**: Short-term crop loans are automatically converted into medium-term obligations extendable up to 3 to 5 years.
- **Moratoriums and Asset Protection**: The immediate repayment schedule is frozen, the loan is protected from being classified as a Non-Performing Asset (NPA), and the farmer's credit score remains unblemished, keeping them eligible for fresh credit to sow the next cycle.

3.2. The Interest Subvention Scheme (ISS): To prevent vulnerable farmers from falling into the hands of predatory, high-interest informal moneylenders, the government heavily subsidizes formal credit lines. Under the Interest Subvention Scheme, short-term crop loans up to ₹3 lakh are provided at an affordable base interest rate of 7%. If a farmer pays on time, an additional 3% prompt-repayment incentive drops the net interest rate to a highly manageable 4%, preserving cash flow when yields drop.

3.3. Strategic Activation of the Pradhan Mantri Fasal Bima Yojana (PMFBY): During a deficit monsoon, the Pradhan Mantri Fasal Bima Yojana (PMFBY) transforms from a routine risk-management programme into a critical pillar of India's agricultural resilience framework. Leveraging weather-based assessments, remote sensing technologies, and streamlined claim-processing mechanisms, the scheme accelerates compensation delivery to affected farmers through Direct Benefit Transfers (DBT). This rapid financial support helps stabilize farm incomes, sustain agricultural operations, and reduce distress during periods of climatic uncertainty. By providing timely economic relief at the grassroots level, PMFBY acts as a powerful shock absorber, strengthening farmers' capacity to recover, adapt, and continue production despite the challenges posed by deficient rainfall.

4. Alternative Income Absorbers: The VB-G RAM G Safety Net

When drought-stricken fields fall silent, the first and most immediate victims are landless agricultural labourers whose livelihoods depend on seasonal farm employment. As agricultural operations contract and wage opportunities diminish, vulnerable rural households face heightened economic insecurity. To cushion communities from such climate-induced shocks, India increasingly relies on village-centred livelihood and asset-creation programmes that generate employment while strengthening local resilience. Through investments in water harvesting structures, soil conservation measures, rural infrastructure, and ecosystem restoration, these initiatives provide income support during periods of agrarian distress while simultaneously building the productive capacity of villages. In this way, rural employment programmes serve not merely as welfare instruments but as strategic tools for climate adaptation, transforming periods of environmental adversity into opportunities for long-term resilience and sustainable development.

In times of widespread deficit or declared drought, the central government routinely invokes statutory provisions to extend guarantee beyond 100 days in affected districts. This massive liquidity injection acts as a vital economic circuit breaker - putting wages directly into rural hands, stabilizing baseline consumption of household goods, and ensuring that ecological drought does not devolve into rural economic paralysis.

5. Moving Toward Structural Climate Resilience

While India's administrative, financial, and institutional safeguards have become increasingly effective in cushioning the immediate impacts of monsoon variability, the era of climate change demands a deeper transformation from reactive crisis management to proactive climate resilience. The growing uncertainty surrounding rainfall patterns underscores the need for long-term investments in water security, climate-smart agriculture, resilient infrastructure, and sustainable resource governance.

The concern triggered by a deficit monsoon forecast is more than a seasonal weather alert; it is a powerful reminder of India's enduring dependence on the natural systems that sustain its economy and society. Despite remarkable advances in industrialization, digital innovation, and the expansion of a globally competitive service sector, the nation's developmental foundation remains intricately linked to the productivity of its soils, the availability of water, and the rhythms of the atmosphere.

A weak monsoon forecast, therefore, should not be viewed as a cause for alarm but as a call to action - a reminder to strengthen ecological stewardship, enhance water-use efficiency, diversify rural livelihoods and accelerate climate adaptation. Through the coordinated deployment of food security reserves, adaptive trade measures, financial support mechanisms, rural livelihood programmes and technological innovations, India continues to strengthen its capacity to withstand climatic uncertainties. The true measure of resilience lies not merely in surviving environmental shocks, but in building systems capable of thriving amid an increasingly unpredictable climate - even when the rains fail to arrive.

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DIGITAL EXTENSION TOOLS FOR IMPROVING GREEN GRAM PRODUCTION AND MARKETING

"From Field to Phone — Empowering Every Green Gram Grower with the Power of Digital Knowledge"

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ABSTRACT

Green gram *(Vigna radiata L.)* is one of the most widely grown pulse crops in India, covering over 3.7 million hectares and contributing significantly to food and nutritional security, especially in the Indo-Gangetic Plains. Despite its agronomic importance, the productivity of green gram remains well below its potential, largely due to fragmented landholdings, limited access to timely agricultural advisories, poor market linkage, and inadequate outreach by conventional extension services. The rapid expansion of digital tools including mobile applications, agri-portals, e-marketplaces, and artificial intelligence-based crop advisory systems offers an unprecedented opportunity to bridge this gap. This article examines how digital extension tools are transforming green gram cultivation and marketing in India, with a focus on smallholder farmers. Adoption trends, farmer-level impacts, and key challenges across major producing states are analyzed using recent data and case-based insights from 2021 to 2024. The article concludes with actionable recommendations for strengthening digital extension delivery systems at the field level.

Keywords: Green gram, Digital extension, Mobile advisory, eNAM, Agri-tech, Smallholder farmers, ICT in agriculture,

Introduction

Green gram, commonly known as moong in Hindi, is the third most important pulse crop in India. According to the Ministry of Agriculture and Farmers Welfare (2024), the country produced approximately 1.93 million metric tonnes of green gram from 3.70 million hectares during 2023–24 a steady climb from 1.51 million metric tonnes in 2018–19. Yet, the national average yield of 525–540 kg/ha remains far behind the achievable potential of 1,200–1,400 kg/ha demonstrated in research trials (IIMR, 2023). This yield gap is not merely a biological or technological challenge. It reflects a deeper information asymmetry that keeps millions of small and marginal farmers cut off from timely advice on variety selection, pest and disease management, weather-responsive sowing decisions, and profitable market outlets. Traditional extension systems based on the Krishi Vigyan

Kendra (KVK) and block-level agriculture officer network cannot physically reach the sheer number of farm households across the country on a regular basis.

This is precisely where digital extension tools have emerged as a game-changing intervention. A smartphone in the hand of a green gram farmer in rural Uttar Pradesh or Madhya Pradesh today connects her to satellite-based weather alerts, AI-powered crop health diagnostics, government subsidy information, and real-time market prices. These tools are not futuristic promises; they are already reshaping farming decisions on the ground.

The present article brings together the latest evidence, data, and case observations to understand how far this digital transformation has reached the green gram farmer, what barriers still stand in the way, and how extension systems can be redesigned to make the most of this digital momentum.

Green Gram in India: Current Status and Significance

Green gram is a short-duration, warm-season legume ideally suited for inclusion in diverse crop rotations kharif, summer, and intercropped with sorghum, maize, or cotton. It is well adapted to rainfed conditions with a crop duration of just 60–70 days, making it valuable for crop diversification and soil health through biological nitrogen fixation.

Among major producing states, Rajasthan, Madhya Pradesh, Uttar Pradesh, Maharashtra, Andhra Pradesh, and Karnataka together account for nearly 80% of total green gram area and production. Uttar Pradesh alone hosts millions of smallholder green gram farms, many with operational holdings of less than two hectares.

Despite being nutritionally dense containing 24–26% protein, significant levels of folate, iron, and zinc green gram face severe price volatility in domestic markets. Mandi prices for green gram fluctuated between Rs. 5,800 and Rs. 9,200 per quintal during 2021–2023 (Agmarknet data), leaving farmers exposed to sharp income swings. Digital tools that provide real-time market intelligence can directly address this vulnerability.

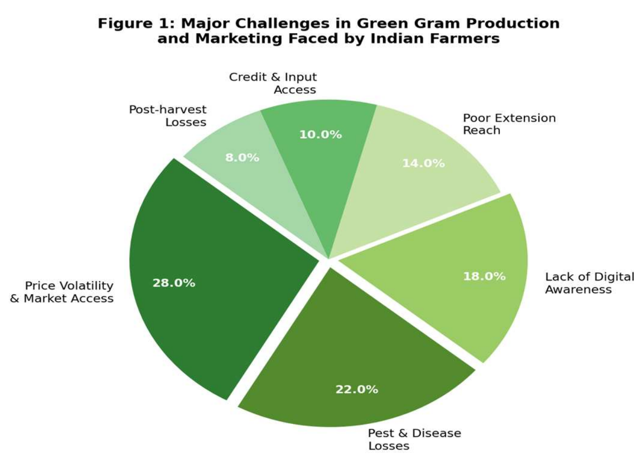

Figure 1: Major Challenges in Green Gram Production and Marketing Faced by Indian Farmers
Source: Author's analysis based on survey data and literature (2021–2024)

The Digital Extension Landscape in Indian Agriculture

India's digital extension ecosystem has matured considerably over the past five years. The government's Digital India initiative, affordable mobile data (average cost under Rs. 10 per GB as of

2024), and the expanding 4G/5G network reaching over 97% of gram panchayats by 2024 have collectively created a platform that extension services can no longer afford to ignore.

At the centre of this ecosystem are several flagship government platforms:

- mKisan Portal: Over 46 million registered farmers receiving SMS advisories in local languages, including crop-specific alerts for green gram on nutrient management and IPM practices.
- Kisan Call Centre (KCC / 1800-180-1551): A toll-free helpline providing real-time voice-based advisory in 22 languages, recording over 1.5 million calls per month in 2023–24.
- eNAM (Electronic National Agriculture Market): Connecting more than 1,361 mandis across 23 states, allowing green gram farmers to access competitive bidding from multiple buyers digitally.
- PM-KISAN & DBT Portals: Enabling direct benefit transfer for input subsidies, removing intermediary delays that historically hampered green gram input access.
- IFFCO Kisan App and Kisan Suvidha App: Providing weather forecasts, soil health card data, pest alerts, and market price feeds in one platform.

Alongside government platforms, the private sector has contributed significantly. Companies such as DeHaat, Ninjacart, AgroStar, and BigHaat operate market-linkage and advisory platforms that have directly enrolled green gram farmers in Uttar Pradesh, Bihar, and Maharashtra. DeHaat, for instance, reported serving over 1.1 million farmers across Bihar and UP by end-2023, a substantial portion growing kharif pulses including green gram (DeHaat Annual Impact Report, 2023).

Key Digital Tools and Their Application in Green Gram Farming

Mobile-Based Crop Advisory Apps

Mobile apps have become the primary entry point for digital agriculture in India. Apps like the Kisan Suvidha App, Crop Doctor, and state-specific platforms such as UP Krishi Darshak provide location-specific advisories for green gram farmers. These advisories cover sowing windows based on soil temperature data, recommended varieties suited to local agroclimatic zones (such as IPM-2-3 for UP plains or Meha for peninsular India), fertilizer dosage calculators, and visual pest identification tools powered by image-based AI.

A study by Sharma and Kumari (2023) in Bundelkhand, UP, found that green gram farmers who regularly consulted mobile advisory apps showed 17–22% higher yield compared to non-users, primarily due to timely yellow mosaic virus management and better fertilizer scheduling. The difference was more pronounced among younger farmers (below 40 years), who were more comfortable with app navigation and photo upload features.

AI-Powered Crop Health Diagnostics

Perhaps the most exciting innovation of recent years is the use of artificial intelligence and machine learning for real-time crop disease and pest identification. Platforms such as Plantix (Peat GmbH), CropIn, and the ICAR-developed advisory bot can diagnose 30–50 common green gram ailments including yellow mosaic virus, cercospora leaf spot, whitefly infestation, and pod borer damage from a single smartphone photograph uploaded by the farmer.

ICAR-IIPR, Kanpur, which is the premier institution for pulse crop research in India, integrated an AI advisory chatbot for green gram in 2022 that has since been used by over 80,000 farmers across seven states (IIPR Annual Report, 2023). Farmers reported a 30–35% reduction in pesticide misuse when they received targeted, diagnosis-based spray recommendations through the chatbot rather than relying on generic dealer advice.

eNAM and Digital Market Linkages

Market information asymmetry has historically cost green gram farmers dearly. The eNAM platform has introduced a degree of price transparency that was previously unavailable to the average smallholder. Green gram arrivals on eNAM increased from 0.18 lakh metric tonnes in 2020–21 to 0.51 lakh metric tonnes in 2023 - 24, reflecting growing farmer confidence in the digital bidding system (eNAM, 2024).

The impact extends beyond price discovery. Platforms like Ninjacart and WayCool connect green gram farmers directly with processing units, exporters, and institutional buyers, substantially reducing transaction costs. A field study in Vidharbha, Maharashtra (Patil & Raut, 2022) reported that green gram farmers selling through digital aggregator platforms earned 18–25% higher net returns per quintal compared to those selling through traditional commission agents.

Weather Intelligence and IoT-Based Monitoring

Green gram is particularly sensitive to unseasonal rains, prolonged dry spells during pod-filling, and excess soil moisture at germination. Digital weather advisory platforms including the India Meteorological Department's mausam.imd.gov.in, Skymet's farmer app, and localised agro-advisory from DAMU (District Agro-meteorology Unit) now deliver block-level, 7-day weather forecasts directly to farmers' phones.

In Kaushambi and Pratapgarh districts of UP, the Gramin Agriculture Mobile Services (GAMS) pilot by ICRISAT delivered automated SMS and voice alerts to green gram farmers before rain events in 2022, enabling timely protective spray applications and delayed harvesting operations. Pilot results showed a 14% reduction in post-harvest losses and improved grain quality (ICRISAT, 2022).

Social Media as an Extension Channel

WhatsApp, YouTube, and Facebook have quietly emerged as highly impactful extension channels, particularly for reaching farmers in peri-urban and semi-urban areas. KVK subject matter specialists in Varanasi, Allahabad, and Lucknow now operate dedicated WhatsApp broadcast groups for green gram farmers, sharing short advisory videos, pest identification images, and market news updates.

The reach of these informal channels should not be underestimated. A study by Singh *et al*., (2022) found that YouTube-based green gram demonstration videos produced in Hindi and Bhojpuri attracted over 50,000 views per video in some KVK channels, far exceeding the physical demonstration reach of any single KVK program.

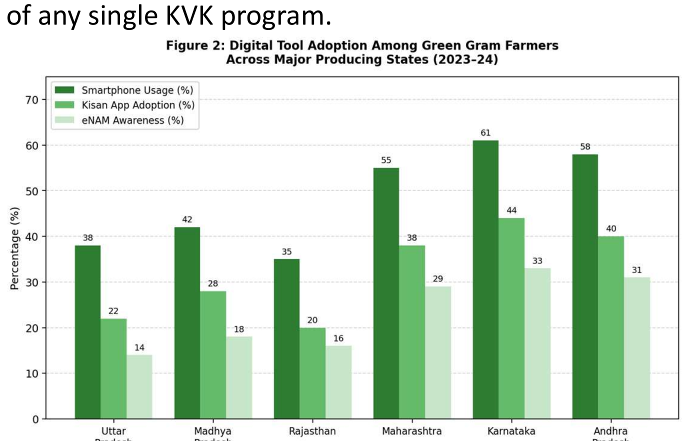

Figure 2: Digital Tool Adoption Among Green Gram Farmers Across Major Producing States (2023–24) Sources: NABARD Digital Agriculture Survey 2024; State Agriculture Department Reports; Author's Compilation

Comparative Overview of Major Digital Tools

Digital Tool	Primary Function	Key Benefit for Green Gram	Adoption Level (2023–24)
Kisan Suvidha App	Crop Advisory, Weather	Pest & disease alerts	Moderate (28–38%)
eNAM Portal	Market Linkage	Better price realisation	Low–Moderate (14–33%)
Plantix / AI Diagnostics	Disease Identification	Targeted spray guidance	Low (10–18%)
DeHaat / AgroStar	Input + Advisory	Doorstep input delivery	Low (8–20%)
WhatsApp KVK Groups	Extension Outreach	Localised agri-advisories	High (45–60%)
IMD / Skymet Weather	Weather Intelligence	Harvest & spray timing	Moderate (30–45%)
mKisan SMS Service	Mass Advisory	Broad reach, no data needed	High (50–65%)

Table 1: Comparative Overview of Digital Extension Tools and Adoption Levels Among Green Gram Farmers Sources: NABARD 2024; State Agriculture Departments; DeHaat Impact Report 2023; eNAM 2024; Author's Compilation

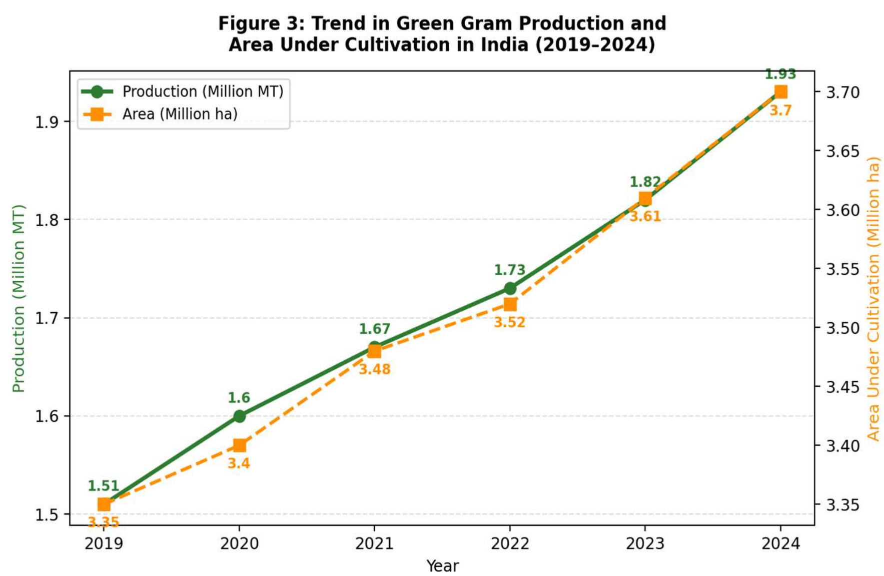

Figure 3: Trend in Green Gram Production and Area Under Cultivation in India (2019–2024) Sources: Ministry of Agriculture & Farmers Welfare, Annual Report 2023–24; Directorate of Pulses Development

Challenges in Digital Extension Adoption

Despite impressive momentum, the uptake of digital tools among green gram farmers in India remains patchy and uneven. Several structural and behavioural barriers continue to limit the reach and impact of these platforms.

The digital divide remains the most fundamental challenge. While urban and peri-urban farmers have embraced apps and online platforms, the older, less-educated farmer in a remote block of Uttar Pradesh or Rajasthan frequently lacks the smartphone literacy to navigate multi-step applications. The National Family Health Survey-5 (2019–21) data confirms that only 33% of rural women in UP own a mobile phone, and female green gram farmers are among the most digitally excluded groups.

Language and interface design also present barriers. Most early agri-apps were designed in English or formal Hindi, failing to connect with the dialect-specific communication preferences of farmers across Bundelkhand, Awadh, Bhojpuri, and Marathi-speaking zones. Localization of content including voice-based interfaces and pictographic navigation has improved in recent years but still requires significant investment.

Connectivity gaps persist in geographies that coincide with major green gram production zones. Rainfed tracts of Bundelkhand and tribal blocks of Madhya Pradesh still report poor mobile internet quality. Without reliable connectivity, even a well-designed advisory app becomes inaccessible at the moment of highest need during the kharif sowing season.

Trust and behaviour change are perhaps the least-discussed but most important barriers. Farmers who have relied on local input dealers and informal village networks for decades do not shift to app-based advice overnight. Building trust requires sustained engagement through demonstration, peer learning groups, and the visible credibility of the recommending institution.

Recommendations for Strengthening Digital Extension

Addressing the challenges outlined above requires a multi-pronged strategy that combines technical improvements, human capacity building, and institutional redesign.

- Establish Village Digital Extension Facilitation Points (VDEFPs) at the gram panchayat level, where a trained agri-digital worker (ideally a KVK-certified young farmer or SHG member) assists non-smartphone-literate farmers in accessing advisory apps and submitting field photos for AI-based diagnosis.
- Mandate local language development for all government-funded agricultural apps, including voice input and output in regional dialects. ICAR and state agricultural universities should lead the development of dialect-specific agri-vocabulary libraries.
- Strengthen eNAM infrastructure by mandating digital assaying, grading, and weighing equipment in all mandis handling green gram. Transparent, standardised grading builds farmer confidence in online selling.
- Integrate green gram into the National Digital Agriculture Mission (NDAM) as a priority crop, creating dedicated decision-support dashboards combining satellite NDVI monitoring, weather data, mandi prices, and pest outbreak alerts in real time.
- Scale up agri-extension content on YouTube, WhatsApp, and short-video platforms through KVK subject matter specialists, with performance-linked content creation incentives for extension workers who reach measurable farmer audiences.
- Design gender-responsive digital tools with features such as audio-visual tutorials in local language, community listening group formats, and integration with women SHG networks to close the gender gap in digital extension access.

Conclusion

The transformation of agricultural extension through digital tools is no longer a pilot experiment it is happening at scale across India's green gram belt. From AI-powered disease diagnosis on a low-end smartphone to real-time price discovery through eNAM, the building blocks of a truly responsive, farmer-centric digital extension system are in place. The data clearly show that farmers who engage with digital advisory and marketing platforms achieve meaningfully higher yields, lower input costs, and better price realisation for their green gram produce.

Yet, the promise of digital extension will remain unfulfilled for millions of smallholders unless deliberate action is taken to close the digital divide in connectivity, in literacy, in language, and in trust. Extension professionals, agricultural universities, policymakers, and agri-tech entrepreneurs must collaborate to ensure that the smartphone in a green gram farmer's hand is not just a communication device but a genuine productivity and prosperity tool.

As India moves toward its goal of doubling farmers' income and achieving nutritional security, digital extension for pulse crops like green gram deserves sustained policy attention, institutional investment, and research innovation. The field is ready. The farmer is waiting. The technology is here. What is needed now is the will to connect them.

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HEAT STRESS: A HIDDEN THREAT IN PIG FARMING

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Abstract

Rising global temperatures and extreme weather events associated with climate change threaten the sustainability of the swine industry. Pigs are highly vulnerable to heat stress because they lack functional sweat glands, have thick subcutaneous fat and produce high metabolic heat due to selection for rapid growth. Heat stress occurs when environmental temperature exceeds the thermoneutral zone, causing pigs to rely mainly on panting and behavioural changes for heat loss. It alters blood flow from internal organs to the body surface, resulting in intestinal hypoxia, impaired gut integrity and systemic inflammation. Maternal heat stress may also affect foetal development, reducing growth performance and altering body composition of offspring. These effects lead to reduced feed intake, poor growth, disease susceptibility, reproductive failure, economic losses and welfare concerns. Mitigation requires ventilation, shade, reduced stocking density, cooling systems, nutritional supplementation and long-term genetic selection for heat-tolerant pigs.

Keywords: Climate change, Swine production, Thermoneutral zone, Animal welfare, Genetic selection, Productivity

Introduction

Pig farming is a rapidly expanding and economically important agricultural sector, particularly in tropical and subtropical regions, driven by the rising global demand for animal protein. However, increasing global temperatures and the growing frequency of extreme heatwaves associated with climate change pose a significant challenge to the sustainability of the swine industry. The Intergovernmental Panel on Climate Change predicts that by 2100, global average surface temperatures may rise by 1.8°C to 4.0°C and increases of 1.5°C to 2.5°C could place approximately 20 to 30 percent of plant and animal species at risk of extinction (FAO, 2007), with serious implications for food security in developing countries.

Pigs are particularly vulnerable to heat stress due to biological limitations that restrict their ability to dissipate excess body heat. As a result, heat stress leads to substantial economic losses and animal welfare concerns. In the United States alone, the swine industry incurs an estimated annual loss of nearly $1 billion due to reduced growth, impaired reproductive performance and increased mortality. Additionally, heat stress significantly compromises animal welfare, causing physiological distress and reduced productivity in affected animals.

What is Heat Stress?

Heat stress is a state of physiological disruption or strain that occurs when environmental conditions, such as high ambient temperature, high relative humidity, thermal radiation and low air movement, exceed the upper critical limit of an animal's thermoneutral zone (Ondruska *et al.,* 2011). In this state, the pig absorbs or generates more heat than it can dissipate to the environment, making it unable to passively maintain its optimal core body temperature, which normally ranges from 38.7°C to 40.0°C with a normal respiration rate of about 20–30 breaths per minute. Exposure to extreme temperatures can cause severe overheating, with body temperature rising to about 43°C and respiration rates reaching up to 180 breaths per minute, which may be fatal. Pigs are particularly susceptible to heat stress due to limited sweating ability, thick subcutaneous fat and relatively small lungs. As a result, heat stress reduces feed intake, growth performance, reproductive efficiency and carcass quality, leading to significant economic losses.

Thermoregulation in Pigs:

Normal Body Temperature and Thermal Comfort Zone:

A pig's normal core body (rectal) temperature ranges optimally between 38.7°C and 40.0°C. The thermoneutral zone (TNZ) is the range of environmental temperatures within which pigs maintain a stable body temperature with minimal metabolic effort and optimal production efficiency (Fig. 1). The TNZ is bounded by two critical thresholds: the Lower Critical Temperature (LCT) and the Upper Critical Temperature (UCT). When temperatures fall below the LCT, pigs experience cold stress and must increase heat production through metabolic activity, diverting energy from growth. When temperatures rise above the UCT, passive heat loss becomes insufficient, leading to heat stress, elevated body temperature and reduced feed intake. The TNZ is not fixed and varies according to several factors. The optimal thermal comfort zone varies by age and weight; for example, it is between 15°C to 20°C for a lactating sow, but 28°C to 38°C for a newborn piglet. Genetics, nutrition and housing conditions significantly influence heat tolerance in pigs. High-producing breeds generate more metabolic heat, while increased feed intake and poor ventilation or flooring can shift the thermoneutral zone and increase heat stress risk.

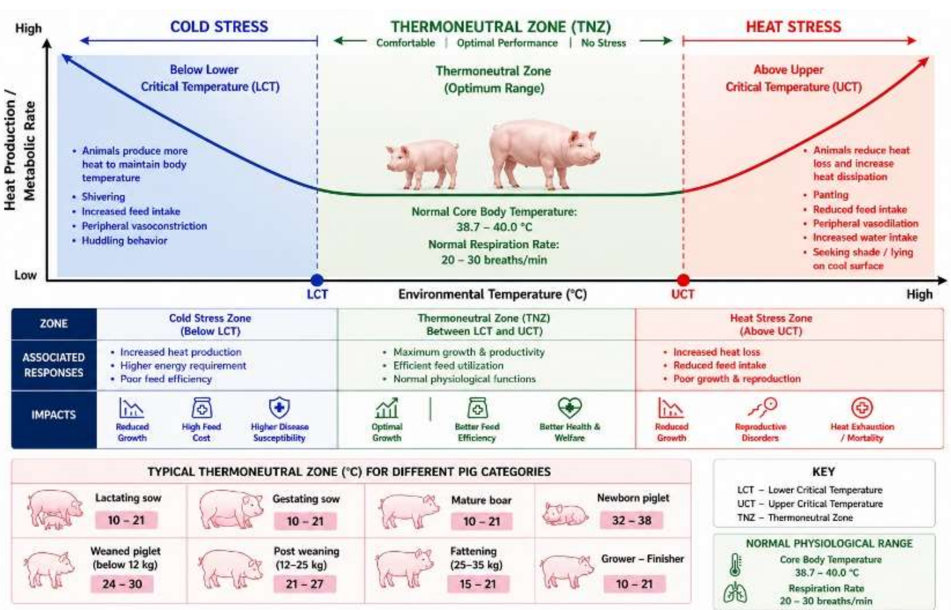

Fig. 1. Thermoneutral Zone (TNZ) in Pigs and its associated responses

Why Pigs Are Vulnerable to Heat Stress?

Pigs are uniquely vulnerable to high temperatures for three key biological reasons. First, pigs possess a thick layer of subcutaneous adipose tissue (fat) which acts as an excellent insulator but severely limits heat dissipation from the body core to the environment. Second, they have very few functional sweat glands, restricting evaporative cooling through the skin. Third, modern commercial pig breeds have been genetically selected for rapid growth and high productivity, resulting in increased metabolic heat production during digestion and growth.

How Pigs Regulate Body Temperature?

Because pigs have limited sweating ability, they rely on physiological and behavioural mechanisms to maintain body temperature by dissipating heat through sensible (non-evaporative) and latent (evaporative) pathways. The primary physiological responses include increased respiration or panting and peripheral vasodilation, which help dissipate heat through evaporation, radiation and convection. Panting becomes especially important when environmental temperatures exceed the upper critical temperature. During severe heat stress, evaporation through panting can account for up to 70% of a pig's total heat loss. Pigs also depend on behavioural adaptations to cope with heat stress. They seek shade, reduce activity and feed intake, lying laterally (fully extended on their sides) and spread out to increase contact with cooler surfaces (Fig. 2) and wallow in water or mud to enhance evaporative and conductive heat loss.

Fig. 2. Lateral Lying Posture of Pigs as a Behavioural Indicator of Heat Stress

How to Diagnose and Monitor Heat Stress in Pigs?

Heat stress can be identified using both environmental measurements and animal-based indicators. Environmental Parameters including continuous monitoring of ambient temperature and relative humidity at the pig level. These parameters can be combined to calculate the Temperature Humidity Index (THI), which is a reliable indicator for predicting the onset of heat stress and guiding timely management interventions. Critical THI values designate the severity of risk: a THI of ≥75 indicates an "Alert" phase where early signs of heat stress appear, 79 to 83 represents "Danger" and a THI > 84 is a "Very Dangerous" or "Emergency" state. The heat stress index chart (Fig. 3) developed by Iowa State University shows that temperatures > 28 °C, even at moderate humidity levels around 30 %, can significantly impair intestinal health and performance in grower-finisher pigs.

Animal-based indicators viz. Increased respiration rate and panting, which can be monitored by observing flank movements. For example, respiration rate in barrows increased from 20 breaths per minute at 18°C to 120 at 32°C, while in sows it increased from 29 at 15°C to 58 at 25°C (Malmkvist *et al*., 2012). Generally, a respiration rate exceeding 50 breaths per minute at rest indicates heat stress. Other important indicators include elevated skin or rectal temperature, which can be measured using thermometers or infrared thermography. Behavioural changes such as increased lying in lateral positions, reduced activity and decreased feed intake are also common during hot conditions. Studies have shown that pigs exposed to 35°C consumed up to 50 % less feed (Pearce *et* *al*., 2013). Additionally, pigs often show increased water intake, skin discoloration and excessive pen fouling, such as defecating in resting areas to create wet surfaces for cooling (Goumon *et al*., 2013; Huynh, 2005). The major causes, signs and symptoms of heat stress in pigs are summarized in Table 1.

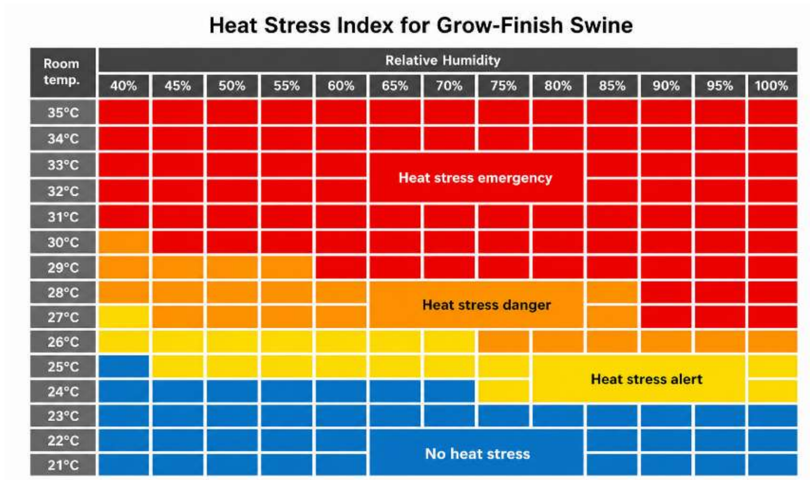

Fig. 3. Heat stress index chart of grower-finisher pigs (Source: Iowa State University)

Category	Type	Key Factors / Indicators
Causes	Environmental factors	High ambient temperature, high humidity, poor ventilation, direct solar radiation
	Managemental factors	Overcrowding, poor housing design, inadequate cooling, warm or limited water supply, feeding during peak heat
	Animal factors	Older and heavier pigs, susceptible breeds, pregnant and lactating sows, high metabolic heat production
Signs and Symptoms	Behavioural signs	Panting, lethargy, lying laterally, reduced feed intake, seeking shade or wet areas, wallowing behaviour
	Physiological signs	Increased respiration rate, increased heart rate, elevated body temperature, skin redness, dehydration
	Severe clinical signs	Open-mouth breathing, muscle cramps, collapse, unconsciousness, death due to hyperthermia or heart failure

Table. 1. Causes, Signs and Symptoms of Heat Stress in Pigs

What are the Effects of Heat Stress on Pigs?

Heat stress has wide-ranging effects on pig growth, reproduction, health, behaviour and overall farm profitability. These impacts occur because pigs reduce feed intake and redirect energy toward maintaining body temperature rather than supporting growth and production.

Impact on Growth and Carcass Quality: One of the earliest responses to heat stress is a reduction in voluntary feed intake, which lowers metabolic heat production but also decreases average daily gain and delays market weight. Heat stress alters nutrient metabolism, leading to reduced protein synthesis and lean muscle growth while increasing fat deposition. As a result, carcasses become fatter with lower meat quality and the incidence of pale, soft and exudative (PSE)-like meat may increase under prolonged heat exposure.

Gastrointestinal and Metabolic Effects: During heat stress, blood flow is redirected from internal organs to the skin to promote heat loss. This reduces oxygen supply to the digestive tract (Intestinal Hypoxia), damaging the intestinal barrier and causing "leaky gut" syndrome. Increased intestinal permeability allows endotoxins to enter the bloodstream (Endotoxemia), triggering inflammation, oxidative stress and weakened immunity. Heat stress also disrupts metabolic regulation, often increasing insulin activity and altering energy utilization, which further affects growth and body composition.

Reproductive Performance: Heat stress significantly reduces reproductive efficiency in both sows and boars. In sows, it can delay puberty, irregular estrus cycles or reduce estrus expression, lower conception and farrowing rates and increased embryonic loss and stillbirths. Lactating sows experience reduced feed intake and milk production, resulting in poor piglet growth and higher pre-weaning mortality. Gestational heat stress can permanently affect foetal development, leading to reduced muscle growth, increased body fat and a significantly higher proportion of light-weight piglets (≤1.1 kg). In boars, elevated testicular temperature decreases semen quality, sperm motility and fertility, with effects that may persist even after temperatures return to normal.

Physiological, Health and Behavioural Changes: Because pigs lack functional sweat glands, they rely heavily on panting to dissipate heat. Prolonged panting can lead to dehydration and respiratory imbalances. Heat-stressed pigs typically show lethargy, reduced activity and increased lying in lateral positions to maximize heat loss. They may seek wet or dirty areas or wallow in urine and faeces to cool themselves. In severe cases, pigs may exhibit open-mouth breathing, collapse and death due to hyperthermia.

Economic and Welfare Implications: These combined effects by Reducing productivity, alongside increased veterinary costs, facility management expenses and direct losses due to high morbidity and mortality heavily constrains the profitability of modern pig farming. In addition, heat stress compromises animal welfare by causing discomfort, distress and increased mortality, making it a major management and ethical concern in modern swine farming.

What are the Practical Strategies to Prevent and Manage Heat Stress in pigs?

There is an urgent need to develop effective and sustainable management strategies to reduce the negative impacts of heat stress, especially in the context of climate change. The primary focus should be on modifying the animal's microenvironment through appropriate heat stress mitigation measures. However, the high cost of advanced cooling technologies often limits their adoption, particularly among smallholder farmers in developing countries. Genetic selection for thermal tolerance offers a potential long-term solution, although it may be associated with reduced productivity under thermoneutral conditions. Therefore, identifying flexible and practical management approaches that can immediately reduce heat stress without compromising production performance is essential. Among these, dietary adjustments and supplementation represent simple, adaptable strategies that can be implemented across different livestock production systems.

Housing Management

- ✓ Ensure proper forced ventilation using exhaust or tunnel ventilation systems to continuously replace hot air with fresh air.
- ✓ Provide adequate roof insulation to reduce heat accumulation inside pig houses.

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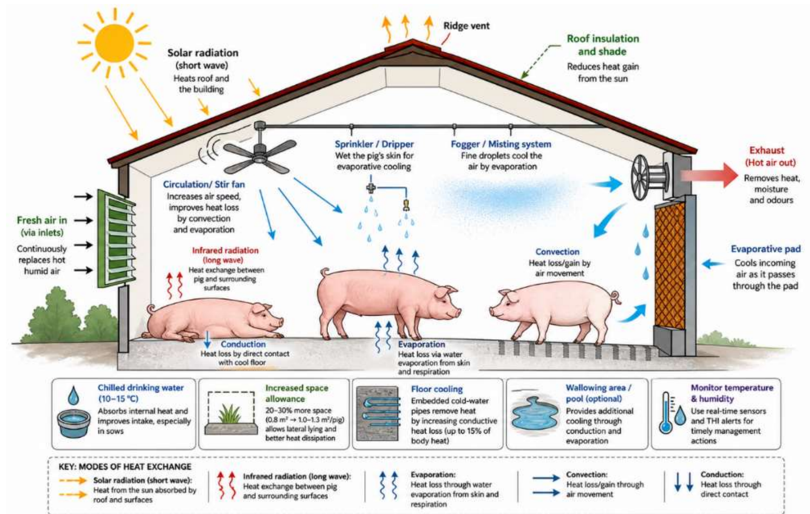

Fig. 4. Thermal Heat Exchange and Cooling Strategies in Pig Housing Systems
(Modified from Mayorga *et al*., 2019**)**

- ✓ Create shade using trees, shade structures, or reflective materials such as white chalk on roofs to block direct solar radiation.
- ✓ Use floor cooling systems (embedded cold-water pipes in concrete floors) to enhance conductive heat loss, as pigs can lose up to 15 percent of body heat through contact with cool surfaces.
- ✓ Apply direct skin wetting by sprinkling or dripping water onto pigs to improve evaporative cooling.
- ✓ Increase air velocity using circulation or high-speed fans to enhance heat dissipation from the animal's body.
- ✓ Increase space allowance by about 20 to 30 % (for example, from 0.8 m^2 to 1.0–1.3 m^2 per pig) to allow pigs to lie laterally and dissipate heat effectively.
- ✓ Install sprinklers, foggers, or misters to reduce ambient temperature through evaporative cooling.
- ✓ Use evaporative cooling pads to lower the temperature of incoming air in pig housing systems.
- ✓ Provide wallowing areas or tanks where feasible to support natural cooling behaviour and improve thermal comfort.

Feeding and watering Management:

- ✓ Shift feeding time to cooler hours such as early morning and late evening to reduce digestive heat production during the hottest part of the day.
- ✓ Formulate high-energy, low-fibre diets by increasing dietary fat and reducing excess crude protein and fermentable fibre to lower metabolic heat increment.
- ✓ Supplement diets with betaine (osmolyte) to maintain cellular water balance, reduce dehydration stress and protect intestinal integrity during heat stress.
- ✓ Include chromium supplementation (for example, chromium picolinate) to improve insulin efficiency, glucose utilization and voluntary feed intake in heat-stressed pigs.
- ✓ Provide supra-nutritional antioxidants such as Vitamin E, Vitamin C, betaine and Selenium, Zinc to reduce oxidative stress and support immune function.

- ✓ Adjust macronutrient composition by lowering crude protein levels while supplying essential amino acids (lysine, methionine, threonine) to maintain growth without increasing metabolic heat.
- ✓ Supply chilled drinking water (approximately 10°C to 15°C) to help absorb internal body heat and improve feed intake and milk production.

Fig. 5. Piglets Using Water to Stay Cool During Hot Weather

Breed and Genetic Approaches:

- ✓ Prioritize selection of heat-tolerant breeds in breeding programs to improve resilience to high environmental temperatures.
- ✓ Utilize indigenous breeds known for superior heat tolerance compared to high-producing exotic breeds such as Large White.
- ✓ Adopt crossbreeding strategies between indigenous and commercial breeds to combine heat tolerance with acceptable growth and production performance.
- ✓ Recognize that intensive selection for rapid growth, high milk yield and large litter size has increased metabolic heat production, making modern commercial pigs more vulnerable to heat stress.
- ✓ Incorporate genetic improvement programs that balance productivity traits with thermal tolerance to ensure long-term sustainability of pig production systems.
- ✓ Use updated decision support and monitoring tools, including improved Temperature Humidity Index (THI) models and real-time alert systems, to better manage heat stress risks in modern pig populations.

Seasonal Management Calendar for Heat Stress Control

- ✓ **Pre-summer preparation:** Clean and service fans, ducts and sprinklers and ensure backup power readiness and establish contingency plans for electrical failures.
- ✓ **Summer management:** Reduce stocking density, adjust feeding time and ration, ensure continuous cool water supply and breeding targets must be managed around anticipated fertility drops.
- ✓ **Heat wave emergency:** Increase airflow, deploy auxiliary fans, spray pigs with water, provide electrolytes and avoid any stressful events like handling or transport and vaccinations.

Role of Farmers and Extension Services:

- ✓ Create awareness programs to educate farmers about the risks and prevention of heat stress.
- ✓ Use early warning systems to alert farmers when Temperature Humidity Index (THI) reaches dangerous levels.

✓ Provide regular training to help farm staff quickly recognize heat stress signs and take immediate action.

The summary table showing severity levels of heat stress in pigs based on environmental conditions, clinical signs, production impact and recommended management actions is given below.

Severity Level	Environmental Indicators	Animal Signs	Production Impact	Recommended Action
Mild Heat Stress (25–29°C)	Temperature slightly above thermoneutral zone, moderate humidity	Slight panting, mild reduction in activity, increased water intake	Minor reduction in feed intake and growth	Provide shade, ensure adequate ventilation, increase water availability
Moderate Heat Stress (30–34°C)	High temperature and humidity, THI approaching danger level	Rapid panting (> 50 breaths/min), reduced feed intake, lethargy, lateral lying	Reduced weight gain, poor feed efficiency, early reproductive effects	Use cooling systems (fans, sprinklers), adjust feeding time, provide electrolytes
Severe Heat Stress (≥ 35°C)	Very high temperature and humidity, THI in emergency range	Open-mouth breathing, extreme panting, collapse, dehydration	High mortality, reproductive failure, major economic loss	Immediate cooling, emergency water supply, reduce stocking density, veterinary intervention

Table.2. Severity Levels of Heat Stress in Pigs

Conclusion

Heat stress remains one of the most formidable challenges limiting global pig production. Because the biological damage caused by hyperthermia is profound, preventive management is vastly more effective and profitable than reactive treatment. By adopting simple, low-cost interventions, such as adjusting feed times, enhancing water availability, reducing stocking densities and ensuring adequate ventilation, farmers can successfully safeguard animal welfare and significantly reduce the crushing economic losses associated with heat stress.

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THE INTELLIGENT LENS: MACHINE LEARNING MODELS AND APPLICATIONS IN QUANTIFYING COMPUTER VISION SYNDROME

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An Overview

Prolonged digital screen exposure across occupational and casual spaces has triggered an expanding modern epidemic: Computer Vision Syndrome (CVS), alternatively referred to as Digital Eye Strain (DES). Traditional clinical diagnostics rely heavily on retroactive, subjective patient feedback and post-symptomatic examinations. However, the intersection of Artificial Intelligence (AI) and Machine Learning (ML) has introduced real-time automated tracking frameworks that monitor ocular state, blink kinematics, and spatial geometry in parallel. This document analyzes the structural models, algorithmic workflows, and deployment metrics governing intelligent CVS quantification tools.

Section 1: The Multi-Stage Machine Learning Pipeline

To mathematically extract micro-fluctuations associated with ocular stress, software deployment platforms leverage structured video pipeline topologies. High variability in raw input frames that caused by moving backgrounds, structural head rotations, and fluctuating ambient luma profiles—requires rigorous multi-stage standardization. The programmatic extraction pipeline is broadly organized into four distinct modules:

- **Data Acquisition:** Real-time capture of high-definition video frames via native consumer webcams, localized near-infrared arrays, or smart ophthalmic hardware.
- **Image Preprocessing & Geometric Standardization:** Isolating the Region of Interest (ROI) containing the periocular structures. This stage normalizes contrast distributions and minimizes out-of-plane head tilt vector noise.

- **Biological Feature Extraction:** Spatial parameter computation mapping specific structural dimensions, such as relative distance distributions across lower and upper palpebral boundaries.
- **Classification Framework:** Inference models processing incoming raw mathematical inputs into categorized diagnostic outputs spanning discrete severity tiers.

Section 2: Strategic Machine Learning Models and Structural Topologies

Automated CVS classification requires two distinct computational paradigms: Deep Learning and Computer Vision to isolate physiological metrics from facial feeds, and Classical Machine Learning to synthesize multivariate tabular fields, including demographic and spatial configuration profiles.

Convolutional Neural Networks (CNNs) & Optimized Architectures

Standard deep vision networks present high parameter counts that conflict with continuous background edge processing. Consequently, modern frameworks prioritize lightweight convolutional designs:

- **MobileNetV2:** Utilizes inverted residuals and depthwise separable convolutions to dramatically cut operational overhead, allowing continuous background execution on mobile units to classify surface alterations, conjunctival hyperaemia, and tearing degradation.
- **MediaPipe Face Mesh:** Integrates custom single-stage deep networks to chart 468 distinct 3D landmarks in real-time, delivering robust spatial tracking of outer periocular contours independent of localized user movement.

Recurrent Neural Networks (RNNs) and Long Short-Term Memory (LSTM) Networks

Because eye strain compounds incrementally across runtime intervals, isolated static evaluations often lack clinical completeness. LSTMs isolate multi-frame temporal context, identifying progressive trends like down-trending blink velocities, expanding intermediate closure durations, and micro-sleep configurations indicating sustained functional strain.

Ensemble Tree Models & Gradient Boosting

When mapping heterogeneous structural matrices (combining behavioral survey inputs, calculated illumination metrics, and physical parameters), gradient-boosted systems demonstrate superior predictive stability. Optimization variants like XGBoost map numerical scoring scales directly against structural classifications.

Section 3: Mathematical Metric Models & The Eye Aspect Ratio (EAR)

To parameterize video data streams into quantifiable inputs, computer vision platforms measure explicit coordinate ratios across the ocular perimeter. The primary indicator for tracking eye closure is the Eye Aspect Ratio (EAR). The calculation maps six individual coordinate points tracking the upper, lower, and horizontal bounds of the eyelid margins. During unconstrained waking hours, the EAR returns a high, stable baseline value. A blink manifests as a sharp, near-zero drop, providing precise tracking of three diagnostic indicators:

- **Blink Frequency:** Healthy baselines reflect approximately 15–20 events per minute. Prolonged visual immersion drives drops of up to 60%, accelerating tear evaporation.
- **Incomplete Blink Co-efficients:** Fatigued visual systems frequently exhibit partial blinks where the eyelids fail to close fully, leaving the inferior cornea exposed to desiccation.
- **Gaze Fixation Trajectories:** Tracks micro-instabilities and rapid spatial drift across high-concentration focus spells.

Section 4: Performance Matrix Across Machine Learning Architectures

Model Architecture	Primary Data Input	Key Computational Advantage	Clinical / System Output Target
MobileNetV2 (CNN)	Video Streams / Static Images	Minimal footprint, fast inference cycles on edge processing hardware	Ocular surface redness and localized inflammation parsing
LSTM (RNN)	Sequential Tracking Matrices	Maintains long-horizon temporal state dependencies	Blink rate structural trends and drowsiness indicator mapping
XGBoost Framework	Tabular Datasets (Survey, Lux, Age)	High accuracy mapping across mixed non-linear features	CVS-Q risk categorization and prognostic scoring
Support Vector Machines	Vector Formats (EAR, Frequency)	Low memory requirement for real-time binary splits	Discrete system categorization: Strained vs Healthy

Section 5: Real-World Software Applications

Industrial and Clinical Implementations: The translation of machine learning architectures from academic theory into enterprise and medical deployment is currently focused within three primary domains.

Consumer Workspace Health Applications

Modern background wellness applications utilize localized webcams to dynamically compute custom fatigue metrics. If consecutive EAR patterns indicate a sustained drop in blink rates or prolonged fixations, the application initiates localized protective adjustments. It can modulate screen color temperatures, scale structural text sizing, or launch interactive micro-rest prompts to encourage regular accommodative resetting.

Advanced Clinical Screening Systems

In modern optometric centers, deep neural networks analyze high-resolution fluorescein dye videos to evaluate the Tear Film Break-Up Time (TBUT). Rather than relying on approximate manual stopwatch timing, convolutional networks track tear break-up coordinates down to individual pixels, detecting localized dry-eye pathologies before macro-structural damage occurs to the corneal epithelium.

Mission-Critical Telematics Systems

In high-stress control rooms, aviation cockpits, and heavy logistics, infrared camera rigs run embedded Vision Transformers (ViTs). Infrared tracking isolates evaluation from ambient glare and operates reliably when personnel wear glasses, allowing early prediction of cognitive drop-offs and ocular fatigue to trigger mandatory safety interventions.

Conclusion

The integration of machine learning into the detection and quantification of Computer Vision Syndrome marks a major advancement in occupational health and optometric diagnostics. Traditional diagnostic models offer static snapshots of eye strain after symptoms have already developed. By combining computer vision frameworks like MobileNetV2 with sequential temporal architectures like LSTMs, modern systems can continuously and non-invasively track real-time physiological marker such as shifting Eye Aspect Ratios (EAR), incomplete blink patterns, and tear film degradation.

Recommendations

- As daily screen dependencies continue to grow, the application of these intelligent systems will shift from standalone consumer utilities toward deeply integrated hardware frameworks. Future smart displays, wearable devices, and corporate wellness platforms will natively incorporate embedded machine learning models that optimize display parameters and environmental factors in real time.
- By transforming our relationship with digital displays from passive exposure to active, intelligent monitoring, machine learning establishes a vital preventive foundation that protects long-term visual health in an interconnected digital world.

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JEEVAMRIT: THE FOUNDATION OF NATURAL FARMING AND SOIL HEALTH RESTORATION

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Abstract

Jeevamrit is a key component of natural farming that promotes soil regeneration through biological processes rather than synthetic inputs. Prepared from locally available materials such as cow dung, cow urine, jaggery, pulse flour, and soil, it acts as a microbial inoculant that enriches the soil ecosystem. Its application enhances the activity of beneficial microorganisms, accelerates nutrient cycling, and improves soil physical and biological properties. By fostering a healthy rhizosphere, Jeevamrit supports plant growth, strengthens nutrient uptake, and contributes to sustainable crop production. In addition, it helps restore degraded soils, improves moisture retention, and reduces dependence on chemical fertilizers, thereby lowering production costs and environmental impacts. As concerns over soil degradation and agricultural sustainability continue to grow, Jeevamrit offers an eco-friendly and farmer-centered approach to restoring soil health and ensuring long-term productivity within natural farming systems.

Introduction

Agriculture is facing increasing challenges due to declining soil fertility, excessive dependence on chemical fertilizers, environmental degradation, and climate variability. Continuous use of synthetic inputs has adversely affected soil biological activity, reduced organic matter content, and weakened the natural capacity of soils to sustain crop production. As a result, there is a growing need for sustainable farming practices that enhance soil health while maintaining agricultural productivity. Natural farming has emerged as an eco-friendly alternative that relies on biological processes and locally available resources rather than external chemical inputs.

Among the various components of natural farming, Jeevamrit occupies a central position because of its role in revitalizing the soil ecosystem. Jeevamrit is a fermented microbial formulation prepared from indigenous cow dung, cow urine, jaggery, pulse flour, and a small quantity of fertile soil. It serves as a rich source of beneficial microorganisms that stimulate biological activity in the rhizosphere, improve nutrient availability, and promote healthy plant growth.

Healthy soil is the foundation of productive and resilient agricultural systems. Soil microorganisms play a crucial role in organic matter decomposition, nutrient transformation, and maintenance of soil structure. The application of Jeevamrit encourages microbial multiplication, improves soil aeration, increases water-holding capacity, and supports the development of a balanced soil food web. These improvements contribute to better root growth, enhanced nutrient uptake, and increased crop performance.

In recent years, Jeevamrit has gained significant attention as a low-cost and environmentally sustainable input that supports soil restoration and reduces dependence on chemical fertilizers.

Therefore, Jeevamrit is widely regarded as the foundation of natural farming and an effective tool for restoring soil health and ensuring long-term agricultural sustainability.

Components of Jeevamrit

Jeevamrit is a fermented microbial formulation used in natural farming to enhance soil biological activity and improve nutrient availability. It is prepared using simple, locally available ingredients that serve as sources of beneficial microorganisms and nutrients. The standard components required for preparing approximately 200 liters of Jeevamrit are:

1. **Indigenous Cow Dung (10 kg)**

Fresh dung obtained from indigenous cows is the primary ingredient of Jeevamrit. It contains a diverse population of beneficial microorganisms, including bacteria, fungi, and actinomycetes, which play a vital role in nutrient cycling and soil fertility enhancement.

2. **Cow Urine (10 liters)**

Cow urine acts as a rich source of nitrogen, minerals, enzymes, and growth-promoting substances. It supports microbial multiplication and contributes to the fermentation process.

3. **Jaggery (2 kg)**

Jaggery provides readily available carbon and energy for microbial growth. It stimulates rapid multiplication of beneficial microorganisms during fermentation.

4. **Pulse Flour (2 kg)**

Flour prepared from pulses such as chickpea, pigeon pea, or black gram serves as a source of proteins and amino acids. It supplies nitrogen and nutrients required for microbial development.

5. **Native Soil (A Handful)**

A small quantity of fertile soil collected from the bunds or undisturbed areas of the farm introduces locally adapted microorganisms into the mixture, enhancing microbial diversity.

6. **Water (200 liters)**

Water acts as the medium for fermentation and microbial activity. Clean, non-chlorinated water is generally preferred to support microbial growth.

Method of Preparation

Step 1: Selection of Container

A plastic drum, cement tank, or earthen container with a capacity of at least 200 liters is selected. Metal containers are generally avoided as they may interfere with microbial activity during fermentation.

Step 2: Mixing of Ingredients

About 200 liters of water is poured into the container. Fresh cow dung is thoroughly mixed in the water, followed by the addition of cow urine. Jaggery and pulse flour are then added and stirred until a uniform solution is obtained. Finally, a handful of fertile soil is mixed into the preparation.

Step 3: Fermentation Process

The mixture is covered with a cotton cloth or jute sack to allow air exchange while preventing contamination. The solution is kept under shade and stirred vigorously in both clockwise and anticlockwise directions two to three times daily. Continuous stirring ensures proper aeration and uniform microbial growth.

Step 4: Incubation Period
The mixture is allowed to ferment for 48-72 hours, depending on environmental conditions. During this period, microbial populations multiply rapidly, transforming the solution into a biologically active formulation.

Step 5: Application
After fermentation, Jeevamrit is ready for use. It can be applied through irrigation water, soil drenching, or fertigation systems. Regular application at intervals of 15–20 days helps improve soil microbial activity, nutrient availability, and overall soil health.

Method of Use of Jeevamrit
Jeevamrit is primarily used as a soil microbial inoculant in natural farming systems. After fermentation for 48-72 hours, it can be applied through different methods depending on crop and field conditions.

Soil Drenching
Jeevamrit is diluted with irrigation water and applied directly to the soil around the root zone. This method enhances microbial activity, nutrient availability, and root development.

Irrigation Application
The fermented solution is mixed with irrigation water and delivered through furrow, flood, or drip irrigation systems. This ensures uniform distribution of beneficial microorganisms throughout the field.

Seedling Treatment
Seedlings can be dipped in a diluted Jeevamrit solution before transplanting to promote root growth and improve establishment in the field.

Benefits of Using Jeevamrit
Jeevamrit is one of the most important biological inputs in natural farming due to its ability to improve soil health, support crop growth, and enhance the sustainability of agricultural systems. Its regular application promotes biological processes in the soil and reduces dependence on synthetic fertilizers. The major benefits of Jeevamrit are discussed below:

Enhances Soil Microbial Activity
Jeevamrit serves as a rich source of beneficial microorganisms that multiply rapidly after application to the soil. These microorganisms participate in the decomposition of organic matter and help transform unavailable nutrients into forms that can be readily absorbed by plants. Increased microbial activity improves the overall biological health of the soil and creates a favorable environment for crop growth.

Improves Nutrient Availability
Although Jeevamrit is not a fertilizer in the conventional sense, it plays an important role in nutrient mobilization. The microbial population stimulated by Jeevamrit helps release essential nutrients such as nitrogen, phosphorus, potassium, and micronutrients from soil reserves. This process improves nutrient-use efficiency and supports balanced plant nutrition.

Restores Soil Health
Continuous use of chemical fertilizers can adversely affect soil structure and biological activity. Jeevamrit helps restore soil vitality by encouraging the growth of beneficial microorganisms and

increasing organic matter decomposition. Its regular use contributes to the development of healthy, fertile, and biologically active soils capable of sustaining long-term agricultural productivity.

Increases Water-Holding Capacity

Healthy soils enriched with microbial activity tend to retain moisture more effectively. Jeevamrit improves soil organic matter decomposition and contributes to better soil structure, which enhances water retention. This benefit is particularly valuable in drought-prone regions where efficient use of available water is essential for crop production.

Promotes Healthy Root Development

A biologically active soil environment supports vigorous root growth. Jeevamrit encourages root proliferation and improves the ability of plants to absorb water and nutrients from the soil. Strong root systems enhance crop establishment, growth, and resilience to environmental stress.

Reduces Dependence on Chemical Inputs

One of the major advantages of Jeevamrit is its ability to reduce the need for synthetic fertilizers and other external inputs. By improving natural nutrient cycling and biological activity, it enables farmers to rely more on locally available resources. This reduces production costs and promotes environmentally sustainable farming practices.

Enhances Crop Growth and Productivity

The combined effects of improved nutrient availability, better root development, and enhanced soil health contribute to healthy crop growth. Farmers practicing natural farming often observe improved plant vigor, better flowering and fruiting, and stable yields when Jeevamrit is applied regularly as part of an integrated management system.

Supports Climate-Resilient Agriculture

Soils with higher biological activity and improved structure are generally more resilient to climatic stresses such as drought, heat, and erratic rainfall. Jeevamrit contributes to the development of such resilient soils, helping farming systems adapt to changing environmental conditions and maintain productivity under stress.

Environmentally Friendly and Sustainable

Jeevamrit is prepared from natural, biodegradable, and locally available materials. Its use minimizes the environmental risks associated with excessive chemical fertilizer application, including soil degradation, water pollution, and loss of biodiversity. Therefore, it supports environmentally responsible agricultural practices and long-term sustainability.

Cost-Effective for Farmers

The ingredients required for preparing Jeevamrit are inexpensive and easily available on most farms. This makes it a practical and affordable option, especially for small and marginal farmers. By reducing expenditure on external agricultural inputs, Jeevamrit contributes to improved farm profitability and resource efficiency.

Conclusion

Jeevamrit has emerged as a fundamental component of natural farming due to its significant role in enhancing soil biological activity, improving nutrient availability, and restoring soil health. Prepared from locally available organic materials, it serves as an effective microbial inoculant that strengthens the natural processes occurring within the soil ecosystem. The use of Jeevamrit not only promotes healthy plant growth and sustainable crop production but also reduces dependence on synthetic fertilizers and other external inputs. By improving soil structure, water-holding capacity, and microbial diversity, it contributes to the long-term productivity and resilience of agricultural systems.

The primary purpose of Jeevamrit is to revitalize soil as a living system and support environmentally sustainable farming practices. Looking ahead, Jeevamrit holds considerable potential for advancing climate-resilient and sustainable agriculture. Further research on its microbial composition, crop-specific applications, and integration with modern farming technologies can enhance its effectiveness and wider adoption. As concerns regarding soil degradation, environmental pollution, and food security continue to grow, Jeevamrit offers a promising, low-cost, and eco-friendly solution for maintaining soil fertility and ensuring the sustainability of future agricultural systems.

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MAHUA AND THE TRIBAL ECONOMY OF CHHATTISGARH: TRADITION, LIVELIHOODS, AND EMERGING OPPORTUNITIES

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Abstract

Forests play a crucial role in sustaining the livelihoods of tribal communities in Chhattisgarh, and among the various non-timber forest products (NTFPs), Mahua (*Madhuca longifolia*) occupies a unique economic, cultural, and ecological position. Traditionally known as the "Tree of Life," Mahua provides food, medicine, income, and livelihood security to forest-dependent households. The flowers, seeds, and other plant parts support household consumption as well as local market activities. Increasing interest in value-added products, women-led enterprises, and Mahua-based rural industries has expanded its economic potential beyond traditional uses. Recent policy initiatives promoting processing, branding, and market development further strengthen its role in tribal development. This article examines the livelihood, nutritional, economic, and entrepreneurial dimensions of Mahua and discusses its emerging role in fostering a resilient forest-based bioeconomy in Chhattisgarh.

Keywords: Mahua, Tribal Livelihoods, NTFPs, Value Addition, Chhattisgarh

Introduction

Chhattisgarh possesses one of the richest forest resource bases in India, with forests covering a substantial proportion of the state's geographical area. For tribal communities, forests serve as a vital source of food, medicine, employment, and income. Among the diverse forest products collected by local communities, Mahua (*Madhuca longifolia*) occupies a special place due to its multiple uses and deep cultural significance. Mahua has been an integral part of tribal life for centuries. Every component of the tree, including flowers, seeds, leaves, bark, and wood, contributes to household welfare. Beyond its traditional role, Mahua is increasingly being recognized as an important livelihood resource capable of supporting climate-resilient rural development, women's entrepreneurship, and value-added enterprise creation.

Mahua: A Multipurpose Forest Resource

Mahua (*Madhuca longifolia*), belonging to the family Sapotaceae, is one of the most important multipurpose tree species found in the tribal regions of central India, particularly in Chhattisgarh. The tree is well adapted to dry tropical and subtropical climates and thrives under rainfed and marginal environmental conditions with minimal management requirements. Flowering generally occurs during March–April, followed by fruiting during April–June. Almost every part of the tree possesses economic value. The flowers are widely used for food, traditional beverages, and value-added products, while the seeds are an important source of edible and industrial oil. Leaves, bark, and other plant parts are utilized in traditional healthcare practices and various household applications. Owing to its high drought tolerance, low-input nature, and ability to provide recurring economic benefits, Mahua serves as an important source of income, food security, and employment for forest-dependent communities. These characteristics make it a climate-resilient livelihood resource and a valuable component of Chhattisgarh's forest-based economy.

Economic Importance and Livelihood Security

Mahua plays a significant role in the tribal economy by providing seasonal income, employment opportunities, and livelihood diversification. Collection and sale of flowers and seeds generate earnings during periods when agricultural activities and wage employment opportunities are limited. From an agricultural economics perspective, Mahua functions as a form of livelihood insurance. During years of crop failure, drought, or reduced employment opportunities, income from Mahua collection helps households stabilize consumption and reduce vulnerability to economic shocks. Unlike annual crops, Mahua generates economic returns from an existing natural resource with minimal external inputs. Chhattisgarh is among India's leading Mahua-producing states, with annual production estimated at nearly five lakh quintals of flowers. During the flowering season, Mahua collection becomes a major economic activity across tribal districts, generating seasonal employment and supplementary income for thousands of households. Field observations indicate that a mature Mahua tree can yield approximately **1**–2 quintals of flowers annually, providing recurring cash income without annual cultivation costs. Women constitute the backbone of the Mahua value chain. Their participation extends from collection and drying to grading, storage, processing, and marketing. Income generated through Mahua often supports household expenditures related to food, healthcare, and education. Consequently, Mahua contributes significantly to women's economic participation and household-level financial security.

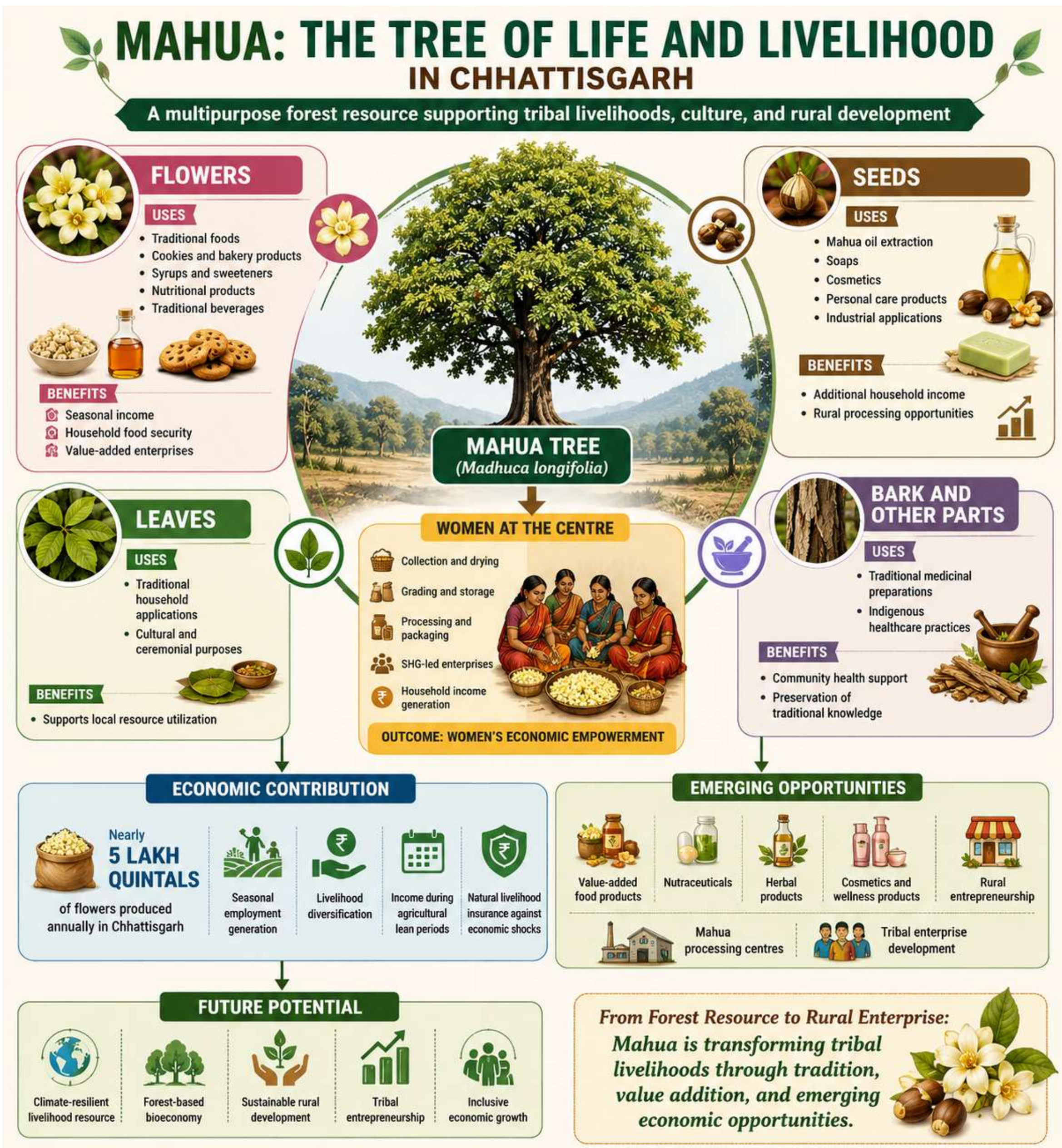
Nutritional Value, Traditional Uses and Women's Entrepreneurship

Mahua flowers have traditionally served as an important supplementary food source in tribal diets. Rich in natural sugars and carbohydrates, they provide a valuable source of energy and can be stored for extended periods. Studies indicate that dried Mahua flowers contain approximately 60–70 percent carbohydrates, highlighting their importance as an energy-rich traditional food. The medicinal significance of Mahua is equally noteworthy. Different parts of the tree, including flowers, bark, leaves, and seed oil, have been used in indigenous healthcare systems for generations. Traditional communities utilize Mahua for managing skin ailments, digestive disorders, inflammation, and general health maintenance. Recent years have witnessed the emergence of women-led self-help groups and rural enterprises focused on Mahua value addition. In Bastar and other tribal regions, women entrepreneurs have successfully transformed Mahua into products such as cookies, laddoos, nutritional foods, herbal products, wellness products, and natural sweeteners. These initiatives demonstrate how value addition can significantly increase income opportunities while simultaneously creating rural employment.

Value Addition and Emerging Market Opportunities

Traditionally, Mahua has been marketed primarily in raw form, limiting the share of value retained by collectors. However, increasing consumer demand for natural foods, herbal products, and indigenous ingredients has created significant opportunities for value addition. Mahua flowers can be processed into powders, syrups, confectionery products, bakery ingredients, nutritional supplements, and herbal formulations. Similarly, Mahua seed oil has applications in cosmetics, soaps, personal care products, and industrial products. Such diversification can enhance producer incomes while generating employment in processing, packaging, branding, and marketing activities. A notable example is the Mahua Processing Centre in Rajnandgaon district, which demonstrates how organized collection, grading, processing, packaging, and product diversification can transform a traditional forest product into a market-oriented enterprise. Such initiatives enable tribal communities to participate not only as collectors but also as processors and entrepreneurs, thereby increasing local value retention and strengthening rural livelihoods. The Chhattisgarh State Minor Forest Produce Federation (CGMFPFED) and various livelihood promotion agencies have also supported procurement, processing, and value-addition initiatives for forest products. These efforts contribute to strengthening local value chains and improving income opportunities for forest-dependent households.

Figure - Infographics illustrating the multipurpose of Mahua



Policy Support and Future Prospects

Chhattisgarh has emerged as one of India's leading states in promoting minor forest produce-based livelihoods. Through procurement mechanisms, value-chain development initiatives, and community-based enterprise promotion, institutional support for forest-dependent communities has steadily expanded. Recent policy initiatives aimed at promoting Mahua-based enterprises, heritage products, and processing activities reflect the growing recognition of Mahua's economic potential. Efforts to improve processing infrastructure, strengthen branding, and facilitate market access can create new opportunities for tribal communities while preserving traditional knowledge systems. The future prospects of Mahua extend beyond traditional uses. Growing demand for natural foods, eco-friendly cosmetics, plant-based ingredients, nutraceuticals, and wellness products positions Mahua as an important component of India's emerging bioeconomy. Strategic investments in entrepreneurship, certification, branding, and market development can transform Mahua into a commercially viable rural enterprise capable of generating sustainable livelihoods.

Conclusion

Mahua is far more than a forest tree. It is a livelihood asset, a source of natural capital, a contributor to food security, and an emerging driver of rural economic development in Chhattisgarh. Its ability to generate income, support women's empowerment, strengthen food security, diversify livelihoods, and provide climate-resilient economic opportunities makes it one of the most valuable non-timber forest products available to tribal communities. The growing recognition of Mahua in public policy, expanding opportunities for value addition, and the emergence of successful tribal enterprises indicate that the species is increasingly being viewed as a strategic economic resource. By investing in sustainable harvesting, processing, branding, market development, and community enterprises, Mahua can continue to strengthen tribal livelihoods while contributing to a resilient, equitable, and sustainable rural economy.

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MICRO-WORM AND MACRO-WORM CULTURE FOR ORNAMENTAL FISH CULTURE

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Introduction

Microworms and Macroworms often referring to larger nematodes like Walter worms, Banana worms, or Grindal worms are highly nutritious, easy-to-culture live feeds essential for raising fry and small ornamental fish. They are entirely cultured in-house and highly economical.

Microworm culture

Setting Up of the Culture

- **i)** **The Container:** Use any clean, opaque or transparent plastic tub or plastic tray with a tight-fitting lid. Poke a few small ventilation holes in the lid and cover them with a breathable material (like filter floss or a cotton pad) to allow air in while keeping pests out.
- **ii)** **The Medium:** Prepare a substrate. For microworms, use plain rolled oats or oatmeal or bread crumbs.
- **iii)** **The Starter:** Let the mixture cool completely to room temperature. Sprinkle a light pinch of active dry yeast over the top (this acts as the worms food). Finally, add your active starter culture evenly across the surface. Then, Mix it properly and cover it with lid.
- **iv)** **Environment:** Keep the culture in a warm, dimly lit area away from direct sunlight and drafts. Maintain temperatures between 21°C to 27°C for optimal growth.

Procedure:

Step:1 Cut the edges and make it into bread crumbs

Step:2 Add some water into bread crumbs and a little bit of already cultured microworms

Step:3 Make small ventilation holes in the lid

Step:4 Lid with a breathable material

Step:5 Leave it for 2-3 days, as the worms consume yeast and bacteria and they will multiply inner walls of container

Harvesting and Feeding

As the worms consume the yeast and bacteria, they will multiply and climb the inner walls of culture container

Harvesting: Use a cotton swab, paintbrush, or fingertip to simply scrape the climbing worms off the sides.

Feeding: Dunk the swab or brush directly into your fry tank. The worms are very small and will shimmer in the water column, triggering a feeding response from tiny fry (like bettas, guppies, and tetras and all other fish fries).

Water Quality: Microworms live for approximately 10 to 12 hours in freshwater. Feed in small portions to prevent the worms from sinking and decaying, which can foul the water.

Maintenance & Sourcing

Over time (typically 2 to 4 weeks), the culture medium will become foul with waste and runnier, slowing down worm production. When the culture begins to smell strongly, it is time to use a spoonful of the old culture to "split" or start a new batch

Macro-wom culture

- Earthworm culture (vermiculture) involves creating a controlled environment for earthworms to reproduce and convert organic waste into nutrient-rich compost.
- Key steps include setting up a shaded, well-draining bed, using epigeic species like *Eisenia fetida*, maintaining moisture around 60%, and feeding them partially decomposed organic waste.

Earthworm culturing unit

- Use the cement cistern like structure for culturing earthworm
- The pit was constructed and the mud was added into it.
- Introduce mother worm into pit
- Ensure the proper ventilation is available for the earthworm.
- The mud should have enough moisture level to live earthworm
- The mud was enriched with the dry leaves and cow dung as a source of food for the earthworms.
- Do not add meat, dairy, oil, or excessive citrus as these can cause odour and attract pest.
- Gently mixing the soil bedding once a week to allow oxygen flow.


Food Sources: Feed them vegetable peels, fruit scraps, coffee grounds, and aged cow dung. Avoid meat, dairy, oily foods, citrus, onions, and garlic, which can harm the worms or attract pests.

Harvesting: Vermicompost is usually ready in 30 to 60 days, depending on the worm-to-waste ratio. After that the earthworm can be collected by hand with gloves. After depuration process, collected worms were fed to brooders of ornamental fishes.

Tubifex Culturing Unit

Culturing *Tubifex* worms requires providing a nutrient-rich substrate, such as aged cow dung or fine mud, combined with a continuous, mild flow of aerated water. This system allows the worms to thrive, feed on organic bacteria, and reproduce rapidly to serve as a sustainable, high-protein live feed.

Container: Use a shallow, wide tray or FRP tank. Ensure it is fitted with an inlet for a continuous, slow stream of water and an outlet with a fine mesh to prevent worms from escaping.

Substrate: Create a culture bed using a mix of roughly 75% aged (composted) cow dung and 25% fine sand. This provides the perfect dense, nutrient-rich environment to worms to burrow and feed.

Water Flow: Maintain a constant, mild water flow or slow drip. *Tubifex* require high dissolved oxygen levels (around 3 mg/L) to survive and multiply, which running water provides.

Stocking: Introduce initial *Tubifex* worms ("seed" worms) into the substrate. They will naturally cluster together and begin to reproduce.

- Use the FRP tank for to culture the tubifex, fine mud substrate is prepared and feed them organic matter vegetable waste, sludge etc., and continuous mild water flow to keep water clean and oxygenated.
- Ensuring a clean, bacterial rich environment that mimics their natural sediment-dwelling habitat for a continuous supply of protein rich food.
- Use plastic containers(jars or tanks) with a dark environment as tubifex are light sensitive.


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THE MIND MATTERS: NAVIGATING INDIA'S EVOLVING MENTAL HEALTH LANDSCAPE

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Abstract
Mental health is increasingly recognized as a fundamental component of overall well-being, encompassing emotional, psychological and social dimensions rather than merely the absence of mental illness. It plays a vital role in shaping individual behaviour, decision-making, productivity and social functioning. In the Indian context, mental health challenges have intensified due to rapid urbanization, post-pandemic stress and changing lifestyles, contributing significantly to the national burden of disease. Despite its importance, a large treatment gap persists, largely driven by stigma, limited awareness and misinterpretation of psychological distress. This document examines the rising mental health concerns, their broader physical and social implications and the policy-level responses introduced by the Government of India. It also outlines major initiatives such as Tele-MANAS, KIRAN Helpline, Manodarpan programme and the District Mental Health Programme aimed at improving accessibility and early intervention. The discussion emphasizes the need for a holistic, community-based and technology-enabled approach to strengthen mental health care delivery and reduce existing disparities.

Keywords: KIRAN Helpline, Life Cycle Approach, Mental Health Disorders, Manodarpan initiative, Tele-MANAS

Introduction
Mental health, which goes beyond the simple absence of mental diseases to include a condition of comprehensive well-being, is becoming more widely acknowledged as the cornerstone of human capital and national growth. A person's ability to manage everyday stressors is a sign of their mental health. Learning, productive work and community service are all made possible by it. Emotional, psychological and social well-being are all components of mental health. It affects people's thoughts, feelings and behaviours as well as how they manage stress, interact with others and make good decisions throughout their lives. It is an essential and integral component of health. Anxiety, depression and other serious disorders can result from poor mental health, which can have a significant impact on relationships, general functioning and physical health. The need for mental health care has grown in India due to post-pandemic difficulties, fast urbanization and rising stress levels. Quality of life is enhanced and emergencies can be avoided with prompt access to assistance and treatment. Acknowledging this, the government is beginning to see mental health as essential to productivity, social stability and inclusive growth. (*PIB Headquarters*, 2026).

Mental health issues are one of the main causes of disability worldwide. Over 1.1 billion individuals or roughly 1 in 7 persons globally, are thought to suffer from a mental illness (WHO, 2025). Mental health disorders account for 5.2% of the world's illness burden, according to a seminal study published in The Lancet. Depressive and anxiety disorders alone account for 6.2% and 4.7% of all Years Lived with Disability (YLD), respectively, with the greatest impact on young people aged 15 to 29. (Lancet, 2020). Approximately 11 out of 100 individuals in India experience mental health issues. With a lifetime prevalence of 13.7% and a current mental morbidity rate of 10.6%, the historic National Mental Health Survey (NMHS) projected that around 150 million Indians need active mental health interventions (NIMHANS, 2016). For many years, the "treatment gap", the percentage of people with mental diseases who do not receive care, remained startlingly high, up to 86% for alcohol use disorders and ranging from 28% to 83% for general mental disorders. (NIMHANS, 2016).

The Government of India (GoI) has updated its framework for mental health in response to this silent epidemic. In order to democratize psychological assistance nationwide, the state has shifted away from segregated institutional care and toward a proactive, technology-driven, rights-based strategy. By putting institutional growth and regional equity at the forefront of public health planning, the Union Budget 2026–2027 represents a significant change in India's mental health policy. The budget promotes the Government of India's inclusive development agenda under "Sabka Sath, Sabka Vikas" and the idea of a Viksit Bharat by bolstering the infrastructure for mental health and trauma care.

The Budget makes mental health a top public health priority in response to the long-standing lack of national-level mental health facilities in North India and the rising need for specialized treatments. In order to lessen the disproportionate burden placed on vulnerable families, it focuses on trauma care support, workforce capacity building and targeted interventions. This demonstrates a resolute and unwavering dedication to fair access to trauma and mental health services. (PIB Headquarters, 2026).

The Silent Crisis: Why We Ignore Mental Health

In Indian society, mental health is often neglected despite its significant influence on everyday productivity and quality of life. According to the NMHS, about 80% of people with mental illnesses had not been treated for more than a year (NIMHANS, 2016). Three deeply ingrained social barriers are the root cause of this startling neglect:

- **Stigma and "Log Kya Kahenge" (What Will People Say?):** The major obstacle to obtaining treatment is still the fear of social exclusion. Mental illness is frequently misinterpreted as a personal weakness, character defect or "madness." This pervasive stigma severely extends social condemnation to family members and immediately jeopardizes a person's access to marriage, work and education. (Journal of Comprehensive Health, 2024).
- **Somatization of Emotional Distress:** Instead of using emotional language to describe psychological anguish, a significant portion of the Indian population uses physical (somatic) symptoms, such as persistent headaches, inexplicable lethargy or localized pain. This phenomenon frequently leads to costly, recurring clinical misdiagnoses for physical conditions while the underlying psychological cause goes untreated.
- **Lack of Broad Awareness:** Rather than being a basic human right, mental healthcare is often misrepresented as an urban luxury or an affluent privilege. In the past, mental health initiatives on the public health agenda were dispersed and received little attention when they were implemented locally.

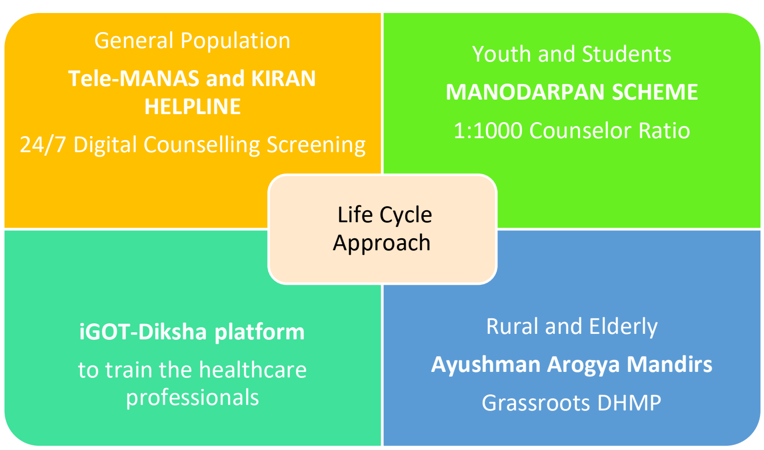
The Domino Effect: Systemic Health Consequences and Risks

Ignoring mental health poses a systemic physiological concern rather than being only a "mind" problem. Long-term psychological suffering and untreated conditions like depression set off a biochemical and metabolic chain reaction that harms physical health:

- **Cardiovascular Impact:** Stress hormones like cortisol and adrenaline are continuously released as a result of endocrine system disruption brought on by long-term stress and anxiety. Persistent vasoconstriction brought on by this elevation results in hypertension, arterial damage and a much-increased clinical risk of myocardial infarctions (heart attacks) and strokes.
- **Immune Suppression:** By reducing leukocyte productivity and changing cytokine profiles, prolonged emotional distress inhibits the body's immunological response. This slows the healing of wounds and makes the body extremely vulnerable to opportunistic bacterial and viral infections.
- **The "Comorbidity" Danger:** Obesity and Type 2 Diabetes are far more likely to occur in those with untreated mental health issues. Both direct metabolic alterations (cortisol-induced insulin resistance) and ensuing lifestyle disturbances—such as extreme sleep fragmentation, unhealthy eating habits and inactivity—are responsible for this.
- **Impaired Executive Functioning:** Chronic distress has a neurological impact on the brain's executive functioning, which includes planning, working memory, emotional control, focus and multitasking. These cognitive processes are located in the prefrontal cortex. Professional setbacks, unstable finances and severely strained interpersonal relationships are often the results of these talents deteriorating.
- **Social and Emotional Well-being**: Social interactions, self-confidence and interpersonal connections are all impacted by mental health.
- **Economic Impact**: The World Health Organization states that mental illnesses have a substantial impact on the worldwide burden of disease and those untreated diseases can result in enormous financial expenses. (Advancing Mental Healthcare in India, 2025)

Government of India (GoI) Initiatives Across Age Groups

The government has put in place a structured "Life Cycle Approach" to carry out the directives of the historic Mental Healthcare Act (2017) and to achieve Sustainable Development Goal (SDG) 3, which specifically calls for the development of mental health and well-being. Targeted interventions for each demographic group are guaranteed by this framework:



1. For the General Population: Tele-MANAS and Kiran Helpline Number

- **Tele-MANAS** -the Tele-Mental Health Assistance and Networking Across States (Tele-MANAS) program is the digital hub of India's mental health policy. It was introduced in 2022 as a key part of the Union Budget and significantly extended throughout 2025–2026 (MoHFW, 2026).
- **Benefits:** It offers prompt, toll-free and totally private psychological counselling. It has a tiered network structure and operates around 24/7, with trained clinical psychologists and psychiatrists handling extreme escalations.
- **Impact Data:** Acute anxiety, depression and sleep disturbances accounted for a sizable portion of the service's approximately 3.5 million calls countrywide by 2026 (MoHFW, 2026). The initiative incorporates the AI-powered "Asmi" chatbot through the Tele-MANAS mobile application, which offers initial cognitive behavioural techniques and instantaneous routing to human counsellors in an effort to further democratize access.
- **Kiran Helpline**
- In response to the rising prevalence of mental illness, especially in the wake of the COVID-19 pandemic, DEPwD, Ministry of Social Justice and Empowerment, established the 24-hour Toll-Free Mental Health Rehabilitation Helpline KIRAN (1800-599-019) in 13 languages. It was introduced yesterday via Webcast, along with a poster, brochure and reference book on hotline, by Union Minister for SJ&E Shri Thaawarchand Gehlot. The helpline works as follows: From anywhere in India, dial the toll-free number 1800-599-0019 using a landline or mobile phone connected to any telecom network.
- Following the welcome message, choose your preferred language by clicking the appropriate button. Then, choose State/UT to connect to the Helpline Centre in your home state or the state of your choice. A mental health professional will assist in resolving the issue or refer you to outside resources (such as a clinical psychologist, rehabilitation psychologist or psychiatrist).
- With BSNL's technical coordination, this toll-free helpline is open twenty-four hours a day, seven days a week. This helpline is used by 25 institutions, including 8 National Institutes. 668 psychiatrists and 660 clinical/rehabilitation psychologists support it. The helpline is available in thirteen languages. Early screening, first aid, psychological support, distress management, mental well-being, preventing deviant behaviours, psychological crisis management and referral to mental health professionals are the helpline's goals. Anxiety, obsessive compulsive disorder (OCD), suicide, depression, panic attacks, adjustment disorders, post-traumatic stress disorders and substance abuse are among the mental health issues that this helpline aims to address. The helpline serves individuals in distress, psychological problems brought on by pandemics and mental health emergencies. (24x7 Toll-Free Mental Health Rehabilitation Helpline Kiran (1800-599-0019) Launched in 13 Languages, 2020).

2. For Children and Adolescents: Manodarpan & Academic Integration

The Ministry of Education expands the Manodarpan program to provide ongoing psychosocial support in recognition of the growing academic demands, digital reliance and developmental changes affecting India's young. (Initiatives Taken by the Government for Mental Health and Emotional Wellbeing of Students, 2021).

- ✓ **School-Based Support:** The government has institutionalized peer-led support system training under the Ayushman Bharat-School Health and Wellness Program, requiring trained "Health and Wellness Ambassadors" in government schools to recognize early indicators of mental distress or disengagement.
- ✓ **Higher Education Guidelines:** Higher Education Institutions (HEIs) are required by recent requirements to actively pursue a standard student-to-counsellor ratio of 1:1000 in order to provide structural protections for exam-related stress management and proactive suicide prevention.

3. For the Elderly and Rural Communities: Grassroots Decentralization

In earlier times, rural residents had to travel hundreds of kilometres for specialized psychiatric care because it was only available in urban tertiary hospitals. Through the District Mental Health Programme (DMHP), the GoI has actively decentralized this, fully integrating it into 1.77 lakh Ayushman Arogya Mandirs (previously Health and Wellness Centres. The Comprehensive Primary Health Care packages offered at these Ayushman Arogya Mandirs now include mental health treatments. Basic screening equipment and a steady supply of necessary psychotropic drugs for depression and psychosis are available at these primary health centres. Under the auspices of Ayushman Bharat, operational instructions and training manuals on Mental, Neurological and Substance Use Disorders (MNS) have been published for different cadres at Ayushman Arogya Mandirs. (*English Releases*, 2026).

4. iGOT-Diksha Colaboration for Mental Health Training

Additionally, the government has partnered with the iGOT-Diksha platform, a 2020 digital learning program, to provide mental health training to frontline staff, community health volunteers and healthcare professionals. This program is centred around:

- Increasing grassroots mental health care capability.
- Giving medical professionals the tools, they need to identify and manage mental illnesses.
- Raising awareness of mental health in rural communities.

India has increased the number of mental health professionals through iGOT-Diksha, guaranteeing improved early intervention techniques and community support systems. (Advancing Mental Healthcare in India, 2025)

Key National Helplines and Institutional Benefits

Initiative	Contact / Access Link	Target Group	Key Systemic Benefit
Tele-MANAS	14416 / 1800-891-4416	All Age Demographics	24/7 tele-counselling available across multiple regional Indian languages; seamless tier-2 clinical referral.
KIRAN Helpline	1800-599-0019	All Age Demographics	Operated by the Ministry of Social Justice & Empowerment; specializes in rehabilitation, crisis intervention and clinical psychology support.
Manodarpan	8448440632	Students, Teachers, & Parents	Academic counselling, exam anxiety management and sustainable emotional support frameworks.

Remedies and the Path to Institutional Recovery

Systemic integration and systemic de-stigmatization form the foundation of India's updated mental health paradigm:

- **Early Screening via ABHA:** The Ayushman Bharat Health Account (ABHA) allows the health system to safely record and monitor long-term mental health history. As patients transfer from primary, intermediate and tertiary health tracking centres, this guarantees full continuity of mental health care and seamless referrals.
- **Preventive Wellness and Yoga:** Yoga and mindfulness activities have been established as approved clinical techniques to lower daily cortisol synthesis in schools, public sector initiatives and contemporary business settings in order to bridge public health with traditional preventive lifestyle therapies.
- **De-institutionalization and Halfway Homes:** In accordance with the rights-based directives of the Mental Healthcare Act (2017), India is actively moving away from long-stay, restrictive mental asylums and toward community-based "Halfway Homes." In order to facilitate their seamless reintegration into civil society, these facilities are intended to help recovering patients build community networks and acquire vocational skills.
- **Proposed National Commission on Mental Health:** Public health advocates and legislative frameworks encourage the establishment of a specialized National Commission on Mental Health to guarantee consistent implementation of these programs. This task force, which is composed of professionals from the fields of psychiatry, public health, social sciences and the judiciary, is set up to direct, oversee and enforce mental health appropriations across national and state ministries in a dynamic manner.

Conclusion

Mental health has emerged as a crucial aspect of sustainable development and overall quality of life. The increasing prevalence of psychological disorders, along with their wide-ranging effects on physical health, productivity and social relationships, underscores the urgency of addressing this issue through comprehensive strategies. India's evolving policy framework reflects a progressive shift toward inclusive, accessible and technology-driven mental health services. Initiatives focusing on digital counselling, school-based interventions and community-level care demonstrate a significant step toward reducing disparities in mental health access. However, long-term improvement requires sustained efforts in awareness generation, stigma reduction, capacity building and integration of services across all levels of healthcare. A coordinated and multidisciplinary approach is essential to ensure effective mental health care for all sections of society.

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PATHOGENOMICS IN PLANT PATHOLOGY

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Abstract

Pathogenomics has emerged as an important approach in plant pathology by enabling comprehensive analysis of pathogen genomes through advanced genome sequencing technologies. It involves the study of whole-genome sequences of fungal, bacterial, viral, and oomycete pathogens to understand virulence, pathogenicity, evolution, and host–pathogen interactions. Integration of genomics, transcriptomics, metagenomics, bioinformatics, and effectoromics has improved our understanding of pathogen diversity and disease development. Databases such as PHI-base, EnsemblFungi, and FungiDB support genome annotation and comparative studies. Effectoromics has further contributed to resistance breeding by identifying resistance genes in plant germplasm. Comparative genomic studies have also revealed the role of transposable elements and dispensable chromosomes in pathogen evolution and host adaptation. Despite major advancements, challenges remain in diagnostics, effector discovery, and prediction of disease outbreaks, highlighting the need for continued research in pathogenomics.

Keywords: Bioinformatics, Effectoromics, Genome sequences, Pathogenomics, Plant Pathology.

Introduction

The advent of genomics has significantly transformed biological research, including the field of plant pathology. During the early genomic era, researchers primarily depended on a single reference genome for studying a species because whole-genome sequencing was expensive and technically demanding. Genomic investigations mainly focused on gene sequences, gene arrangement, regulatory regions, and genome organization. However, rapid advancements in sequencing technologies and the substantial reduction in sequencing costs have enabled genomes to be analyzed more rapidly, with greater depth and accuracy (Schwarze *et al*., 2018). As a result, reliance on a single reference genome is now considered insufficient for understanding the complete genetic diversity within a species. Comparative analysis of multiple genomes has therefore gained importance, leading to the development of the “pan-genome” concept, which includes both core and accessory genes present among different individuals of a species (Sherman *et al*., 2020).

The increasing availability of genomic information has also highlighted the importance of understanding the relationship between genotype and phenotype. Biological traits are influenced not only by gene composition but also by complex interactions among genes, regulatory elements, and environmental factors (Ahnert *et al*., 2017). In this context, pathogenomics has emerged as a high-resolution approach for studying the genomes of plant pathogens, including fungi, bacteria, viruses, oomycetes, and nematodes. Pathogenomics involves the generation, annotation, and comparative analysis of whole-genome sequences to identify genes associated with virulence, pathogenicity, metabolism, and host adaptation. It also facilitates comparison of these genes among related pathogens and helps identify potential molecular targets for disease management (Schmidt *et al*., 2017).

In recent years, pathogenomics has become an essential component of modern plant pathology because it provides deeper insights into plant–microbe interactions and pathogen evolution. Plant pathogens continue to pose major threats to global food security and agricultural sustainability, causing significant yield and economic losses worldwide. Understanding the genomic architecture and molecular mechanisms underlying pathogenicity is therefore crucial for the development of effective disease management strategies. Comparative genomic studies have revealed the presence of rapidly evolving genomic regions, effector genes, transposable elements, and accessory chromosomes that contribute to pathogen adaptability and virulence.

Furthermore, pathogenomics integrates several advanced disciplines such as comparative genomics, transcriptomics, metagenomics, bioinformatics, and effectoromics to better understand host–pathogen interactions at the molecular level. These approaches not only improve disease diagnostics and epidemiological surveillance but also support resistance breeding and precision disease management. Consequently, pathogenomics has become a powerful tool for elucidating the genetic basis of plant diseases and developing sustainable approaches for crop protection in changing environmental conditions.

Techniques Used in Pathogenomics

Sequencing

Sequencing is the process of determining the exact order of nucleotides in DNA or RNA molecules. It enables researchers to decode genetic information and understand the structure, function, and evolution of genes and genomes. Sequencing technologies have become fundamental tools in pathogenomics for studying pathogen diversity, virulence, host adaptation, and evolutionary relationships. Major sequencing approaches used in pathogenomics include first-generation sequencing, next-generation sequencing (NGS), and third-generation sequencing technologies.

Types of Sequencing

First-Generation Sequencing

First-generation sequencing marked the beginning of modern genomic research. Frederick Sanger introduced the concept of DNA sequencing in 1975 and later developed the chain-termination or dideoxy sequencing method, which became the foundation of early genome analysis (Sanger and Coulson, 1975). In 1977, two landmark sequencing methods were introduced: the Sanger dideoxy sequencing technique and the Maxam-Gilbert chemical degradation method (Sanger *et al*., 1977; Maxam and Gilbert, 1977).

The Sanger sequencing method relied on incorporation of dideoxynucleotides during DNA synthesis, resulting in termination of chain elongation at specific bases. In contrast, the Maxam–Gilbert method involved chemical cleavage of labeled DNA fragments at particular nucleotide positions followed by separation using gel electrophoresis. Although first-generation sequencing methods provided highly accurate results, they were labor-intensive, time-consuming, and costly for large-scale genomic studies. Nevertheless, these methods laid the foundation for the development of advanced high-throughput sequencing technologies used in modern pathogenomics.

Next-Generation Sequencing (NGS)

Next-generation sequencing (NGS) is a high-throughput sequencing technology capable of generating millions to billions of DNA sequences in a single run. Platforms such as Roche 454, Illumina, and SOLiD use parallel sequencing approaches with different chemistries, including pyrosequencing, sequencing by ligation, and sequencing by synthesis. Among these, Illumina is the most widely used platform due to its high accuracy and efficiency. NGS has significantly advanced pathogenomics by enabling rapid whole-genome sequencing, comparative genomics, transcriptomics, and identification of virulence-associated genes (Lu *et al*., 2016).

Third-Generation Sequencing

Third-generation sequencing involves direct sequencing of single DNA molecules without the need for PCR amplification, thereby reducing sequencing errors and amplification bias (Schadt *et al*., 2010). These technologies generate long sequencing reads and provide more accurate analysis of repetitive and complex genomic regions. Platforms such as Pacific Biosciences (PacBio) and Oxford Nanopore Technologies are widely used in third-generation sequencing and have greatly improved genome assembly and structural variation analysis in pathogenomics.

Databases

A large proportion of genome sequences available in public databases belong to pathogenic fungi, particularly plant pathogenic fungi that infect important food crops such as cereals, fruits, vegetables, and legumes (Aylward *et al*., 2017). Since fungal pathogens pose major threats to global food security and agricultural sustainability, they have become important models for genome sequencing and pathogen evolution studies (Plissonneau *et al*., 2017).

Pathogenomics relies heavily on specialized databases that provide genome annotation, gene function prediction, and comparative genomic information. These databases help researchers identify virulence genes, study pathogen–host interactions, and analyze evolutionary relationships among pathogens. Important pathogenomics databases include PHI-base, EnsemblFungi, FungiDB, and CFGP, each serving as valuable resources for genomic and functional studies of plant pathogens:

PHI-base

PHI-base (Pathogen–Host Interaction database) is a publicly accessible database that contains experimentally validated pathogenicity, virulence, and effector genes from fungal, bacterial, and oomycete pathogens (Urban *et al*., 2015). It serves as an important resource for identifying genes involved in pathogen infection and host interaction. The database also includes information on antifungal compounds and their target genes in collaboration with the Fungicide Resistance Action Committee (FRAC), making it useful for disease management and development of control strategies.

Database of virulence factors in fungal pathogens

Experimental biologists and computational biologists can use the database and/or the predicted virulence factors to guide their search for new virulence factors and/or discovery of new pathogen–host interaction mechanisms in fungi (Lu *et al.,* 2012).

EnsemblFungi

EnsemblFungi is an online genome browser specifically developed for fungal genomes. It contains genomic data obtained mainly from the International Nucleotide Sequence Database Collaboration and allows researchers to visualize, analyze, and compare fungal genome sequences through the Ensembl genome browser interface (Kersey *et al*., 2010). The database serves as an important resource for comparative genomics and functional analysis of fungal pathogens.

FungiDB

FungiDB is a part of the EuPathDB family of databases that integrates whole-genome sequences, genome annotations, and experimental as well as environmental isolate data of fungal species (Stajich *et al*., 2012; Basenko *et al*., 2018). The database provides tools for comparative genomics, gene expression analysis, and various bioinformatics studies through an interactive web-based data mining platform, making it valuable for pathogenomics research.

CFGP (Comparative Fungal Genomics Platform)

CFGP 2.0 is an interactive bioinformatics platform developed for comparative fungal genomics. It contains an archive of 283 genomes representing 152 fungal and oomycete species and provides access to multiple bioinformatics tools for genome analysis (Choi *et al*., 2013). The platform supports comparative studies, functional analysis, and genomic research of plant pathogens, making it a useful resource in pathogenomics.

Effectors and Plant-Pathogen Interaction

Pathogen genome studies have significantly improved our understanding of plant–pathogen interactions through the identification and characterization of virulence factors known as effectors. Many plant pathogens, including bacteria, fungi, oomycetes, and nematodes, secrete proteins and other molecules into host cells to suppress plant defense responses and promote infection (Kamoun, 2006). These secreted molecules, collectively called effectors, play important roles in host colonization, pathogenicity, and disease development.

Effectors alter the structure and function of host cells either by facilitating infection or by triggering plant defense responses (Huitema *et al*., 2004). During infection, plants recognize pathogen-associated molecular patterns (PAMPs) through pattern recognition receptors, resulting in PAMP-triggered immunity (PTI) (Dodds *et al*., 2010). However, pathogens produce effectors that suppress these defense mechanisms and enhance virulence. Some effectors, known as avirulence (AVR) proteins, can be recognized by plant resistance (R) genes, leading to activation of effector-triggered immunity (ETI) and hypersensitive response, which restrict disease progression.

Comparative genomic studies have shown that effector genes evolve rapidly and are often located in dynamic, repeat-rich regions of pathogen genomes. These rapidly evolving effectors help pathogens adapt to host defenses and environmental pressures, making them central components in the co-evolution of plants and pathogens.

Effectoromics

Effectoromics is a high-throughput functional genomics approach that uses pathogen effectors to identify resistance (R) genes in plant germplasm and has become an important tool in modern resistance breeding (Ellis *et al*., 2009). This approach helps in rapid detection of plant genes that recognize specific pathogen effectors and contribute to disease resistance (Oh *et al*., 2009).

Major advantages of effectoromics include rapid identification of R genes, detection of recognition specificity, differentiation of functional redundancy, and support in effective R gene deployment. Advances in genome sequencing and bioinformatics have facilitated the prediction of large numbers of effector genes from pathogen genomes, while biological assays help validate their functions. Thus, effectoromics bridges the gap between computational prediction and functional analysis, making it a valuable strategy for understanding plant–pathogen interactions and improving crop resistance breeding.

Supernumerary Chromosomes

Genome analysis of several fungal phytopathogens, including *Fusarium*, *Alternaria*, and *Mycosphaerella* species, has revealed the presence of supernumerary or conditionally dispensable chromosomes (CDCs) (Akagi *et al*., 2009; Ma *et al*., 2013). These chromosomes are not essential for fungal survival but often contain genes associated with pathogenicity and host specificity. Many CDCs carry toxin-producing genes and virulence determinants that contribute to disease development. For example, in *Alternaria alternata*, genes involved in host-specific toxin production are located on CDCs, influencing the ability of the pathogen to infect particular host plants (Mirocha *et al*., 1992). Transfer of these chromosomes between strains can alter host range and pathogenicity, highlighting their important role in pathogen evolution and adaptation.

Gene Clusters

Gene clusters are groups of functionally related genes located together on chromosomes and are commonly found in fungi (Walton *et al*., 2012). Many of these clusters are involved in the biosynthesis of secondary metabolites, including toxins associated with pathogenicity. Horizontal gene transfer (HGT) of entire gene clusters enables fungi to rapidly acquire new metabolic and virulence traits. Comparative genomic studies have shown that several toxin biosynthesis clusters, such as sterigmatocystin and epipolythiodioxopiperazine (ETP) clusters, have evolved through HGT and gene duplication events (Slot *et al*., 2011; Patron *et al*., 2007). Gene clustering also helps maintain complete metabolic pathways, reducing the risk of losing essential pathway components during chromosomal recombination.

Role of Transposable Elements

Transposable elements (TEs) are mobile genetic elements that play an important role in the evolution and adaptability of fungal phytopathogens. Rapid evolution of plant pathogens often leads to the breakdown of host resistance and creates major challenges in disease management (Finnegan *et al*., 1985). With the advancement of genome sequencing technologies, researchers have gained deeper insights into the molecular mechanisms underlying fungal pathogenicity and adaptation (Nadarajah *et al*., 2017).

TEs are abundant in eukaryotic genomes and contribute significantly to genome plasticity through mutations, chromosomal rearrangements, and altered gene expression (Le Rouzic *et al*., 2007). In fungal pathogens, transposable elements influence pathogenicity, host range, and evolutionary processes by generating genetic variation and promoting genome restructuring (Pritham *et al*., 2007; Fedoroff *et al*., 2012). These elements also facilitate rapid adaptation to environmental changes and host defenses, thereby contributing to the survival and virulence of fungal pathogens. Understanding the role of TEs is therefore essential for studying pathogen evolution and developing effective disease management strategies.

Horizontal Gene Transfer

Horizontal gene transfer (HGT), also known as lateral gene transfer, refers to the transfer of genetic material between unrelated organisms rather than through normal parent-to-offspring inheritance (Doolittle *et al*., 1999). In microorganisms, HGT plays an important role in genome evolution, adaptation, and acquisition of new traits. In bacteria, HGT occurs through mechanisms such as conjugation, transformation, and transduction, whereas in fungi the mechanisms are less clearly understood.

Studies have shown that fungal species can exchange genetic material through processes such as hyphal fusion and anastomosis, allowing transfer of DNA, RNA, or organelles between species (Friesen *et al*., 2006). Although HGT contributes less to fungal genome evolution compared to bacteria, it can still have significant effects on pathogenicity, metabolism, and environmental adaptation. Transfer of genes associated with nutrient utilization, toxin production, and virulence has enabled fungi to adapt to new ecological niches and hosts. Therefore, HGT is considered an important evolutionary mechanism contributing to genetic diversity and adaptability in plant pathogens.

Conclusion

Pathogenomics has emerged as an important discipline in plant pathology by providing detailed insights into the genetic diversity, evolution, and pathogenic mechanisms of plant pathogens. The integration of advanced sequencing technologies and bioinformatics tools has enabled rapid characterization of pathogen genomes and improved understanding of host-pathogen interactions. Comparative genomics and functional studies have identified important virulence factors, effector proteins, and adaptive genomic regions involved in disease development and host colonization.

Furthermore, pathogenomics has contributed significantly to disease diagnostics, resistance breeding, epidemiological surveillance, and precision disease management. The identification of resistance genes and pathogen-specific targets has enhanced the development of sustainable crop protection strategies. Despite major advancements, continued research is required to better understand pathogen evolution, discover novel effectors, and improve prediction of disease outbreaks. Overall, pathogenomics will continue to play a vital role in strengthening agricultural sustainability and global food security under changing environmental conditions.

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PHOTOVOLTAIC SYSTEMS IN SUSTAINABLE AGRICULTURE MANAGEMENT IN INDIA

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Abstract

Photovoltaic (PV) systems are increasingly shaping sustainable agriculture in India by providing clean energy while enhancing resource efficiency and farm productivity. This article explores the role of agrivoltaics integrating crop cultivation with solar energy generation in improving land-use efficiency, water conservation, and climate resilience. Researchers reported that partial shading from PV panels can reduce heat stress, lower water consumption, and maintain crop yields, while solar-powered irrigation systems significantly cut energy costs. Programmes such as Pradhan Mantri Kisan Urja Suraksha evam Utthaan Mahabhiyan (PM-KUSUM) further support adoption by expanding access to solar pumps. Despite challenges including high initial investment and crop-specific design constraints, Photovoltaic systems offer substantial environmental and economic benefits. Overall, photovoltaic technologies present a viable pathway toward climate-smart, energy-efficient, and sustainable agricultural development in India.

Keywords: Photovoltaic systems, agrivoltaics, sustainable agriculture, Energy efficient.

Introduction

Photovoltaic (PV) systems are increasingly emerging as a transformative solution in sustainable agriculture management in India, offering a clean and renewable source of energy for modern farming operations. By converting sunlight directly into electricity, these systems reduce dependence on fossil fuels, lower greenhouse gas emissions, and enhance energy security in rural areas. In agricultural contexts, PV technology supports a wide range of applications, including irrigation pumping, greenhouse climate control, crop drying, and precision farming tools. The integration of photovoltaic systems with agricultural practices often referred to as agrivoltaics. It also enables dual land use, where crops and solar panels coexist, optimizing land productivity while improving microclimatic conditions for certain crops. This article explores how photovoltaic systems are being woven into sustainable agricultural management in India, what are their benefits, and what challenges remain before they become a mainstay of Indian farming.

Agrivoltaics Systems

Agrivoltaics derived from "agriculture" and "photovoltaics". It is the practice of growing crops or rearing livestock alongside solar panels on the same land. This dual-use approach helps optimize land efficiency, especially in areas with limited space, while also creating beneficial microclimates such as partial shading that can reduce water evaporation, protect crops from extreme weather, and sometimes improve yields for shade-tolerant plants. At the same time, farmers gain an additional income stream from solar power, making agriculture more economically resilient. Fig. 1 shows how agrivoltaic systems combine solar panels and farming on the same land.

Fig. 1 Operational workflow of Agrivoltaic systems

How Solar Panels Benefit Crops and Water

Solar panels can benefit crops and water use by creating partial shade that protects plants from excessive heat and harsh sunlight, helping them grow better in hot climates. This shade also reduces water evaporation from the soil, which helps to retain moisture for longer periods. Overall, solar panels help conserve water, support healthier crops, and make farming more efficient.

Temperature Regulation and Shade Benefits

Partial shading from solar panels can actually help crops grow better by lowering heat stress and conserving soil moisture. Researchers reported that agrivoltaic systems reduced canopy temperatures by about 3–4 °C and enhanced photosynthesis in pearl millet (bajra). Other studies in semi-arid regions have also found that crops like wheat and chickpea use water more efficiently under this partial shading, while maintaining similar yields during the rabi season, with no significant decline in production. Fig. 2 shows that agrivoltaics system in elevated PV panels above crop rows.

Fig. 2: An agrivoltaics system showing elevated PV panels above crop rows

Water Use Efficiency and Land Equivalent Ratio

Solar panels improve crop water-use efficiency by providing partial shade, which reduces soil evaporation and lowers plant heat stress. This helps crops retain moisture, use water more effectively, and maintain good yields with less irrigation. Researchers found that agrivoltaic plots showed a 35–45% reduction in soil evaporation compared with open fields, significantly reducing irrigation frequency for cumin and groundnut. Figure 3 shows that comparison of Land Equivalent Ratio (LER) between conventional farming and agrivoltaic systems at various locations. Agrivoltaic systems have higher Land Equivalent Ratio (LER) values (1.42–1.55) than conventional farming (1.00), indicating better land-use efficiency.

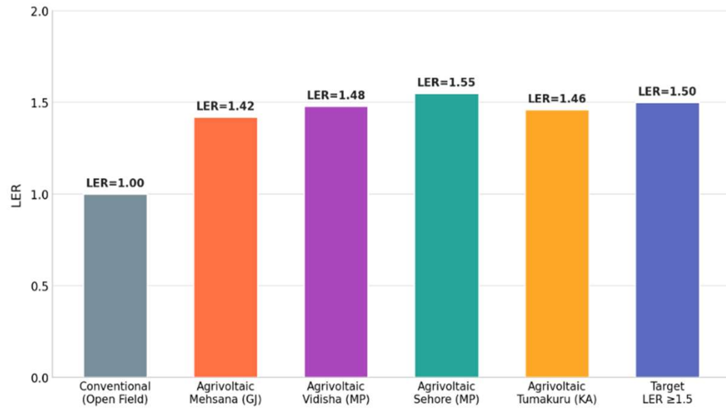

Fig. 3 Land Equivalent Ratio (LER) comparison across different systems

Solar-Powered Irrigation and Smart Systems

The PM-KUSUM scheme (Pradhan Mantri Kisan Urja Suraksha evam Utthaan Mahabhiyan), launched in 2019, targets 3.5 million solar-powered irrigation pumps nationwide, replacing costly and polluting diesel pumps used by small and marginal farmers. By 2024, over 2.8 million solar irrigation pumps had been installed under PM-KUSUM and state schemes, making India home to one of the world's largest solar irrigation programmes. Researchers designed a solar-powered precision irrigation controller for paddy cultivation integrating soil moisture sensors, weather API data, and a machine learning model trained on historical evapotranspiration records. The system reduced water use by 28% compared to flood irrigation, while maintaining yields within 5% of the state average.

The following image (Fig. 4) illustrates a solar-powered smart irrigation system, showing how energy and water flow through different stages. Solar panels capture sunlight and generate electricity, which is regulated by a charge controller and stored in batteries for continuous use. A smart controller then uses data from field sensors and weather stations to determine when irrigation is needed. Water is drawn from a source like a borewell or pond and pumped through pipelines to the crops. The system operates automatically, optimizing water usage, reducing energy costs, and improving crop productivity with minimal human intervention.

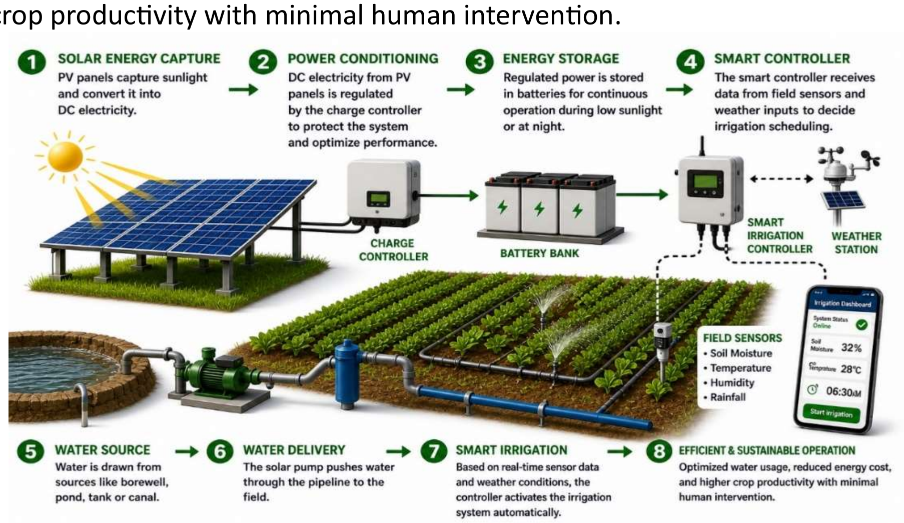

Fig. 4: Solar-powered smart irrigation system integrating with PV panels

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Agrivoltaics Across India: Key Deployments

India's agrivoltaic landscape is expanding across diverse agro-climatic zones. In Rajasthan, the RRECL commissioned a 1 MW system near Jodhpur (2022) where elevated panels allow cultivation of aloe vera and isabgol, retaining ~92% of conventional solar output and reducing water use by 30%. In Karnataka, KREDL pilot projects in Tumakuru showed ragi and groundnut experiencing minimal yield loss under partial shading, with farmers earning an additional ₹45,000–60,000 per acre annually from solar energy. Gujarat's canal-top solar initiative by SSNNL generates over 1,600 MW of electricity while significantly reducing canal water evaporation a model now being replicated in other states. Nationally, TERI estimates that utilising just 0.5% of India's net sown area for agrivoltaics could generate over 100 GW of electricity a figure that underscores the technology's transformative potential.

Challenges and Barriers

Agrivoltaics in India holds significant promise but faces multiple practical and institutional challenges that limit its widespread adoption. Installation costs are 20–45% higher than conventional solar systems due to the need for elevated and complex structures, making it less accessible for smallholder farmers who have limited access to credit. Technical difficulties also arise in designing systems suitable for diverse cropping patterns, as shade-tolerant crops like ginger and turmeric perform well under panels, while shade-sensitive crops such as maize and sunflower can experience yield losses if shading is not properly managed. External factors like extreme weather events can damage both crops and infrastructure, while regulatory and policy uncertainties further complicate implementation. Some of the other challenges are shown in the following image (Fig. 5).

Fig. 5 Challenges of Agrivoltaic systems in India

Conclusion

For sustainable agriculture management in India, photovoltaic systems are far more than an energy source. They are a tool for climate adaptation, a buffer against drought, an income diversifier for smallholders, and when combined with precision irrigation and AI - a pathway toward genuinely regenerative food systems. Scaling agrivoltaics to just 1% of India's net sown area could meet 15–20% of the country's electricity demand while boosting farm incomes and agricultural resilience. Continued research into Indian crop-specific designs, strengthened financing under PM-KUSUM and NABARD, and clear state-level regulatory frameworks are essential to maximise impact particularly in achieving net-zero emissions in Indian agriculture. The sun has always been the original power source for Indian farming. With agrivoltaics, farmers can now harvest its energy twice once through their crops, and once through their solar panels.

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REDUCING FLOWER DROP AND ENHANCING YIELD IN PIGEONPEA: PRACTICAL STRATEGIES FOR HIGHER PRODUCTIVITY

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Abstract
Pigeonpea (*Cajanus cajan* (L.) Millsp.) is an important pulse crop valued for its nutritional significance and contribution to sustainable agriculture. However, excessive flower and pod drop remain major constraints to achieving higher yields, often resulting in substantial productivity losses. Flower abscission in pigeonpea is influenced by a combination of genetic, physiological, nutritional, and environmental factors, including moisture stress, high temperatures, nutrient deficiencies, and pest damage. Recent studies have highlighted significant genotypic differences in flower retention among landraces, hybrids, and advanced breeding lines, indicating opportunities for genetic improvement. Among agronomic interventions, potassium plays a crucial role in enhancing photosynthesis, assimilating translocation, water-use efficiency, and stress tolerance. Foliar application of potassium during flowering and early pod development has been reported to improve flower retention, pod setting, and grain yield by providing rapid nutrient availability during critical reproductive stages.

Keywords: Pigeonpea, flower abscission, flower drop, foliar nutrition, potassium, pod set, yield improvement.

Introduction
Pigeonpea (*Cajanus cajan* (L.) Millsp.) is one of the most important pulse crops cultivated across tropical and subtropical regions. In India, it serves as a major source of dietary protein and contributes significantly to soil fertility through biological nitrogen fixation. Despite its potential, pigeonpea productivity remains below achievable levels in many production systems. One of the major constraints is excessive flower and pod drop, which can result in substantial yield losses.

A pigeonpea plant is capable of producing hundreds of flowers during its growth cycle. However, only a small proportion of these flowers eventually develop into mature pods. Environmental stresses, nutrient deficiencies, hormonal imbalances, and genetic factors often trigger floral abscission, reducing the conversion of flowers into harvestable pods. Recent studies have highlighted the role of potassium nutrition and improved crop management practices in minimizing flower drop and enhancing yield.

This article discusses the causes of flower abscission in pigeonpea and presents practical strategies, including foliar potassium application, to improve crop productivity.

Why Does Flower Drop Occur in Pigeonpea?
Flower abscission is a natural physiological process in which flowers detach from the plant before pod formation. While a certain level of flower shedding is normal, excessive abscission significantly reduces yield potential.

Research by Kulkarni *et al*., 2019 reported considerable genotypic variation in flower retention among pigeonpea landraces, hybrids, and advanced breeding lines. This indicates that both genetic makeup and environmental conditions influence flower retention capacity.

Several factors contribute to flower drop:

- Moisture stress during flowering and pod initiation
- High temperature and dry winds
- Nutrient deficiencies, particularly potassium
- Competition among developing flowers and pods for assimilates
- Insect pest damage
- Hormonal imbalance within the plant
- Limited photosynthate availability during reproductive growth

The problem becomes more severe when crops encounter drought or nutrient stress during the flowering phase.

Potassium: A Key Nutrient for Flower Retention

Potassium is often referred to as the "quality nutrient" because of its vital role in plant metabolism. Unlike nitrogen and phosphorus, potassium does not become part of plant structures but regulates numerous physiological processes.

Potassium helps:

- Improve photosynthesis efficiency
- Enhance translocation of carbohydrates
- Regulate stomatal opening and water use efficiency
- Improve enzyme activity
- Increase tolerance to drought and heat stress
- Promote flower retention and pod development

Studies conducted by Ravindranath *et al*., 1985 demonstrated that foliar application of potassium during reproductive stages positively influenced growth and yield attributes in pigeonpea. Foliar feeding provides nutrients directly to plant tissues, ensuring rapid absorption when root uptake is limited under stress conditions.

Foliar Application: A Smart Nutrient Management Tool

Foliar nutrition has emerged as an effective supplementary strategy for pulse crops. During flowering and pod initiation, nutrient demand increases substantially. Soil-applied nutrients may not always meet this demand, particularly under moisture-limited conditions.

Benefits of Foliar Potassium Sprays

- Rapid nutrient absorption and utilization.
- Reduces flower shedding and improves pod set.
- Enhances tolerance to drought and temperature stress.
- Increases pod number and grain yield (Ali *et al*., 2016).

Foliar potassium application in pigeonpea improves flower retention, pod formation, photosynthesis, and nutrient-use efficiency. It also enhances stress tolerance, resulting in higher grain yield.

Strategies to Reduce Flower Drop

- Maintain balanced nutrition based on soil test recommendations.

- Apply foliar potassium during flowering and early pod development.
- Ensure adequate soil moisture, especially during flowering.
- Manage pests and diseases through integrated approaches.
- Use high flower-retaining, efficient pigeonpea varieties.

Table 1. Major Causes of Flower Drop in Pigeonpea and Their Effects

Cause	Effect on Crop
Moisture stress	Reduced flower retention and pod set
Potassium deficiency	Poor assimilate translocation and increased abscission
High temperature	Pollen sterility and flower shedding
Insect damage	Direct destruction of flowers and buds
Nutrient imbalance	Reduced reproductive growth
Hormonal imbalance	Premature flower detachment

Integrating Science with Farm Practice

Modern pigeonpea production requires a shift from traditional nutrient management to more targeted approaches that address crop needs during critical growth stages. Flowering and pod initiation represent periods when the plant is particularly sensitive to stress. Even short-term nutrient or moisture limitations can lead to substantial reproductive losses. Research evidence consistently indicates that potassium plays a crucial role in maintaining reproductive success. Foliar application serves as an efficient method of delivering this nutrient precisely when the crop requires it most. Combined with balanced fertilization, proper irrigation management, and pest control, foliar potassium nutrition can substantially improve productivity.

Conclusion

Flower drop remains one of the most important biological constraints limiting pigeonpea productivity. While some degree of floral abscission is inevitable, excessive flower shedding can be effectively managed through scientific crop management practices. Among these, potassium nutrition—particularly through foliar application during reproductive stages—has shown significant potential in improving flower retention, pod development, and final yield. Farmers who adopt balanced nutrition, timely foliar potassium sprays, moisture conservation practices, and effective pest management can substantially reduce reproductive losses and achieve higher productivity. As research continues to advance, integrating these practical strategies into routine cultivation practices will play a key role in realizing the full yield potential of pigeonpea.

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POLLINATOR DECLINE IN INDIA: CAUSES, CONSEQUENCES AND CONSERVATION

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Introduction

Pollinators are indispensable components of both natural and agricultural ecosystems. They facilitate the transfer of pollen from the anthers to the stigma of flowers, enabling fertilization and the production of fruits and seeds. While wind and water contribute to pollination in certain plant species, a substantial proportion of flowering plants depend on animal pollinators, particularly insects. Bees, butterflies, moths, flies, beetles, and wasps collectively provide pollination services that support biodiversity and agricultural productivity.

Globally, approximately 75% of leading food crops benefit from animal-mediated pollination, emphasizing the critical role of pollinators in food production systems (Klein *et al*., 2007). India, one of the world's biodiversity-rich countries, hosts a diverse assemblage of pollinators that contribute significantly to the production of fruits, vegetables, oilseeds, spices, and plantation crops. However, increasing evidence suggests that pollinator populations are experiencing alarming declines due to multiple anthropogenic and environmental pressures.

The decline of pollinators is emerging as a major concern for sustainable agriculture, food security, and ecosystem stability. Understanding the causes and consequences of pollinator loss is essential for developing effective conservation strategies and ensuring agricultural resilience in the coming decades.

Importance of Pollinators in Agriculture

Pollinators play a crucial role in improving crop yield, fruit quality, seed production, and genetic diversity. Insect-mediated pollination often enhances fruit size, weight, shape, nutritional quality, and market value. Several economically important crops grown in India depend partially or entirely on insect pollination.

Table 1. Major Pollinator-Dependent Crops in India

Crop	Major Pollinators	Benefits of Pollination
Mustard	Honey bees, solitary bees	Increased seed yield and oil content
Sunflower	Honey bees, wild bees	Improved seed filling and productivity
Apple	Honey bees, bumble bees	Better fruit set and fruit quality
Mango	Bees, flies and wasps	Enhanced fruit production
Cucurbits	Honey bees and solitary bees	Improved fruit size and uniformity
Litchi	Honey bees	Higher fruit set and yield
Almond	Honey bees	Increased nut production

Apart from agriculture, pollinators are essential for maintaining ecosystem functioning by supporting the reproduction of numerous wild plant species. Their ecological services contribute significantly to biodiversity conservation and environmental sustainability.

Causes of Pollinator Decline

Habitat Loss and Fragmentation

Rapid urbanization, industrialization, infrastructure development, and agricultural intensification have resulted in extensive habitat destruction. Natural landscapes that provide nesting sites, shelter, and floral resources for pollinators are being continuously reduced. Habitat fragmentation further limits pollinator movement and decreases population viability.

Excessive Use of Pesticides

Indiscriminate use of pesticides, particularly broad-spectrum insecticides, poses a major threat to pollinator health. Exposure to pesticides may cause direct mortality or sublethal effects such as impaired navigation, reduced foraging efficiency, weakened immunity, and decreased reproductive success. Pollinators frequently encounter pesticide residues through contaminated nectar, pollen, and water sources.

Climate Change

Climate change is increasingly influencing pollinator populations through altered temperature regimes, irregular rainfall patterns, and extreme weather events. Changes in flowering phenology may disrupt the synchrony between pollinators and flowering plants, reducing pollination efficiency and affecting both plant and pollinator survival (Potts *et al*., 2010).

Monoculture Farming Systems

Large-scale monoculture cultivation often provides floral resources only during a limited flowering period. The lack of diverse flowering plants throughout the year creates nutritional stress for pollinators and contributes to declining populations.

Diseases, Parasites and Invasive Species

Pollinator populations are also threatened by pathogens, parasites, and invasive species. Honey bee colonies, for example, may be affected by mites, viruses, fungi, and bacterial diseases, which can weaken colonies and reduce pollination services.

Table 2. Major Threats Responsible for Pollinator Decline

Threat	Impact on Pollinators
Habitat destruction	Loss of nesting and foraging habitats
Pesticide exposure	Mortality and behavioral abnormalities
Climate change	Phenological mismatch and range shifts
Monoculture agriculture	Reduced floral diversity
Diseases and parasites	Colony weakening and mortality
Urban expansion	Habitat fragmentation

Consequences of Pollinator Decline

Reduced Agricultural Productivity

The decline of pollinator populations directly affects crop productivity. Reduced pollination leads to lower fruit set, poor seed formation, decreased crop quality, and ultimately economic losses for farmers. Crops with high pollinator dependency are particularly vulnerable.

Threat to Food and Nutritional Security

Many nutrient-rich foods, including fruits, vegetables, nuts, and oilseeds, depend on insect pollination. A reduction in pollination services may compromise food availability and nutritional diversity, affecting human health and food security.

Biodiversity Loss

Pollinators and flowering plants share highly specialized ecological relationships. A decline in pollinator populations can reduce plant reproductive success, leading to decreased plant diversity and disruption of ecosystem functioning.

Economic Implications

Pollination services contribute significantly to agricultural economies worldwide. The decline of pollinators may increase production costs, reduce farm profitability, and affect rural livelihoods dependent on pollinator-dependent crops.

Conservation Strategies for Pollinators

The conservation of pollinators requires integrated approaches involving farmers, researchers, policymakers, and local communities.

Adoption of Pollinator-Friendly Farming Practices

Farmers can establish flowering strips, hedgerows, and field margins containing nectar-rich plants to provide food resources throughout the year. Such habitats enhance pollinator abundance and diversity.

Rational Use of Pesticides

Integrated Pest Management (IPM) practices should be promoted to reduce dependence on chemical pesticides. Whenever pesticide application is necessary, spraying should be carried out during periods of low pollinator activity, preferably during evening hours.

Habitat Restoration and Conservation

Protection and restoration of natural habitats, including grasslands, forests, wetlands, and agroforestry systems, can significantly improve pollinator survival and reproduction.

Diversified Cropping Systems

Crop diversification, mixed cropping, and intercropping provide continuous floral resources and support diverse pollinator communities.

Research and Monitoring

Long-term monitoring of pollinator populations is essential for assessing population trends, identifying emerging threats, and developing science-based conservation policies.

Public Awareness and Capacity Building

Creating awareness among farmers, students, and the general public regarding the ecological and economic importance of pollinators is crucial for successful conservation initiatives.

Table 3. Conservation Measures and Expected Benefits

Conservation Measure	Expected Benefit
Flowering field margins	Increased nectar and pollen availability
Reduced pesticide use	Improved pollinator survival
Habitat restoration	Enhanced nesting opportunities
Crop diversification	Greater pollinator diversity
Pollinator monitoring	Better conservation planning
Awareness programmes	Increased stakeholder participation

Pollinator Conservation and Viksit Bharat 2047

As India progresses towards the vision of Viksit Bharat 2047, sustainable agricultural development will be a cornerstone of national growth. Pollinators are fundamental to achieving food security, nutritional security, biodiversity conservation, and climate-resilient agriculture. Protecting pollinator populations aligns directly with national goals of sustainable development, ecological balance, and enhanced agricultural productivity.

The integration of pollinator conservation into agricultural policies, landscape management strategies, and research programmes can significantly contribute to resilient food production systems and long-term environmental sustainability.

Conclusion

Pollinators constitute an invaluable natural resource that supports agricultural productivity and ecosystem health. However, habitat loss, pesticide misuse, climate change, monoculture farming, and biological stressors are driving alarming declines in pollinator populations. The consequences of pollinator loss extend beyond agriculture, threatening biodiversity, food security, and ecological stability.

Adoption of pollinator-friendly farming practices, conservation of natural habitats, reduced pesticide dependence, and increased public awareness are essential for reversing current trends. As India moves toward Viksit Bharat 2047, safeguarding pollinators must become a national priority to ensure sustainable agriculture, environmental resilience, and food security for future generations.

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ARTIFICIAL INTELLIGENCE IN AGRICULTURE: DECISION MAKER OR DECISION SUPPORT SYSTEM?

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Artificial Intelligence (AI) is rapidly entering agricultural systems across the world. From crop monitoring and disease diagnosis to weather forecasting and market intelligence, AI is being promoted as a transformative force capable of revolutionizing farming. Governments, research institutions, agri-tech companies, and policymakers increasingly view AI as a solution to many of the challenges confronting modern agriculture. However, amidst this enthusiasm, a fundamental question remains largely unanswered: Should Artificial Intelligence function as a decision maker or merely as a decision support system in agriculture?

The distinction is critical. A decision maker independently determines the course of action, whereas a decision support system assists humans in making better decisions. In agriculture, where biological variability, environmental uncertainty, socio-economic constraints, and local realities interact continuously, this distinction becomes even more important. While AI has immense potential to strengthen agricultural decision-making, the complexity of farming suggests that it should be regarded as a support system rather than a substitute for farmer judgment. The future of agriculture lies not in replacing farmers with algorithms but in combining technological intelligence with human experience.

Can Agriculture Be Reduced to Data?

Agriculture is fundamentally different from manufacturing industries where processes are highly standardized and predictable. A factory may produce identical outputs under identical conditions, but agriculture operates within a living ecosystem influenced by countless variables. Two neighbouring farmers cultivating the same crop with similar inputs may obtain entirely different results due to differences in soil conditions, irrigation availability, microclimate, management practices, or unforeseen environmental events.

This complexity raises an important concern. Can agricultural realities be fully represented through datasets and algorithms? Or does effective decision-making require contextual understanding that extends beyond data? The answer to this question determines whether AI can ever become an independent decision maker in agriculture.

When Field Reality differs from Database Reality

A simple example illustrates this challenge.

Consider a paddy field where the crop shows yellowing of leaves. An AI system trained on agricultural databases and image libraries may identify the symptom as nitrogen deficiency, since yellowing is one of the most common indicators of inadequate nitrogen nutrition. Based on this diagnosis, the system may recommend the application of urea.

However, when an extension professional visits the field and interacts with the farmer, a different picture may emerge. The yellowing may actually be caused by stem borer infestation, where damage to the stem affects nutrient and water movement within the plant. Alternatively, the field may be suffering from iron deficiency, zinc deficiency, poor drainage, root damage, or prolonged cloudy weather. In such situations, applying additional nitrogen may not solve the problem and could even increase production costs unnecessarily.

This example highlights a fundamental challenge in agricultural diagnosis. The same visible symptom yellowing of leaves can result from multiple causes. Accurate diagnosis often requires an understanding of field history, soil conditions, water management, pest incidence, weather patterns, and local farming practices. Such contextual interpretation continues to depend heavily on farmer experience and extension expertise.

The Invisible Knowledge Stored in Farmers' Minds

The strength of farmers lies precisely in contextual understanding. Experienced farmers continuously observe their fields. They recognize subtle changes in crop growth, soil conditions, insect populations, and environmental signals. Many of these observations are never documented in scientific databases. They exist as experiential knowledge accumulated over decades.

Farmers often know which portion of a field suffers from waterlogging, which area is prone to pest attacks, and which crop variety performs better under local conditions despite official recommendations suggesting otherwise. Many farmers can predict rainfall changes, identify pest outbreaks at an early stage, and anticipate crop responses based on observations that cannot easily be quantified. This knowledge is dynamic, location-specific, and continuously evolving. Artificial Intelligence currently has limited capacity to capture such experiential knowledge. It can analyse historical patterns, but it cannot fully replicate the practical wisdom acquired through years of farming experience.

Agriculture is not Just Science; It is also Human Decision-Making

Another aspect frequently ignored in discussions about AI is that agriculture is not purely a technical activity. Farming decisions are influenced by numerous social and economic considerations. A recommendation may be scientifically sound but practically impossible to implement. A farmer may know the recommended fertilizer dosage but lack the financial resources to purchase inputs. Irrigation may be advised, but water may not be available. Pest management may be recommended, but labour shortages may prevent timely application. Market uncertainty may influence harvesting decisions.

Artificial Intelligence can process data, but it cannot fully understand these human realities. It cannot appreciate the emotional, financial, and social dimensions that influence agricultural decisions. Farming is ultimately a human enterprise, and human judgment remains indispensable.

Where AI Can Make a Real Difference

Despite these limitations, AI possesses tremendous potential to strengthen agriculture when used appropriately. AI can improve weather forecasting and provide early warnings about extreme weather events. It can support pest and disease surveillance through image recognition systems. Precision nutrient management can reduce input costs and improve fertilizer-use efficiency. Satellite-based crop monitoring can help identify stress conditions before they become visible to the human eye. AI can also improve market intelligence and assist farmers in making better marketing decisions. These applications can increase efficiency, reduce risks, and support sustainable agriculture. However, AI should function as a decision-support system rather than a decision-maker.

The Critical Role of Agricultural Extension in the AI Era

As AI becomes more prominent, the importance of agricultural extension will increase rather than decrease. Extension professionals serve as the bridge between scientific knowledge and field realities. They validate recommendations, interpret local conditions, and help farmers adapt technologies to their specific circumstances.

In the future, extension workers will not merely transfer technologies. They will also help farmers evaluate AI-generated recommendations, distinguish useful information from misleading outputs, and integrate digital tools into practical farming operations. Without strong extension support, even the most advanced technologies may fail to deliver meaningful benefits at the farm level.

Building the Foundation: The Future Roadmap for AI in Agriculture

1. The future success of AI in agriculture will depend less on the sophistication of algorithms and more on the quality of the ecosystem supporting them. The first requirement is the creation of comprehensive, real-time, field-level agricultural databases. At present, much of the available agricultural data originates from research stations, scientific publications, and technical bulletins. While scientifically sound, these sources often fail to capture the diversity and complexity of actual farming situations.
2. A second priority is the documentation and digitization of farmers' experiential knowledge. Farmers possess vast amounts of practical information related to local soils, weather patterns, pest behaviour, water management, and crop responses. Integrating such knowledge into digital platforms can significantly enhance the contextual accuracy of AI systems.
3. Third, future AI systems should move beyond generalized recommendations and evolve into hyper-local advisory platforms capable of considering field-specific conditions. The effectiveness of agricultural AI will depend on its ability to understand local realities rather than merely applying generalized scientific rules.
4. Fourth, agricultural extension systems must be digitally empowered. Extension professionals will increasingly act as interpreters between AI-generated recommendations and field realities. Their role will be critical in validating recommendations, identifying anomalies, and ensuring that technological solutions remain farmer centric.
5. Finally, investments in digital literacy among farmers are essential. Farmers must understand not only how to use AI tools but also when to question them. Technology should enhance critical thinking, not replace it.

Conclusion

Artificial Intelligence has immense potential to transform agriculture by improving access to information, enhancing efficiency, and supporting timely decision-making. However, AI is only as reliable as the data on which it is trained, and agriculture often involves complex field realities that cannot be fully captured through databases alone. Farmers possess invaluable experiential knowledge, while extension professionals provide the critical link between scientific recommendations and local conditions. Therefore, AI should be viewed as a Decision Support System rather than a Decision Maker. The future of agriculture does not lie in replacing farmers with machines. It lies in combining the computational power of Artificial Intelligence with the practical wisdom of farmers, the scientific knowledge of researchers, and the field experience of extension professionals. Only when these four pillars work together can agriculture become truly smart, resilient, sustainable, and capable of meeting the challenges of the coming decades.

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HEAT STRESS AND ITS INFLUENCE ON LIVESTOCK PRODUCTIVITY AND BREEDING EFFICIENCY

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Abstract

Livestock farming is increasingly facing the challenge of rising temperatures due to climate change. Among the various environmental stressors affecting farm animals, heat stress is one of the most serious because it directly influences animal health, productivity, and reproductive efficiency. When animals are exposed to high temperatures for prolonged periods, they experience physiological and metabolic disturbances that reduce feed intake, growth, milk production, disease resistance, and fertility.

Keywords: Heat stress, climate change, livestock productivity, reproduction.

Introduction

Livestock play a crucial role in supporting rural livelihoods and ensuring food and nutritional security. However, changing climatic conditions are posing new challenges to animal production systems worldwide. One of the most visible consequences of climate change is the steady increase in environmental temperature. Heat waves are becoming more frequent and more intense, exposing animals to conditions that often exceed their comfort zone. When an animal is unable to dissipate excess body heat effectively, it experiences heat stress. This condition disrupts normal physiological functions and affects productivity, health, and reproduction (Sejian *et al*., 2018). It not only lowers farm profitability but also compromises animal welfare.

How Animals Respond to Heat Stress

Animals possess several natural mechanisms to regulate body temperature. Under hot conditions, they increase respiration rate, consume more water, reduce physical activity, and seek shade whenever possible. Sweating and panting help remove excess heat from the body. While these responses help animals survive short periods of high temperature, prolonged exposure places tremendous strain on their physiological systems. Energy that would normally be used for growth, milk production, or reproduction is redirected toward maintaining body temperature. Consequently, productive performance begins to decline.

Effects of Heat Stress on Livestock Performance

Reduced Feed Intake and Growth

One of the first signs of heat stress is a decline in feed intake. Animals instinctively eat less because digestion generates additional body heat. Although this response helps reduce heat production, it also decreases nutrient intake. As a result, animals gain weight more slowly and exhibit poorer feed efficiency. Prolonged heat stress adversely affects growth performance in cattle, sheep, goats, and poultry, resulting in significant economic losses for farmers (Das *et al*., 2016).

Decline in Milk Production and Reproductive Performance

During hot weather, a substantial portion of energy is diverted toward cooling the body rather than supporting milk synthesis. Consequently, milk yield and quality often decline during summer months. An increase in temperature can significantly reduce fertility in both male and female animals. Animals often display weak or silent estrus, making heat detection more difficult. Embryos formed during periods of heat stress are more vulnerable to developmental failure, leading to lower conception rates and increased embryonic mortality (Rhoads, 2023). When animals are exposed to prolonged thermal stress, sperm concentration, motility, and viability decline. Studies suggest that prenatal heat stress can influence the future productivity and adaptability of offspring, highlighting the importance of maintaining maternal comfort during gestation (Sejian *et al*., 2018).

Effects on Health and Immunity

Elevated temperatures trigger oxidative stress, which can damage cells and tissues throughout the body. Animals under heat stress often show higher incidences of mastitis, respiratory disorders, and metabolic diseases. Research has shown that thermal stress can alter immune-cell function and inflammatory responses, reducing the animal's ability to fight pathogens effectively (Cartwright *et al*., 2023).

Managing Heat Stress in Livestock

Although heat stress cannot be eliminated, its impact can be greatly reduced through effective management practices.

Providing a Cooler Environment

Simple measures such as shade structures, improved ventilation, cooling fans, sprinklers, and misting systems can significantly improve animal comfort. In grazing systems, planting trees and providing natural shade are cost-effective solutions.

Nutritional Strategies

Feeding animals during the cooler hours of the day encourages feed intake. Diets should be nutrient-dense and highly digestible to compensate for reduced feed consumption. Supplementing antioxidants, vitamins, minerals, and electrolytes can help animals cope with thermal stress and maintain productivity.

Ensuring Adequate Water Supply

Water is the most important nutrient during periods of heat stress. Animals require substantially more water when temperatures rise. Providing continuous access to clean, cool drinking water is essential for maintaining hydration and supporting the body's cooling mechanisms.

Breeding for Heat Tolerance

Long-term adaptation to climate change will require the development of more heat-resilient livestock populations. Indigenous breeds often possess valuable traits related to thermotolerance and environmental adaptability. Incorporating these traits into breeding programs can help create animals that remain productive even under challenging climatic conditions (Cartwright *et al*., 2023).

Conclusion

Heat stress has emerged as one of the greatest challenges confronting livestock production. Its effects extend far beyond temporary discomfort, influencing feed intake, growth, milk production, immunity, fertility, and overall animal welfare. Addressing this challenge requires a combination of improved management practices, strategic nutritional interventions, effective cooling systems, and long-term genetic improvement programs. By adopting climate-smart livestock production strategies, farmers can safeguard animal health, maintain productivity, and build more resilient production systems for the future.

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RNA INTERFERENCE FOR SUSTAINABLE CROP PROTECTION AND AGRICULTURAL ADVANCEMENT

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Abstract

RNA interference (RNAi) has emerged as a powerful tool in agricultural biotechnology, offering precise and environmentally sustainable solutions for crop protection and improvement. This review examines the applications, mechanisms, challenges, and future prospects of RNAi in agriculture. Through sequence specific gene silencing, RNAi enables effective management of insect pests, pathogens, and weeds while minimizing adverse effects on non-target organisms. In addition to crop protection, RNAi contributes to enhanced abiotic stress tolerance, improved nutritional quality, and increased crop productivity. Technologies such as Host Induced Gene Silencing (HIGS) and Spray Induced Gene Silencing (SIGS) have expanded its practical applications and strengthened its potential for sustainable farming. However, challenges related to dsRNA stability, delivery efficiency, regulatory frameworks, production costs, and public acceptance continue to limit large scale adoption. Future integration of RNAi with nanotechnology and advanced breeding approaches is expected to accelerate its implementation, making RNAi a promising strategy for enhancing food security and promoting sustainable agricultural development.

Keywords: Crop protection, Food security, Gene silencing, RNA interference (RNAi), Sustainable agriculture.

Introduction

The rapid advancement of molecular biotechnology has revolutionized modern agriculture by providing innovative tools for crop improvement and protection. Among these, RNA interference (RNAi) has emerged as a highly promising technology owing to its ability to selectively regulate gene expression. Through precise gene silencing, RNAi offers novel strategies for managing agricultural pests and diseases while reducing dependence on conventional chemical pesticides and their associated environmental risks (Dunwell *et al*., 2010). As agricultural systems increasingly confront challenges arising from climate change, shrinking natural resources, and the growing demand for food, the development of sustainable and environmentally responsible crop protection approaches has become imperative.

RNAi technology presents significant opportunities for enhancing crop resilience against a broad spectrum of biotic and abiotic stresses, thereby contributing to improved agricultural productivity and food security. Its capacity to target specific genes allows for effective pest and pathogen control with minimal impact on non-target organisms and surrounding ecosystems. Despite its considerable potential, the successful implementation of RNAi based technologies in agriculture remains influenced by several factors, including regulatory requirements, intellectual property concerns, efficient delivery methods, and public perceptions regarding genetically modified organisms (GMOs). Nevertheless, recent progress in innovative delivery platforms, particularly spray induced gene silencing (SIGS) and nanoparticle mediated delivery systems, has expanded the practical applicability of RNAi. Coupled with supportive regulatory frameworks and increased public awareness, these developments are expected to strengthen the role of RNAi as a key component of sustainable agricultural practices in the future (Jacobsen *et al*., 2009).

RNA Interference (RNAi)

RNA interference (RNAi) is a naturally occurring biological mechanism that regulates gene expression through sequence specific degradation of messenger RNA (mRNA), resulting in the suppression of target gene activity. This process is primarily mediated by small regulatory RNA molecules, including small interfering RNAs (siRNAs) and microRNAs (miRNAs), which are generated from double stranded RNA (dsRNA) precursors and function in post transcriptional gene regulation. By directing the degradation or translational repression of complementary mRNA molecules, RNAi serves as an essential cellular pathway for controlling gene expression and maintaining genomic stability.

In agricultural biotechnology, RNAi has gained considerable attention as an advanced and environmentally friendly approach for crop protection. Unlike conventional pesticides, which often exhibit broad spectrum activity and may adversely affect beneficial organisms, RNAi enables highly specific targeting of genes that are critical for the survival, development, or reproduction of pests and pathogens. One common strategy involves engineering plants to produce dsRNA molecules that correspond to specific gene sequences within target organisms. Following ingestion, these dsRNA molecules are processed into siRNAs that interfere with the expression of essential genes, thereby impairing the growth, reproduction, or viability of the target pest or pathogen (Avila dos Santos *et al*., 2019). The remarkable specificity of RNAi minimizes unintended effects on non-target species, promotes environmental sustainability, and supports the development of safer and more effective crop protection strategies. Consequently, RNAi has become a cornerstone of modern agricultural biotechnology and a promising tool for achieving sustainable agricultural production.

Importance of RNAi in Modern Agricultural Practices

RNA interference (RNAi) has emerged as one of the most influential biotechnological innovations in contemporary agriculture, offering a highly specific and environmentally sustainable approach to crop protection. Unlike conventional chemical pesticides, which often exert broad spectrum effects on both target and non-target organisms, RNAi enables precise suppression of genes associated with the survival, development, or pathogenicity of specific pests and pathogens. This targeted mode of action significantly reduces ecological disturbance while minimizing the dependence on chemical inputs (Gartland *et al*., 2018).

The growing importance of RNAi in modern agriculture is largely attributed to its ability to enhance crop productivity and resilience while supporting sustainable farming practices. Through sequence specific gene silencing, RNAi based technologies provide effective protection against a wide range of insect pests, fungal pathogens, viruses, and other agricultural threats. Among the most promising developments is the exogenous application of double stranded RNA (dsRNA), which enables direct delivery of gene silencing molecules without the need for permanent genetic modification of the crop. This approach has demonstrated considerable success in selectively controlling pest populations while reducing unintended effects on beneficial organisms and surrounding ecosystems (Jacobsen *et al*., 2009).

In addition to its applications in pest and disease management, RNAi has become an important tool in crop improvement programs. Advances in RNAi mediated genetic engineering have facilitated the development of crop varieties with enhanced resistance to biotic and abiotic stresses, improved nutritional quality, and increased productivity. These innovations contribute to the stability and resilience of agricultural production systems, particularly under changing environmental conditions. Collectively, the precision, effectiveness, and environmental compatibility of RNAi technologies position them as a key component of future agricultural strategies aimed at achieving sustainable food production and global food security **(**Gartland *et al*., 2018; Jacobsen *et al*., 2009).

Applications of RNAi in Crop Protection

RNA interference (RNAi) has emerged as a powerful and innovative approach for crop protection, offering highly targeted solutions for the management of agricultural pests and diseases. The technology functions through the introduction of double stranded RNA (dsRNA) molecules that trigger sequence specific silencing of essential genes in target organisms. This mechanism enables precise suppression of pests and pathogens while avoiding many of the drawbacks associated with conventional chemical pesticides. Unlike broad spectrum agrochemicals, which often affect beneficial organisms and contribute to environmental contamination, RNAi based approaches provide a more selective and environmentally compatible alternative (Dunwell *et al*., 2010).

Recent advancements in RNAi technology have significantly expanded its practical applications in agriculture. Among the most notable developments are spray induced gene silencing (SIGS) and host induced gene silencing (HIGS), both of which have demonstrated considerable potential for enhancing crop protection across a wide range of agricultural systems **(**Dunwell *et al*., 2010; Gartland *et al*., 2018). SIGS involves the external application of dsRNA molecules onto plant surfaces, enabling targeted control of pests and pathogens without permanent genetic modification of the crop. In contrast, HIGS relies on the endogenous production of dsRNA within transgenic plants, providing continuous protection against specific biological threats.

The adoption of these RNAi based technologies has strengthened the capacity of crops to defend themselves against insects, fungi, viruses, and other harmful organisms. By enhancing plant resilience and reducing dependence on synthetic pesticides, RNAi contributes to improved crop performance, increased yields, and greater environmental sustainability. As concerns regarding food security, pesticide resistance, and ecological health continue to intensify, RNAi is increasingly recognized as a key component of next generation crop protection strategies. Continued research and technological refinement are expected to further enhance its effectiveness, supporting the development of resilient and sustainable agricultural systems capable of meeting future global food demands (Gartland *et al*., 2018).

RNAi for Viral Disease Management in Plants

RNA interference (RNAi) has become an important tool for the management of viral diseases in plants, offering a highly specific and environmentally sustainable alternative to conventional disease control methods. The technology exploits the natural gene silencing machinery of plants to recognize and degrade viral RNA molecules, thereby preventing viral replication and limiting disease progression. Through the introduction of carefully designed double stranded RNA (dsRNA) molecules that correspond to viral genomic sequences, RNAi enables selective suppression of viral pathogens without affecting non target organisms or disrupting ecological balance (Avila dos Santos *et al*., 2019).

The growing interest in RNAi based viral disease management is largely driven by increasing concerns regarding the environmental consequences and limited effectiveness of traditional chemical control measures against plant viruses. Unlike chemical pesticides, which generally have little direct impact on viral pathogens, RNAi targets the genetic material of the virus itself, providing a precise and efficient means of disease suppression. Both transgenic and non-transgenic approaches have demonstrated significant potential in enhancing resistance to viral infections. In particular, Spray Induced Gene Silencing (SIGS) and host mediated RNAi strategies have shown considerable promise in strengthening plant defense responses while supporting environmentally responsible agricultural practices (Avila dos Santos *et al*., 2019).

One of the most successful examples of RNAi application in agriculture is the development of resistance against Papaya ringspot virus (PRSV) in papaya. The introduction of RNAi based resistance mechanisms through genetic engineering enabled effective suppression of viral infection, leading to a substantial reduction in disease incidence and the recovery of papaya production in regions severely affected by the virus (Tennant *et al*., 2001; Ferreira *et al*., 2014). This achievement is widely regarded as a landmark example of the practical value of RNAi technology in crop protection and demonstrates its capacity to safeguard agricultural productivity against devastating viral diseases.

Despite its considerable potential, several challenges continue to limit the widespread adoption of RNAi based viral management strategies. Efficient delivery of dsRNA molecules, maintenance of their stability under field conditions, and the potential emergence of viral variants capable of overcoming RNAi mediated resistance remain important areas of investigation (Kolliopoulou *et al*., 2017). Addressing these limitations will be essential for maximizing the long-term effectiveness of RNAi technologies in disease management. Nevertheless, the successful deployment of RNAi against viral pathogens highlights its potential to reduce crop losses, enhance agricultural resilience, and promote sustainable food production. As research continues to refine delivery systems and improve efficacy, RNAi is expected to play an increasingly significant role in integrated plant disease management programs and future agricultural innovation.

Potential for RNAi in Sustainable Agriculture

RNA interference (RNAi) is increasingly regarded as a transformative technology with significant potential to advance sustainable agricultural production. By enabling precise regulation of gene expression, RNAi provides innovative solutions for managing pests, pathogens, and other biological constraints that limit crop productivity. Unlike conventional chemical pesticides, which often affect a broad range of organisms and may result in environmental degradation, RNAi based technologies operate through highly specific gene silencing mechanisms. This precision minimizes unintended effects on beneficial organisms and promotes environmentally compatible crop protection strategies.

The foundation of RNAi mediated crop protection lies in the application of double stranded RNA (dsRNA) molecules that activate natural gene silencing pathways. Once introduced into the target organism, these molecules trigger the degradation of specific messenger RNAs, thereby disrupting the expression of genes essential for survival, development, or pathogenicity. The high degree of specificity associated with this process enables effective control of agricultural pests while preserving ecological balance and reducing risks to non-target species.

A prominent example of the successful implementation of RNAi in sustainable agriculture is its application against the Western corn rootworm (*Diabrotica virgifera*), one of the most destructive insect pests affecting maize production. Transgenic maize plants engineered to express dsRNA targeting critical insect genes demonstrated substantial reductions in pest survival and feeding damage, resulting in enhanced crop protection and improved yields (Baum *et al*., 2007). This achievement highlighted the potential of RNAi technologies to provide durable pest resistance while decreasing dependence on synthetic chemical inputs.

In addition to pest management, RNAi offers opportunities for improving crop resilience, safeguarding yields, and promoting resource efficient agricultural practices. As global agriculture faces increasing challenges associated with population growth, climate change, emerging pest pressures, and environmental degradation, the demand for sustainable and innovative crop protection technologies continues to grow. RNAi is well positioned to address these challenges by providing effective, environmentally responsible, and adaptable solutions for modern farming systems.

Continued advances in RNAi research, delivery technologies, and regulatory frameworks are expected to further expand its agricultural applications. Through its ability to reduce chemical dependency, enhance crop performance, and support ecological sustainability, RNAi is increasingly recognized as a cornerstone of next generation agricultural biotechnology. Its integration into crop production systems has the potential to contribute substantially to global food security while fostering resilient and sustainable agricultural landscapes for future generations (Dunwell *et al*., 2010; Gartland *et al*., 2018).

RNAi in Crop Improvement

RNA interference (RNAi) has emerged as a transformative tool in agricultural biotechnology, offering highly precise approaches for crop improvement and protection. Through sequence specific gene silencing, RNAi enables the targeted suppression of undesirable genes in plants, pests, and pathogens, thereby facilitating the development of crop varieties with enhanced resistance, improved productivity, and superior agronomic performance. Unlike conventional crop protection methods that often rely heavily on chemical pesticides, RNAi based technologies provide a more selective and environmentally sustainable alternative.

The application of RNAi in crop improvement extends beyond pest and disease management to the enhancement of plant resilience against a wide range of biotic and abiotic stresses. Technologies such as Host Induced Gene Silencing (HIGS) and Spray Induced Gene Silencing (SIGS) have significantly broadened the scope of RNAi applications by enabling precise targeting of pests and pathogens without adversely affecting beneficial organisms or disrupting ecological balance. These approaches exploit the natural gene silencing machinery to interfere with essential biological processes in target organisms, thereby strengthening crop defense mechanisms while reducing dependence on synthetic agrochemicals (Dunwell *et al*., 2010).

The remarkable specificity of RNAi aligns closely with the objectives of sustainable agriculture. By minimizing off target effects and reducing environmental contamination, RNAi based strategies contribute to the development of safer and more ecologically compatible agricultural systems. Furthermore, the technology provides opportunities for improving crop quality, stress tolerance, and resource use efficiency, making it a valuable component of future food production systems. As global agriculture faces increasing challenges related to climate change, pest outbreaks, and growing food demands, RNAi offers innovative solutions for maintaining productivity while promoting environmental stewardship.

Despite its considerable promise, several challenges continue to limit the large-scale adoption of RNAi technologies. The stability of RNA molecules under field conditions, efficient delivery to target organisms, variability in gene silencing responses, and differences in regulatory frameworks across countries remain significant obstacles. In addition, public perception and acceptance of biotechnology-based innovations play an important role in determining the pace of adoption. Continued research aimed at improving delivery systems, validating field performance, and establishing clear regulatory guidelines will be essential for realizing the full potential of RNAi in sustainable crop improvement and agricultural development (Avila dos Santos *et al*., 2019).

Enhancing Nutritional Content through RNAi

Improving the nutritional quality of crops has become a major objective of modern agriculture, particularly in response to widespread micronutrient deficiencies and increasing concerns regarding global food security. RNA interference (RNAi) offers a powerful and precise approach for crop biofortification by enabling the selective regulation of genes involved in nutrient biosynthesis, accumulation, and metabolism. Through targeted gene silencing, RNAi can enhance the concentration and bioavailability of essential nutrients in staple crops, thereby contributing to improved human health and nutritional well-being.

The application of RNAi in nutritional enhancement is based on its ability to modify specific metabolic pathways without altering unrelated physiological processes. By suppressing genes that limit nutrient accumulation or promote the synthesis of undesirable compounds, researchers can redirect metabolic flux toward the production of beneficial nutrients. Recent advances in technologies such as Host Induced Gene Silencing (HIGS) and Spray Induced Gene Silencing (SIGS) have further expanded the potential of RNAi for crop improvement, providing precise and efficient methods for regulating gene expression while minimizing environmental concerns associated with conventional transgenic approaches (Gartland *et al*., 2018).

One of the most notable examples of RNAi mediated biofortification is the enhancement of provitamin A content in rice. Researchers successfully targeted the lycopene ε cyclase (LCY e) gene, a key enzyme involved in carotenoid biosynthesis. Silencing this gene redirected metabolic activity toward increased β carotene accumulation in rice endosperm, thereby improving the nutritional value of the crop and offering a potential strategy for combating vitamin A deficiency in populations that rely heavily on rice as a staple food (Beyer *et al*., 2002; Paine *et al*., 2005). This achievement demonstrated the capacity of RNAi to address critical nutritional challenges through precise metabolic engineering.

Similarly, RNAi based approaches have been explored to improve the nutritional quality of wheat by enhancing the bioavailability of essential minerals such as iron and zinc. One strategy involves the suppression of genes associated with phytate biosynthesis. Phytate acts as an anti-nutritional factor by binding minerals and limiting their absorption in the human digestive system. Reduction of phytate levels through RNAi mediated gene silencing has been shown to improve mineral availability, thereby increasing the nutritional value of wheat grains (Dutta *et al*., 2017).

The integration of RNAi into biofortification programs offers a promising pathway toward developing nutrient enriched crops capable of addressing both hidden hunger and food insecurity. By simultaneously improving nutritional quality and maintaining agricultural productivity, RNAi contributes to the broader goals of sustainable agriculture and public health. As advances in gene silencing technologies continue to enhance precision, efficiency, and accessibility, RNAi is expected to play an increasingly important role in the development of resilient, nutritious, and environmentally sustainable crop production systems (Charoonnart *et al*., 2018).

Role of RNAi in Improving Yield

Crop yield remains one of the most important determinants of agricultural productivity and global food security. RNA interference (RNAi) has emerged as a valuable tool for enhancing crop yield by enabling the precise regulation of genes involved in plant growth, development, metabolism, and stress responses. Through targeted gene silencing, RNAi can optimize physiological processes that directly influence biomass production, reproductive success, and overall crop performance (Gartland *et al*., 2018).

One of the primary mechanisms through which RNAi contributes to yield improvement is the suppression of genes that negatively affect plant growth or limit resource utilization. By modulating the expression of such genes, RNAi can enhance photosynthetic efficiency, improve nutrient uptake, and promote more effective allocation of metabolic resources. These improvements often translate into increased biomass accumulation, greater reproductive output, and ultimately higher yields. In addition, RNAi mediated regulation of genes involved in developmental pathways can contribute to desirable agronomic traits such as improved plant architecture, enhanced grain filling, and increased harvest index (Dunwell *et al*., 2010).

RNAi also plays a crucial role in protecting yield potential by enhancing resistance to pests, pathogens, and environmental stresses. Crop losses resulting from biotic and abiotic stresses remain a major constraint to agricultural production worldwide. By strengthening natural defense mechanisms and improving stress tolerance, RNAi helps maintain plant health and productivity under challenging conditions. Enhanced resistance to insects, diseases, drought, and salinity can substantially reduce yield losses and improve production stability across diverse agricultural environments (Gartland *et al*., 2018).

Another important advantage of RNAi technology is its potential to reduce dependence on chemical pesticides and other external inputs. The development of crops with improved intrinsic resistance can lower production costs, decrease environmental contamination, and support more sustainable farming systems. Such benefits are particularly significant in the context of climate change and increasing concerns regarding the environmental impacts of intensive agriculture (Dunwell *et al*., 2010).

As advances in RNAi research continue to expand its applications, the technology is expected to contribute substantially to future yield improvement strategies. Its ability to simultaneously enhance productivity, improve resilience, and support sustainable agricultural practices positions RNAi as a key component of next generation crop breeding and biotechnology programs. Consequently, RNAi has the potential not only to increase crop yields in the short term but also to promote the long-term sustainability and resilience of global food production systems (Dunwell *et al*., 2010; Gartland *et al*., 2018).

Challenges in Implementing RNAi Technology

Despite its considerable promise as a tool for crop protection and improvement, the practical implementation of RNA interference (RNAi) technology in agriculture remains constrained by several regulatory, environmental, technical, and social challenges. Addressing these limitations is essential for ensuring the successful translation of RNAi from experimental research to large scale agricultural applications.

One of the most significant challenges relates to the regulatory environment surrounding biotechnology derived agricultural products. In many countries, RNAi based crops and products are evaluated under regulatory frameworks originally designed for genetically modified organisms. Lengthy approval procedures, evolving regulatory requirements, and inconsistencies between jurisdictions can delay commercialization and increase development costs. Furthermore, public concerns regarding biotechnology often influence policy decisions and market acceptance, underscoring the importance of transparent communication and public engagement regarding the safety and benefits of RNAi based technologies (Gartland *et al*., 2018).

Environmental factors also present substantial obstacles to the effective deployment of RNAi. Double stranded RNA molecules are inherently susceptible to degradation by ultraviolet radiation, temperature fluctuations, rainfall, and microbial activity. This limited environmental stability can reduce the persistence and effectiveness of dsRNA under field conditions, thereby restricting the duration of protection provided by RNAi based applications (Dunwell *et al*., 2010). Ensuring adequate stability and maintaining biologically effective concentrations of dsRNA in diverse agricultural environments remain important areas of ongoing research.

Another critical challenge involves the efficient delivery of dsRNA to target organisms. Successful gene silencing requires that dsRNA molecules reach specific pests or pathogens in sufficient quantities while avoiding unintended impacts on non-target species. Variability in uptake mechanisms among different organisms can significantly influence RNAi efficacy, resulting in inconsistent performance across target species. Consequently, the development of reliable and efficient delivery systems is essential for maximizing the practical value of RNAi based technologies.

Recent technological advances have begun to address some of these limitations. Nanoparticle mediated delivery systems, including layered double hydroxides (LDHs) and chitosan-based nanoparticles, have demonstrated considerable potential for enhancing dsRNA stability, protecting molecules from environmental degradation, and facilitating controlled release following application. These innovations improve the persistence and uptake of dsRNA, thereby increasing the effectiveness of RNAi mediated gene silencing under field conditions (Mitter *et al*., 2017).

Similarly, Spray Induced Gene Silencing (SIGS) has emerged as a promising non transgenic approach for crop protection. Field and greenhouse studies have demonstrated the effectiveness of foliar applied dsRNA in controlling plant pathogens and pests. For example, applications targeting *Botrytis cinerea* in grapevine systems have shown the potential of SIGS to reduce fungal infection while minimizing adverse effects on beneficial microorganisms and the surrounding environment (Wang *et al*., 2016). These findings highlight the capacity of innovative delivery technologies to overcome some of the practical limitations that have historically constrained RNAi adoption.

Although significant progress has been made, further research is required to improve dsRNA stability, optimize delivery systems, reduce production costs, and enhance the consistency of gene silencing responses across different agricultural settings. Continued advances in these areas, combined with supportive regulatory frameworks and increased public awareness, will be critical for realizing the full potential of RNAi as a sustainable agricultural technology. By overcoming current barriers, RNAi can become an effective and reliable tool for improving crop productivity, reducing environmental impacts, and supporting long term agricultural sustainability.

Future Prospects of RNAi in Agriculture

RNA interference (RNAi) is poised to play an increasingly important role in the future of agriculture as the demand for sustainable, efficient, and environmentally responsible crop production continues to grow. The technology offers unparalleled precision in gene regulation, enabling targeted control of pests, pathogens, and other biological constraints that negatively affect crop productivity. As advances in molecular biology, genomics, and biotechnology continue to accelerate, RNAi is expected to become an integral component of next generation agricultural systems aimed at enhancing productivity while reducing environmental impacts.

One of the most promising developments in this field is Spray Induced Gene Silencing (SIGS), a technology that enables the external application of double stranded RNA (dsRNA) molecules directly onto plant surfaces. Unlike transgenic approaches, SIGS does not require permanent modification of the plant genome, making it an attractive alternative for crop protection. This characteristic may simplify regulatory approval processes in certain regions and help address public concerns regarding genetically modified organisms. Furthermore, SIGS provides flexibility in application, allowing growers to target specific pests and pathogens as needed while maintaining a high degree of environmental compatibility (Dunwell *et al*., 2010).

The integration of RNAi with nanotechnology represents another major advancement with the potential to significantly improve the effectiveness of RNAi based applications. Nanoparticle mediated delivery systems can protect dsRNA molecules from environmental degradation, enhance their stability, and facilitate efficient uptake by target organisms. These carriers also enable controlled release and precise delivery, increasing gene silencing efficiency while reducing unintended effects on non-target organisms. Such innovations are expected to overcome some of the most significant technical limitations currently associated with RNAi and contribute to the development of more reliable field applications (Gartland *et al*., 2018).

Beyond pest and disease management, future applications of RNAi are likely to extend to crop improvement, nutritional enhancement, stress tolerance, and yield optimization. The ability to precisely regulate gene expression offers opportunities to develop crops with improved resilience to drought, salinity, temperature extremes, and other environmental stresses associated with climate change. In addition, RNAi may contribute to the development of nutrient enriched crops and varieties with enhanced resource use efficiency, thereby supporting both agricultural sustainability and global food security.

The large-scale adoption of RNAi technologies has the potential to transform agricultural practices by reducing dependence on synthetic pesticides and promoting more sustainable approaches to crop management. As scientific understanding continues to expand and delivery systems become increasingly efficient, RNAi is expected to become a cornerstone of precision agriculture. Its capacity to combine effective crop protection with environmental stewardship positions it as one of the most promising tools for addressing the challenges of future food production. Consequently, the continued advancement and responsible implementation of RNAi technologies are likely to play a pivotal role in shaping resilient and sustainable agricultural systems for future generations.

Conclusion

RNA interference (RNAi) has emerged as one of the most innovative and versatile technologies in modern agricultural biotechnology, offering significant opportunities for crop protection, improvement, and sustainable production. Through its ability to mediate highly specific gene silencing, RNAi provides effective strategies for controlling insect pests, pathogens, and weeds while minimizing the environmental impacts commonly associated with conventional chemical pesticides. The precision and adaptability of RNAi have established it as a valuable tool for addressing many of the biological challenges that threaten agricultural productivity and food security.

The applications of RNAi extend far beyond pest and disease management. As demonstrated across numerous studies, RNAi can contribute to enhancing nutritional quality, improving tolerance to abiotic stresses, increasing crop yields, and supporting the development of resilient agricultural systems. Emerging technologies such as Host Induced Gene Silencing (HIGS), Spray Induced Gene Silencing (SIGS), and nanoparticle mediated delivery systems have further expanded the practical potential of RNAi, making its implementation increasingly feasible under diverse agricultural conditions.

At the same time, the successful integration of RNAi into modern agriculture requires careful consideration of regulatory, technical, and societal challenges. Regulatory frameworks must evolve to accommodate the unique characteristics of RNAi based products while ensuring environmental and biological safety. In addition, issues related to intellectual property rights, public perception, and equitable access to biotechnology remain important factors influencing the widespread adoption of RNAi technologies. Addressing these challenges through evidence-based regulation, stakeholder engagement, and continued scientific innovation will be essential for maximizing the benefits of RNAi in agriculture.

The future of crop improvement is likely to involve the integration of conventional breeding approaches with advanced molecular technologies, including RNAi, cisgenesis, and other precision breeding tools. Such complementary strategies offer the potential to accelerate the development of crops capable of meeting the demands of a growing global population while maintaining environmental sustainability. As knowledge of plant genetics, physiology, and molecular interactions continues to expand, RNAi is expected to become an increasingly important component of agricultural innovation (Jacobsen *et al*., 2009; Dunwell *et al*., 2010).

In conclusion, RNAi represents a transformative technology with the capacity to reshape modern agriculture through precise, effective, and environmentally responsible crop management. Its continued development and responsible implementation have the potential to enhance food security, reduce agricultural reliance on chemical inputs, and support the transition toward more sustainable and resilient farming systems. As research and technological advancements continue to refine its applications, RNAi is likely to remain a cornerstone of future agricultural biotechnology and sustainable crop production.

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RNAi-BASED PEST CONTROL: THE FUTURE OF SPECIES-SPECIFIC INSECT MANAGEMENT

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Introduction

Agriculture faces a persistent challenge from insect pests that cause substantial yield losses across crops worldwide. For decades, synthetic pesticides have been the cornerstone of pest management; however, their extensive and often indiscriminate use has led to several concerns, including environmental pollution, pesticide resistance, destruction of beneficial organisms, and potential risks to human health. As agriculture moves toward sustainability, there is an increasing need for innovative technologies that can effectively control pests while minimizing ecological impacts. Among the emerging approaches, RNA interference (RNAi)-based pest control has attracted considerable attention as a revolutionary tool for next-generation crop protection.

RNAi technology offers a unique approach by targeting specific genes within pest insects, thereby suppressing their growth, development, or survival. Unlike conventional pesticides that often affect a broad range of organisms, RNAi provides highly selective pest management, making it one of the most promising advances in modern agricultural entomology.

Understanding RNA Interference

RNA interference is a naturally occurring biological process found in plants, animals, and insects. It functions as a gene-regulation mechanism that can silence specific genes and prevent the production of essential proteins.

The process begins when an insect encounters double-stranded RNA (dsRNA), a molecule designed to match a target gene. Once inside the insect's body, the dsRNA is processed into small interfering RNAs (siRNAs), which guide cellular machinery to degrade the corresponding messenger RNA (mRNA). As a result, the targeted gene can no longer produce the protein required for normal physiological functions.

When critical genes related to feeding, growth, reproduction, or survival are silenced, the insect becomes weakened or dies. This precise mode of action distinguishes RNAi from conventional insecticides and highlights its potential as a highly targeted pest management strategy.

Why RNAi is Different from Conventional Insecticides

Traditional insecticides typically act by disrupting the nervous system or other physiological processes of insects. While effective, these chemicals may also affect non-target organisms such as pollinators, natural enemies, and other beneficial arthropods.

RNAi technology, in contrast, operates with remarkable specificity. Scientists can design dsRNA molecules that target genes unique to a particular pest species. This specificity reduces the likelihood of adverse effects on beneficial insects and other non-target organisms.

Another important advantage is the environmentally friendly nature of RNA molecules. Unlike many chemical pesticides that may persist in soil and water, RNA molecules degrade naturally, reducing concerns about long-term environmental contamination.

Agricultural Applications of RNAi Technology

Research on RNAi-based pest management has expanded rapidly over the past decade. Scientists have successfully demonstrated gene silencing in numerous economically important insect pests.

One of the most notable examples is the management of the fall armyworm (*Spodoptera frugiperda*), an invasive pest that has become a major threat to maize production in India and many other countries. RNAi strategies targeting essential genes have shown promising results in reducing larval survival and feeding damage.

Similarly, RNAi has been explored against cotton bollworm (*Helicoverpa armigera*), brown planthopper (*Nilaparvata lugens*), western corn rootworm (*Diabrotica virgifera virgifera*), and several other agricultural pests. In many cases, significant reductions in pest populations and crop damage have been reported under laboratory and field conditions.

Researchers are also investigating sprayable RNA-based formulations, which may provide farmers with a practical alternative to conventional pesticides. Such products could be applied similarly to traditional sprays while offering greater specificity and environmental safety.

Benefits for Sustainable Agriculture

The growing interest in RNAi technology is driven by its potential contributions to sustainable agriculture.

- **Species-Specific Pest Control**

One of the greatest strengths of RNAi is its precision. Because dsRNA molecules are designed to match specific genes, the technology can target harmful pests without negatively affecting beneficial insects such as honey bees, ladybird beetles, parasitoids, and predatory mites.

- **Reduced Environmental Impact**

RNA molecules are biodegradable and generally do not persist in the environment for extended periods. This characteristic can significantly reduce the ecological footprint associated with pest management practices.

- **Management of Insecticide Resistance**

Resistance development is a major challenge in modern crop protection. Many pest species have evolved resistance to multiple classes of insecticides, making control increasingly difficult. RNAi introduces a completely different mode of action, offering new opportunities for resistance management and integrated pest control programs.

- **Compatibility with Integrated Pest Management**

RNAi technology can complement biological control, cultural practices, resistant crop varieties, and other components of Integrated Pest Management (IPM). Such integration can improve pest suppression while reducing dependence on chemical pesticides.

Challenges to Wider Adoption

Despite its tremendous potential, RNAi technology is not without challenges.

One of the major limitations is the stability of dsRNA under field conditions. Exposure to sunlight, rainfall, and environmental enzymes can degrade RNA molecules before they reach the target insect. Scientists are therefore developing advanced formulations and delivery systems to improve stability and effectiveness.

Another challenge involves efficient delivery. Different insect groups vary in their susceptibility to RNAi, and some species readily absorb dsRNA while others do not. Understanding these biological differences remains an active area of research.

Production costs, regulatory approval processes, and public acceptance are additional factors that may influence the commercialization of RNAi-based products. Continued research and innovation will be essential to overcome these barriers and ensure successful adoption.

Future Perspectives

The future of RNAi-based pest management appears highly promising. Advances in biotechnology, genomics, and nanotechnology are accelerating the development of more efficient RNA delivery systems and cost-effective production methods.

Scientists envision a future where farmers can use highly specific RNA-based sprays to control pests while preserving beneficial insects and maintaining ecological balance. Such technologies could play a crucial role in reducing pesticide residues, protecting biodiversity, and enhancing agricultural sustainability.

As precision agriculture continues to evolve, RNAi is expected to become an integral component of environmentally responsible crop protection strategies. The technology aligns closely with global efforts to promote sustainable food production while minimizing adverse impacts on ecosystems.

Conclusion

RNA interference represents a transformative approach to insect pest management. By harnessing the power of gene silencing, RNAi enables highly targeted control of pest species while minimizing risks to beneficial organisms and the environment. Although technical and regulatory challenges remain, ongoing scientific advancements are rapidly bringing RNAi-based solutions closer to practical agricultural applications.

In an era where sustainable agriculture is both a necessity and a priority, RNAi technology offers a glimpse into the future of crop protection, one where precision, safety, and ecological responsibility work hand in hand. The successful integration of RNAi into pest management programs could significantly contribute to global food security while supporting the long-term health of agricultural ecosystems.

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ROLE OF AGRICULTURE AS A VOCATIONAL COURSE IN SCHOOLS

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Introduction

Agriculture is not only the source of food but also the foundation of rural life and economic development. In a country like India, where a large section of the population depends on farming and related activities, agricultural education has great importance. Introducing agriculture as a vocational course in schools can help students develop practical skills, scientific knowledge, and a positive attitude toward farming and rural development. Vocational education in agriculture focuses on learning by doing. It connects classroom knowledge with real-life farming practices and prepares students for employment, self-reliance, and entrepreneurship. At the school level, agricultural education can create awareness among young learners about food production, environmental protection, and sustainable use of natural resources.

Importance of Agricultural Vocational Education in Schools

Development of Practical Skills

One of the major benefits of agricultural vocational courses is skill development. Students learn practical activities such as seed sowing, nursery raising, compost preparation, irrigation management, and plant protection. These activities improve their confidence and help them understand agricultural practices in a simple and practical way.

Creation of Employment Opportunities

Agricultural vocational education helps students become self-dependent. After completing school education, students can start small agricultural enterprises such as mushroom cultivation, dairy farming, poultry keeping, floriculture, or vegetable production. This can reduce unemployment among rural youth and create opportunities for income generation.

Promotion of Scientific Farming

Modern agriculture requires scientific methods and improved technologies. Through vocational courses, students learn about soil health, balanced fertilizer use, water management, organic farming, and modern cultivation techniques. Such knowledge helps in increasing productivity and improving farm management.

Encouraging Interest in Agriculture

Today, many young people move away from farming because they see it as difficult or unprofitable. Agricultural education in schools can change this mindset by showing students that agriculture is a modern and technology-based profession with many career opportunities.

Support for Rural Development

Skilled and educated youth can contribute to the development of rural communities. Agricultural vocational courses help students understand local agricultural problems and find practical solutions. This improves agricultural production and strengthens rural economies.

Environmental Awareness

Agricultural education also teaches students about conservation of soil, water, forests, and biodiversity. It promotes eco-friendly farming methods and encourages sustainable agricultural practices that protect the environment for future generations.

Approaches for Effective Implementation

Practical-Based Learning

Agricultural education should focus more on practical work than theoretical teaching. Students learn better when they actively participate in farming activities.

School Gardens and Demonstration Plots

Every school should develop small gardens or demonstration farms where students can practice cultivation methods. These gardens can serve as outdoor laboratories.

Community Participation

Local farmers, agricultural officers, and experts should be invited to schools to share their experiences and practical knowledge with students.

Collaboration with Agricultural Institutions

Schools can collaborate with agricultural universities, training centers, and extension agencies for technical support, field visits, and student training programs.

Use of Modern Technology

Digital tools, videos, mobile applications, and smart farming technologies should be used to make learning more interesting and effective.

Skill-Oriented Curriculum

The curriculum should be designed according to local agricultural needs and employment opportunities. Greater emphasis should be given to skill development and entrepreneurship.

Teaching Methods in Agricultural Vocational Education

Demonstration Method

Teachers can demonstrate agricultural practices such as grafting, compost preparation, seed treatment, or irrigation methods for better understanding.

Learning by Doing

Students should directly participate in field activities such as planting, weeding, watering, and harvesting. Practical involvement improves learning outcomes.

Field Visits

Educational visits to farms, nurseries, dairy units, and research stations help students observe modern agricultural practices.

Project Work

Students can undertake small projects like vegetable cultivation, mushroom production, or compost preparation. Project-based learning develops creativity and responsibility.

Group Discussions and Seminars
Discussions encourage students to share ideas, solve problems, and improve communication skills.

Audio-Visual Methods
Charts, models, videos, and multimedia presentations make agricultural concepts easy to understand and more attractive for students.

Challenges in Agricultural Vocational Education
Although agricultural vocational education has many benefits, some challenges still exist. Many schools lack trained teachers, practical facilities, and financial support. Sometimes agriculture is not considered an attractive career by students and parents. Limited infrastructure and insufficient teaching materials also affect the quality of vocational education. To overcome these problems, governments and educational institutions should provide proper training, modern facilities, and awareness programs to encourage agricultural education in schools.

Conclusion
Agriculture as a vocational course in schools plays a significant role in developing skilled, confident, and responsible young people. It provides practical knowledge, creates employment opportunities, and promotes sustainable farming practices. Agricultural vocational education not only strengthens the agricultural sector but also contributes to rural development, food security, and environmental protection. By introducing well-planned agricultural vocational programs in schools, society can prepare a new generation that values agriculture, adopts modern technologies, and contributes positively to national development.

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HIGH-VALUE SEAWEED SPECIES FOR SUSTAINABLE AQUACULTURE

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Abstract

Seaweed farming is among the most rapidly expanding sectors of global aquaculture, producing more than 35 million tonnes of wet biomass each year (FAO, 2022). Macroalgae are widely utilized as food, animal feed, fertilizers, biofuel resources, and raw materials for pharmaceutical products. A thorough understanding of the biological characteristics, ecological requirements, and cultivation practices of major seaweed species is crucial for promoting sustainable coastal aquaculture. This article provides an overview of the key traits of the most commercially valuable cultivable seaweeds based on findings from recent reviewed studies.

Introduction

Seaweeds, also known as macroalgae, are among the most efficient photosynthetic organisms on the planet. Unlike conventional agricultural crops, they do not require freshwater, fertile land, or chemical fertilizers for growth, making them an environmentally sustainable resource. Growing naturally in marine and brackish-water environments, seaweeds convert sunlight and dissolved nutrients into biomass at remarkably high rates. In coastal ecosystems, seaweeds play a vital ecological role by serving as primary producers that support diverse food webs. They provide food, shelter, and nursery habitats for numerous marine organisms, including fish, crustaceans, mollusks, and other invertebrates. Additionally, seaweeds contribute significantly to the sequestration of atmospheric carbon dioxide, a process known as blue carbon storage, helping to mitigate climate change and improve ocean health. The global seaweed aquaculture industry is largely dominated by a few commercially important genera, including Saccharina (kelps), Undaria (wakame), Pyropia (nori), Eucheuma and Kappaphycus (carrageenan-producing red algae), and Gracilaria (agar-producing red algae). Collectively, these genera account for more than 96% of worldwide cultivated seaweed production and support a multi-billion-dollar industry supplying food, hydrocolloids, pharmaceuticals, cosmetics, animal feed, fertilizers, and biofuel feedstocks. As seaweed farming expands into new geographical regions to meet increasing global demand, it is essential to understand the biological and ecological characteristics of individual species. Factors such as growth rate, temperature and salinity tolerance, thallus structure, reproductive biology, nutrient requirements, and biochemical composition determine the suitability of a species for cultivation in particular environment. Successful seaweed farming therefore depends on selecting species that are well adapted to local environmental conditions. The principle that “seaweed farming is not simply transplanting a species it is matching biology to environment” highlights the importance of aligning species-specific traits with site characteristics. A thorough understanding of these relationships is crucial for achieving high productivity, maintaining environmental sustainability, and ensuring the long-term success of seaweed aquaculture operations.

Overview of Major Cultivable Seaweeds

The following table summarises the most important cultivable seaweed genera, their taxonomic group, Principal products, preferred environmental conditions, and cultivation method.

Species / Genus	Group	Main product	Temp (°c)	Salinity (ppt)	Cultivate method
Caulerpa lentillifera (Sea Grapes)	Green (Chlor ophyta)	Fresh salad, vitamins, cosmetics	25 - 32	25 -35	Pond; sea bottom anchoring
Ulva spp. (Sea Lettuce)	Green (Chlor ophyta	Food, bioremediation, feed, biogas	10 - 28	10 - 35	Tank/RAS; IMTA; pond; ocean farm
Pyropia / Porphyra (Nori)	Red (Rhodo phyta)	Food wraps, nutraceuticals	5 – 20	25 - 35	Net cultivation; semi-floating rafts
Kappaphycus alvarezii (Cottonii)	Red (Rhodo phyta)	Carrageenan, food,cosmetics	25 - 30	28 - 34	Bottom-off, floating longline, pond
Eucheuma denticulatum (Spinosum)	Red (Rhodo phyta)	Carrageenan (iota), food	24 - 30	28 - 35	Fixed-off bottom; floating lines
Gracilaria spp.	Red (Rhodo phyta)	Agar, abalone feed, bioremediator	15 - 28	15 - 35	Pond culture; longline; integrated IMTA
Saccharina japonica (Kombu)	Brown (Phae ophyta)	Food,alginate,a nimal feed, biogas	5 – 15	28 – 34	Longline; rope seeding; indoor hatchery
Undaria pinnatifida (Wakame)	Brown (Phae ophyta)	Food (salads, soups), fucoidan	5 – 18	30 – 34	Longline rafts; suspended nets
Sargassum spp. Brown (Phae	Brown (phaeophyta)	Fertilizer, fucoidan, feed, biogas	20 – 28	25 - 35	Net bags; rope; open sea rafts

Table 1. Summary of key cultivable seaweed genera, their environmental optima, main products, and farming methods. Sources: FAO (2022); Buschmann *et al.*, (2017); Hurd *et al.*, (2014); Zemke-White & Ohno (1999).

Major Seaweed Groups and Their Defining Traits

3.1 Green Macroalgae (Chlorophyta) – The Versatile Newcomers

Green macroalgae are gaining increasing attention in modern aquaculture due to their rapid growth, environmental adaptability, and diverse commercial applications. Their potential in food production, aquaculture feed, and water quality management has made them important emerging species in sustainable seaweed farming.

***Caulerpa lentillifera* (Sea Grapes)**

Caulerpa lentillifera, commonly known as Sea Grapes or Green Caviar, is a siphonous green alga recognized for its distinctive grape-like ramuli and high culinary value. Widely consumed as a fresh salad vegetable in Japan and several Southeast Asian countries, it is appreciated for its crisp texture and nutritional benefits. The species grows rapidly in shallow, warm-water ponds with temperatures ranging between 25°C and 32°C. Although its delicate structure and limited post-harvest shelf life present challenges for storage and transportation, its premium market demand and high economic returns continue to support intensive cultivation practices.

***Ulva* Species (Sea Lettuce)**

Species of *Ulva*, commonly referred to as Sea Lettuce, have become increasingly important in land-based recirculating aquaculture systems (RAS) and Integrated Multi-Trophic Aquaculture (IMTA). Their popularity stems from their remarkable ability to absorb excess nutrients from aquaculture effluents, thereby improving water quality and contributing to environmentally sustainable farming operations. *Ulva* species possess a broad tolerance to varying environmental conditions and serve as a valuable feed source for abalone, sea urchins, and several fish species. Under nutrient-rich and well-illuminated conditions, they can achieve growth rates exceeding 15% per day. However, effective control of sporulation during cultivation remains a significant area of ongoing scientific research.

Fig 1: *Caulerpa lentillifera*

Fig 2: Sea Lettuce

3.2 Red Macroalgae (Rhodophyta) – Commercially Important Cultivated Species

Red macroalgae represent one of the most economically significant groups of cultivated seaweeds worldwide. They are widely farmed for the production of hydrocolloids, food products, and environmental services, contributing substantially to global aquaculture and coastal livelihoods.

Kappaphycus alvarezii* and *Eucheuma denticulatum

Kappaphycus alvarezii and *Eucheuma denticulatum* are tropical red seaweeds extensively cultivated in countries such as the Philippines, Indonesia, and Tanzania. These species are highly valued for their ability to produce carrageenan, an important hydrocolloid used as a gelling, stabilizing, and thickening agent in food, cosmetic, and pharmaceutical industries. K. alvarezii is particularly rich in kappa-carrageenan, while E. denticulatum is a major source of iota-carrageenan, with carrageenan content typically ranging from 20–40% of dry weight.

Commercial cultivation is generally carried out through vegetative propagation, where small fragments of healthy thalli are used as planting material. Under favorable environmental conditions, including temperatures of 25–30°C and high light intensity, these seaweeds can achieve rapid growth rates of approximately 3–8% per day. Despite their commercial importance, cultivation is often challenged by the occurrence of "ice-ice" disease and excessive epiphytic growth, both of which can significantly reduce biomass yield and crop quality.

***Gracilaria* Species**

Species of *Gracilaria* are among the most widely cultivated red algae and serve as the principal source of agar, a valuable polysaccharide used in food processing, microbiological media, and biotechnology applications. These seaweeds exhibit remarkable adaptability to varying salinity conditions, thriving in environments ranging from 15 to 35 ppt. Their euryhaline nature allows successful cultivation in estuarine, lagoon, and coastal pond systems across both tropical and temperate regions.

In addition to agar production, *Gracilaria* species play an important environmental role in Integrated Multi-Trophic Aquaculture (IMTA) systems. By efficiently absorbing dissolved nitrogen and phosphorus released from fish and shrimp farms, they help improve water quality while generating an additional harvestable crop. Their broad environmental tolerance and ecological benefits make them highly suitable for sustainable aquaculture development.

Pyropia

Pyropia, previously classified under the genus *Porphyra*, is a highly valued edible seaweed cultivated extensively in East Asian countries for the production of Nori. This species possesses a unique diplohaplontic life cycle, in which the visible, edible blade stage alternates with a microscopic diploid stage known as the conchocelis phase. The conchocelis grows within calcareous shells and is maintained under controlled hatchery conditions to produce spores that are subsequently used for seeding cultivation nets.

The harvested blade stage, commonly processed into Nori sheets, is rich in protein, containing approximately 30–40% of its dry weight, making it one of the most nutritious cultivated seaweeds. *Pyropia* grows best in cold, nutrient-rich waters and is highly prized for its nutritional value, taste, and economic importance in the global seaweed industry.

Fig 1: *Kappaphycus alvarezii* **Fig 2.*Eucheuma denticulatum***

Fig 3.*Gracilaria* **Fig 4. *Pyropia***

Brown Macroalgae (Phaeophyta) – The Kelp Giants

Brown macroalgae, commonly known as kelps, are among the largest and most economically important seaweeds cultivated worldwide. These species are highly valued for their rapid growth, high biomass production, and diverse industrial applications, including food, hydrocolloid extraction, pharmaceuticals, and biofuels.

Saccharina japonica

Saccharina japonica is the most extensively cultivated seaweed species in the world, with an annual production exceeding 20 million tonnes. It is primarily farmed in East Asian countries such as China, Japan, and South Korea, where it forms the backbone of the seaweed aquaculture industry. This kelp is characterized by its exceptional growth rate, capable of elongating by up to 10 cm per day under favorable environmental conditions. The species contains significant amounts of alginate, accounting for approximately 15–40% of its dry weight, making it an important raw material for the food, pharmaceutical, and biotechnology sectors.

The species thrives in cold, nutrient-rich coastal waters and possesses a heteromorphic life cycle involving distinct microscopic and macroscopic stages. This life-cycle pattern facilitates controlled hatchery production of seedlings, ensuring a reliable supply of planting material for commercial cultivation. Its broad and flat blade-like fronds provide a large surface area for photosynthesis, maximizing light absorption and enhancing productivity in subtidal marine environments.

Fig 1: ***Saccharina japonica.***

Fig 2 : ***Undaria pinnatifida***

Undaria pinnatifida **(Wakame)**

Undaria pinnatifida, commonly known as Wakame, is another commercially important brown seaweed cultivated extensively in temperate coastal regions. It is a winter annual species characterized by delicate, feather-like pinnate fronds that typically grow between 1 and 2 meters in length. Wakame performs best in cool waters ranging from 5°C to 18°C and demonstrates rapid seasonal growth, enabling high biomass yields within a relatively short cultivation period.

A notable feature of this species is the development of specialized reproductive structures called sporophylls, which produce spores used for hatchery propagation and large-scale farming. Wakame is highly valued as an edible seaweed due to its distinctive taste, nutritional benefits, and bioactive compounds. Among these compounds, fucoidan has attracted considerable scientific interest because of its potential immunostimulatory, antioxidant, and health-promoting properties. Owing to its fast growth and adaptability, U. pinnatifida is particularly well suited for cultivation using simple and cost-effective longline farming systems.

Essential Traits for Commercial Farming

Traits	Significance	Key reference
Growth rate (SGR)	Determines biomass yield and harvest frequency; varies with temperature, irradiance and nutrients	Hurd *et al*., (2014)

Traits	Significance	Key reference
Temperature range	Defines geographic suitability and seasonal cultivation window; narrow ranges limit site selection	Buschmann *et al*., (2017)
Salinity tolerance	Euryhaline species (e.g. Gracilaria) suitable for estuarine pond culture; stenohaline species need open ocean sites	Zemke-White & Ohno (1999)
Reproductive strategy	Vegetative (Kappaphycus), spore-based (Saccharina, Pyropia) or fragmentation; determines seed production method	Hwang *et al*., (2019)
Biochemical composition	Hydrocolloid content (alginate, agar, carrageenan), protein, lipid and pigment levels determine market value	Bixler & Porse (2011)
Disease susceptibility	'Ice-ice', epiphytism (Kappaphycus); Gall formation(Gracilaria);affects monoculture viability	Largo *et al*., (2020)
Attachment & morphology	Holdfasts (kelps), rhizoids (Gracilaria), siphonous (Caulerpa) governs stocking method on ropes/nets/ponds	Ohno (1993)
IMTA compatibility	Nutrient uptake capacity makes red and green algae ideal biofilters in fish/shellfish co-culture	Chopin & Tacon (2021)

Table 2. Critical biological and ecological traits influencing the commercial viability of seaweed cultivation. SGR = Specific Growth Rate.

Environmental Sustainability and Ecological Considerations

Seaweed cultivation is often considered one of the most environmentally sustainable forms of aquaculture. Unlike fed aquaculture systems, macroalgae do not require supplementary feed, fertilizers, or other external nutrient inputs for growth. Instead, they utilize naturally available sunlight, carbon dioxide, and dissolved nutrients from the surrounding water. Through carbon uptake and long-term storage mechanisms, including biomass export to deeper ocean waters, seaweeds can contribute to carbon sequestration and climate change mitigation. Despite these environmental benefits, large-scale seaweed monoculture may present several ecological concerns. The introduction of non-native species into new regions can lead to biological invasions, as observed with Undaria pinnatifida in parts of New Zealand and Europe. Extensive reliance on vegetative or clonal propagation may also reduce genetic diversity, resulting in genetic homogenization and potentially lowering the resilience of cultivated populations to environmental changes and disease outbreaks. Furthermore, dense seaweed farms can modify local water circulation patterns, alter hydrodynamic processes, and reduce light availability for other marine organisms, thereby affecting surrounding ecosystems. To address these challenges, Integrated Multi-Trophic Aquaculture (IMTA) has emerged as a sustainable and scientifically validated farming approach. IMTA involves the co-cultivation of seaweeds alongside finfish and shellfish, creating a balanced production system in which the waste generated by one organism becomes a resource for another. Seaweed species such as Gracilaria, Ulva, and Saccharina effectively absorb dissolved nitrogen and phosphorus released from fish culture operations, thereby improving water quality and reducing the risk of eutrophication. At the same time, the harvested seaweed biomass provides an additional economic product, enhancing both the environmental and financial sustainability of aquaculture systems.

Conclusion

The success of seaweed aquaculture depends on matching species-specific biological traits to local Environmental conditions. Brown kelps dominate cold-water production; tropical red algae supply the Hydrocolloid industry; and emerging green algae offer versatile solutions for land-based and integrated Systems. As climate change shifts thermal regimes coastally, understanding the physiological Tolerances and adaptive capacity of cultivated species will become ever more critical. Future research priorities include selective breeding for disease resistance and enhanced biochemical Yield, development of offshore cultivation systems for scalability, and expansion of IMTA frameworks to Underutilised coastal regions worldwide.

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SEAWEED BIOSTIMULANTS: THE OCEAN'S GIFT FOR RESILIENT AGRICULTURE

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Introduction

Seaweed biostimulants are emerging as a vital, eco-friendly solution to mitigate the growing threats of abiotic stresses like drought and salinity in modern agriculture. Derived from marine macroalgae, these non-nutrient formulations stimulate natural physiological processes in plants, enhancing nutrient uptake, root development, and overall stress tolerance. In India, the application of seaweed extracts is rapidly expanding across major row crops such as wheat, rice, sugarcane, and maize, consistently demonstrating significant yield improvements and robust growth. Supported by clear regulatory frameworks like the Fertiliser (Control) Order and government initiatives under the Pradhan Mantri Matsya Sampada Yojana (PMMSY), seaweed farming is transitioning from a coastal niche to a mainstream agricultural input. By integrating these biostimulants into regular farming practices, farmers can achieve climate-resilient agriculture, ensure food security, and promote environmental sustainability.

Keywords: Seaweed biostimulants, Abiotic stress, Climate-resilient agriculture, Marine macroalgae, Crop yield

Seaweeds are the colourful marine macroalgae that present in our coastal waters. These remarkable plants belong to three major groups. Red algae (Rhodophyta), brown algae (Phaeophyta), and green algae (Chlorophyta) make up this diverse family. Seaweeds require no arable land, irrigation, or fertilisers. They flourish naturally in coastal environments. This makes them an eco-friendly crop. They also capture carbon and support marine life. The global seaweed industry is experiencing remarkable growth. Market value reached USD 1.1 billion in 2024 for biostimulants alone. The sector is projected to reach USD 3.0 billion by 2034. This represents a compound annual growth rate of 10.5 per cent. Much of this growth comes from biostimulants. These are natural products that enhance plant health and resilience.

Biostimulants are non-nutrient formulations that stimulate natural processes in plants. They improve nutrient use, growth, and stress tolerance. Seaweed extracts are particularly rich in active molecules. These include polysaccharides, amino acids, osmolytes (like glycine betaine and proline), vitamins, minerals, and small amounts of plant hormones (auxins and cytokinins).

When applied as foliar spray or soil treatment, these compounds prime plants to grow better. They help crops endure stress, even though the extract itself is not a fertiliser. India's government now recognises seaweed extracts as a formal biostimulant category. This recognition came through amendments to the national Fertiliser (Control) Order in 2021 and 2024.

Fig. *Colourful genera of useful algal bloom*

The Stresses Threatening Crops

Modern farms face multiple abiotic stresses. Drought, salinity, heat, and cold can devastate yields. Roughly 20 per cent of irrigated land worldwide is salt-affected. Salinity alone cuts crop yields by 30 to 70 per cent. Drought is similarly crippling. Studies predict that by 2050 nearly half of global farmland will suffer extreme salt or drought stress. High salt forces plants to lose water and accumulate toxic sodium. Drought starves plants of moisture. These stresses generate damaging reactive oxygen species (free radicals) in plant cells. They weaken photosynthesis and often cause stunted growth or death. Farmers urgently need nature-based solutions. Climate change is intensifying these challenges.

How Seaweed Biostimulants Work

Seaweed extracts work through a synergy of mechanisms. The compounds they supply and trigger cover multiple physiological processes. First, they boost antioxidant enzymes to protect cells from oxidative stress. Second, they increase osmolytes (proline, sugars, betaines) for better water retention. Third, they supply auxins and cytokinins, delaying senescence and promoting growth. Fourth, they activate nutrient transporter genes, improving nitrogen, sulphur, and iron absorption. Fifth, they maintain sodium-potassium balance, reducing salt toxicity. Sixth, they induce genes for growth hormones and stress tolerance. Finally, they enhance root development and water use efficiency under stress conditions.

Global and Indian Market Trends

The global biostimulants market is expanding rapidly. The market was valued at USD 4.46 billion in 2025. It is projected to reach USD 7.84 billion by 2030. This represents a CAGR of 11.9 per cent. Seaweed extracts form a major segment of this market. Europe dominated with 42.5 per cent market share in 2024. However, the Asia-Pacific region is growing fastest. It is expected to grow at 6.21 per cent CAGR from 2025 to 2032. Countries like India, China, and Japan are driving this growth.

In India, the biostimulants market is experiencing impressive growth. The market was valued at USD 355.53 million in 2024. It is projected to reach USD 1,135.96 million by 2032. This represents a remarkable CAGR of 15.64 per cent. Seaweed extracts commanded 38.8 per cent share of the India biostimulants market in 2024. Row crops, including rice, wheat, and sugarcane, held 86.4 per cent market share. These crops are advancing at 10.32 per cent CAGR through 2030.

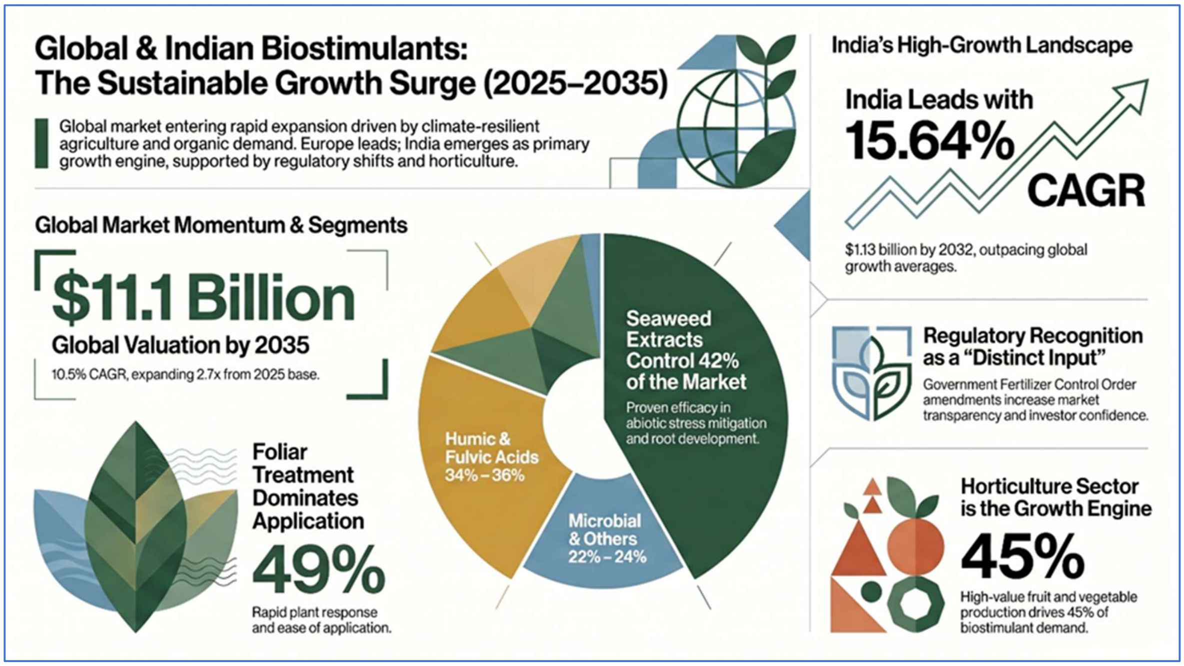

Fig: Biostimulant growth surge in Agriculture (expected)

India's Seaweed Farming Revolution

India has made remarkable progress in seaweed cultivation. The country's 7,500 km coastline offers immense potential. Research institutions have identified 384 sites covering 24,707 hectares suitable for seaweed cultivation. Seaweed production increased from 18,890 tonnes in 2015 to 74,083 tonnes in 2024. The government launched the Pradhan Mantri Matsya Sampada Yojana (PMMSY) in June 2020. The scheme has a total investment of Rs 20,050 crore. Of this, Rs 640 crore is earmarked specifically for seaweed development from 2020 to 2025.

Under PMMSY, the government has approved extensive infrastructure. A total of 47,245 seaweed culture raft units have been sanctioned across five states. The government share amounts to Rs 247 lakh. Additionally, 63,881 units using monoline and tubenet methods have been approved. These are expected to produce over 28,374 tonnes of seaweed. Tamil Nadu leads in seaweed cultivation area. The area increased from 69.26 hectares in 2020-21 to 107.93 hectares in 2024-25. Gujarat has also shown steady growth, reaching 5.86 hectares during the same period.

The government established a Multipurpose Seaweed Park in Tamil Nadu. The total investment is Rs 127.7 crore. This park supports integrated cultivation, processing, and product development. Applications include food, nutraceuticals, pharmaceuticals, cosmetics, and agriculture. Lakshadweep has been notified as a Seaweed Cluster. The Mandapam Regional Centre of ICAR-CMFRI has been designated as a Centre of Excellence for seaweed development. In October 2024, the Department of Fisheries issued Guidelines for Import of Live Seaweeds. This allows import of high-quality seed strains to boost production.

Field Research and Case Studies

Extensive research has validated the benefits of seaweed biostimulants across various crops. Studies from India and abroad demonstrate consistent yield improvements. The following tables present key findings from recent field trials and research studies.

Table 1. Recent Indian field studies on seaweed biostimulants and its effect on crop

Crop	Common Seaweed Extracts Used	Key Benefits for Farmers
Wheat (Triticum aestivum)	Kappaphycus alvarezii, Gracilaria edulis, Sargassum, A. nodosum	• Greener leaves with higher chlorophyll • Increased overall grain yield and protein content • Improved tolerance to drought and salty soils
Rice (Oryza sativa)	Kappaphycus, Gracilaria, Sargassum, A. nodosum	• Faster seed germination and stronger seedlings • Better uptake of soil nutrients • Noticeable improvement in final paddy yield
Maize (Zea mays)	Kappaphycus alvarezii, Gracilaria edulis, A. nodosum	• Faster germination and robust early root/shoot growth • Enhanced photosynthesis and nutrient absorption • Increased total grain yield
Soybean (Glycine max)	Kappaphycus alvarezii, A. nodosum	• Improved nutrient uptake from the soil • Better ability to withstand dry spells (drought tolerance) • Enhanced overall pod and seed yield
Sugarcane (Saccharum officinarum)	A. nodosum	• Taller plants with increased leafy biomass • Improved sugar content and water retention (less wilting) • Reduced damage from common pests like borers and aphids

(Adopted from Ali et al., 2021)

Commercial Products and Companies

Several major companies have established presence in India's seaweed biostimulant market. UPL Limited, Coromandel International, Rallis India, BASF, and Syngenta lead the sector. In December 2022, KRIBHCO (Krishak Bharati Cooperative Limited) introduced SIVARIKA, a seaweed biostimulant product. This marked a significant step in indigenous product development. Coromandel International committed Rs 1,000 crore in July 2024 towards speciality and nano-fertiliser lines, including biostimulants.

Globally, leading companies include Syngenta, Corteva, and BASF. In October 2024, BASF partnered with Acadian Plant Health to expand biostimulant offerings. The partnership incorporates seaweed biostimulants into BASF's BioSolutions portfolio. In April 2025, Bayer AG launched AnHai Long in the Chinese market. This seaweed biostimulant addresses soil degradation, nutrient absorption issues, and abiotic stress. Liquid seaweed extracts dominate the market due to ease of application.

Regulatory Framework in India

The Government of India notified biostimulant regulations through the Fertiliser (Inorganic, Organic or Mixed) (Control) Amendment Order, 2021 and 2024. This provides a clear regulatory framework. Manufacturers or importers must provide specific information to the Central Biostimulant Committee (CBC). Required information includes chemistry details (source, chemical and physical properties, analytical methods, shelf life). Bio-efficacy trials and toxicity analysis reports are mandatory. Heavy metal analysis reports must also be submitted. An affidavit stating product safety is required.

The government has provided specifications for various biostimulants. These include humic and fulvic acid, seaweed extract, botanical extract, and mixed biostimulants. This regulatory clarity has encouraged industry investment. It has also ensured product quality and farmer confidence.

Future Prospects and Integration

Climate change will continue to intensify agricultural stress. Seaweed biostimulants are emerging as a key tool for climate-resilient farming. They enhance crop tolerance to drought and salinity. They protect yields without reliance on synthetic fertilisers or pesticides. When integrated with precision irrigation and resilient crop varieties, benefits can be further amplified. This represents a sustainable approach to modern agriculture.

Beyond crop productivity, seaweed farming supports coastal livelihoods. It provides employment particularly for women and self-help groups. Currently, 7,230 members in Tamil Nadu, 378 in Gujarat, 120 in Andhra Pradesh, and 40 in Lakshadweep are engaged in seaweed cultivation. The sector contributes to environmental sustainability. Seaweed cultivation aids water purification and carbon sequestration. These additional benefits make it an attractive proposition.

Ongoing research is refining seaweed-derived compounds. Scientists are working on alginate and carrageenan extraction. The goal is to develop crop-specific biostimulant formulations. This targeted approach will maximise benefits for different crops. Advanced extraction techniques are being developed. Enzyme-assisted extraction shows particular promise. It can be tailored to target specific compounds based on algae biomass characteristics.

Summary

Seaweed is transitioning from a marine byproduct to a critical agricultural input. It offers a sustainable, multifunctional solution. It improves crop growth, yield, and resilience under changing climatic conditions. The market is experiencing robust growth. Global seaweed biostimulant market will reach USD 3.0 billion by 2034. India's biostimulant market will reach USD 1,135.96 million by 2032. Government support through PMMSY and regulatory clarity through FCO amendments provide strong foundations.

The scientific evidence supporting seaweed biostimulants continues to grow. Field studies consistently demonstrate yield improvements. They show enhanced stress tolerance across diverse crops and conditions. The integration of seaweed biostimulants with modern farming practices represents a promising pathway. It offers sustainable intensification of agriculture. It provides climate resilience. It ensures food security for growing populations.

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SPORTS NUTRITION: AN INTEGRAL DIMENSION OF FOOD AND NUTRITION

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Sports nutrition is a specialized field that integrates human nutrition with exercise science to support physical performance, recovery, and overall health. It is not limited to elite athletes but is equally relevant for all physically active individuals. Since physical training places increased demands on the body, a well-planned, evidence-based diet becomes essential to meet energy needs, enhance endurance, and prevent fatigue and injury.

During physical activity, the body's metabolic rate increases, leading to greater utilization of nutrients. The key components of sports nutrition include carbohydrates, proteins, fats, water, vitamins, and minerals. These nutrients collectively maintain physiological balance and support performance. Energy for all biological activities is derived from adenosine triphosphate (ATP), which is continuously broken down and regenerated during exercise through different energy systems in the body.

Carbohydrates are the primary and most efficient source of energy, particularly during moderate to high-intensity exercise. They are metabolized either aerobically or anaerobically depending on oxygen availability. Proteins play a crucial role in muscle repair and recovery, while fats serve as an important energy source during prolonged, low-intensity activities.

Micronutrients, including vitamins and minerals, are equally important despite not directly providing energy. B-complex vitamins aid in energy metabolism, while vitamin D and calcium are essential for bone health. Iron plays a vital role in oxygen transport, and its deficiency can impair endurance and performance. Other minerals such as magnesium, zinc, and potassium are important for muscle contraction, nerve function, and maintaining electrolyte balance. Athletes must ensure adequate intake of these micronutrients to avoid deficiencies.

Hydration is a critical component of sports nutrition, especially in hot climates like India. Fluid loss through sweat can lead to dehydration, negatively affecting performance, coordination, and concentration. Even a small loss of body water can impair physical efficiency. Therefore, maintaining hydration before, during, and after exercise is essential. Natural beverages such as water, coconut water, lemon water, and buttermilk are effective and accessible options.

Antioxidants play a protective role against oxidative stress caused by intense physical activity. Exercise increases the production of free radicals, which can damage cells and delay recovery. Antioxidants such as vitamins C and E, along with compounds found in fruits, vegetables, nuts, and whole grains, help neutralize these harmful effects and support faster recovery.

Diet should be balanced, affordable, and based on locally available foods. Traditional Indian diets can effectively meet the nutritional needs of athletes when properly planned. Staples such as wheat, rice, and millets (jowar, bajra, ragi), combined with pulses like moong, masoor, and chana, provide a strong nutritional foundation. Milk and milk products offer high-quality protein and calcium, while nuts, oilseeds, jaggery, fruits, and green leafy vegetables supply essential micronutrients and antioxidants.

Certain groups require special attention. Vegetarian athletes must ensure adequate intake of protein, iron, zinc, and vitamin B12 through careful food combinations and fortified foods. Athletes with diabetes need to monitor carbohydrate intake and blood glucose levels to maintain balance during physical activity. Female athletes are at risk of the Female Athlete Triad, which includes low energy intake, menstrual irregularities, and poor bone health, highlighting the need for proper nutrition and medical guidance.

In conclusion, sports nutrition is a vital component of athletic success and overall well-being. A balanced and individualized diet, combined with proper hydration and adequate micronutrient intake, enhances performance, supports recovery, and prevents long-term health issues. Leveraging traditional dietary practices along with scientific knowledge can provide effective and sustainable nutrition solutions for athletes at all levels.

Practical Guidelines for Sports Personnel

- Consume a balanced diet including cereals, pulses, milk, fruits, vegetables, and healthy fats.
- Include millets (jowar, bajra, ragi) to improve nutrient intake.
- Ensure adequate protein through dal, paneer, soy, eggs, or lean meat.
- Take a light, carbohydrate-rich meal before exercise (e.g., banana, poha, upma).
- Consume a combination of carbohydrates and protein after exercise for recovery.
- Maintain proper hydration using water, coconut water, or buttermilk.
- Include antioxidant-rich foods like fruits, vegetables, nuts, and seeds.
- Avoid excessive processed foods and unnecessary supplements.
- Pay special attention to individual needs such as vegetarian diets, diabetes, and female health.

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AWARENESS OF 4R PRINCIPLES TO FARMER FOR EFFECTIVE MANAGEMENT OF SOIL HEALTH

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Introduction

With increasing fertilizer prices and decreasing soil productivity and ongoing environmental changes, there is a need for scientific farming. Implementing scientific farming technology has become indispensable for the economic development of farmers. Incorrect use and over usage of chemical fertilizers for higher yields is deteriorating the soil quality and making it infertile over a period of time. As a result, not only does the crop yield decrease, but there are also severe negative impacts on the quality of the crops grown. Under these circumstances, the 4R principles (Right Source, Right Rate, Right Time, and Right Place) serve as an excellent guideline for efficiently delivering the necessary nutrients to crops. These principles do not just identify fertilizer usage but also lay a foundation for sustainable agriculture.

Key words: Fertilizer use, Soil productivity, Soil Quality and Sustainable Agriculture

Importance of Soil Testing

Soil health test is a foundation for increasing farmers' crop yields and improving agricultural productivity. Through these tests, the fertility, nutrient levels, and deficiencies present in the soil are determined. Soil tests are highly useful in determining what needs to be done to increase crop quality and yield. The collected samples are analyzed, and Soil Health Cards are issued based on them.

Benefits of a Soil Health Card:

- Applying Fertilizers only as and when needed this reduces addition costs for farmers
- Right Choice of Fertilizers helps in preventing the overuse of fertilizers like Urea or D.A.P. beyond the required dosage.
- By optimum fertilizer application soil pH is Balanced
- The organic carbon in the soil remains undamaged.
- Providing appropriate nutrients to the soil ensures good crop growth.
- This not only results in a quality yield but also increases the income per acre.

The 12 Parameters in the Soil Health Card:

- **Macronutrients:** Nitrogen (N), Phosphorus (P), Potassium (K).
- **Secondary Nutrients:** Sulphur (S).
- **Micronutrients:** Zinc (Zn), Iron (Fe), Copper (Cu), Manganese (Mn), Boron (B).
- **Physical Condition:** pH value, EC (Electrical Conductivity), OC (Organic Carbon).

Fig. 1: Soil Health Card with Soil Nutrients Status for Farmers Reference

Detailed Explanation of the 4R Principles

1. Right Source

The core scientific principles that define right source for a specific set of conditions are the following. Supply nutrients in plant-available forms. Ensure the nutrient applied is plant-available or is in a form that converts into a plant-available form in the soil in a timely manner in addition to improving soil physical and chemical properties. For example, nitrate is too easily lost from flooded soils, and urea on the surface of alkaline soils loses ammonia too easily. Recognize synergisms among nutrient elements and sources. For instance, nitrogen can increase availability of applied phosphorus. Applied phosphorus can reduce availability of zinc. Fertilizers complement manures. Recognize blend compatibility. Avoid combinations that attract moisture when mixed and match granule sizes when blending. Recognize benefits and sensitivities to associated elements. Most nutrients have an accompanying ion that may be beneficial, neutral or detrimental to the crop. For example, the chloride in muriate of potash can benefit corn, but also increases salt risk and may be detrimental to some fruits. Some sources of P fertilizer may contain plant available Ca and S, and small amounts of Mg and micronutrients. Control effects of non-nutritive elements. For example, natural deposits of some phosphate rock contain non-nutritive trace elements. The level of addition of these elements should be kept within acceptable thresholds. Select the correct source of nutrient for your soil ensuring a balanced supply of essential plant nutrients including granular or liquid fertilizers or manures.

2. Right Rate (Right Quantity)

The core scientific principles that define right rate for a specific set of conditions are the following. Assess plant nutrient demand. During a plant's growth cycle, nutrient demand both in quantity and quality fluctuates. Applying the right rate means you are giving the plant the amount and combination of nutrients it needs for optimum performance at that particular growth stage. Use methods to assess soil nutrient supply. This will include soil analysis to tell you what nutrients are in the soil and their availability. It can also include plant tissue analysis to tell what nutrient is the limiting factor to plant development at that particular time. Perform annual soil testing. Assess all available nutrient sources. If you're planning to use soil amendments, take into account how much nutrient they will be providing. If you use surface water, there may be low levels of nutrients in the water. Some loss is unavoidable, so to meet plant demand, the amount of loss must be considered. For instance, if there is substantial rain after applying fertilizer, a large percentage of the nitrogen you applied may leach out of the root zone. In this case, an additional application of nitrogen may be warranted. For nutrients unlikely to be retained in the soil (think nitrogen), the most economic rate of application is where the last unit of nutrient applied is equal to the amount of nutrient the plant will take up during that growth stage. For nutrients retained in the soil, their value to future crops should be considered. Calibrate application equipment to accurately deliver target rates.

3. Right Time

The core scientific principles that define right time for a specific set of conditions are the following. Assess timing of plant uptake. Nutrients should be applied to match the seasonal crop nutrient demand, which depends on planting date, plant growth characteristics, sensitivity to deficiencies at particular growth stages, etc. Assess dynamics of soil nutrient supply. Mineralization of soil organic matter supplies a large quantity of some nutrients, but if the crop's uptake need precedes its release, deficiencies may limit productivity. Recognize dynamics of soil nutrient loss. For example, leaching losses tend to be more frequent in the spring and fall. Evaluate growing/gardening logistics. For example, multiple applications of nutrients may or may not be reasonably feasible. Nutrient applications should not be onerous or interrupt normal gardening activities.

4. **Right Place**

Right place means positioning needed nutrient supplies strategically so that a plant has access to them. Proper placement allows a plant to develop properly and realize its potential yield, given the environmental conditions in which it grows. Consider where plant roots are growing. Nutrients need to be placed where they can be taken up by growing roots when needed. Consider soil chemical reactions. Concentrating soil-retained nutrients like P in bands or smaller soil volumes can improve availability. Suit the goals of the growing system. Subsurface placement techniques can help conserve nutrients and water. Manage spatial variability. Assess soil differences within the growing area in crop grown, soil nutrient content, and vulnerability to nutrient loss.

Benefits of Adopting the 4R Principles

Adopting the 4R principles offers several benefits; they are crucial in protecting soil fertility, reducing fertilizer waste, and increasing crop yields. Along with this, the return on investment for farmers increases, and environmental pollution is reduced. Problems like water pollution and soil degradation can also be kept under control. Using fertilizers based specifically on the Soil Health Card makes these principles even more beneficial.

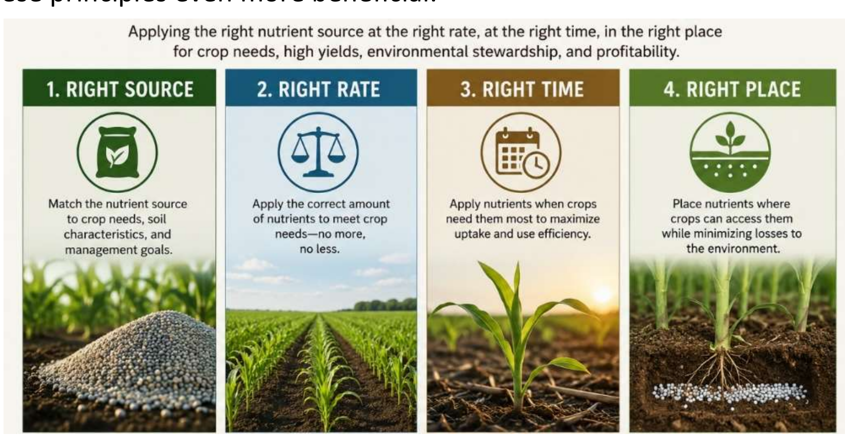

Fig. 2: The Four R's of Nutrient Management

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Awareness Program (Kisan Goshti)

As part of the *Mera Gaon Mera Gaurav* (My Village My Pride) initiative, the ICAR-Central Research Institute for Dryland Agriculture (CRIDA), Hyderabad, organized a *Kisan Goshti* (farmers' meet) on the topic **"Balanced Use of Fertilizers"** on April 29, 2026, in Haridaspur village, Kondapur mandal, Sangareddy district. This program was conducted as part of the nationwide campaign for the judicious use of fertilizers undertaken by ICAR, New Delhi. Scientists Dr. G. Pratibha, Dr. K. Ravi Shankar, and Dr. V. Girijaveni participated and created awareness among about 42 farmers on best farming practices, water conservation, the importance of soil testing, and balanced fertilizer usage.

The event saw the participation of TGIIC Chairperson Smt. T. Nirmala Jagga Reddy Garu, ATMA Chairman Y. Prabhu Garu, and J.D.A. K. Shiva Prasad Garu, along with other agricultural officials, scientists, and students. They emphasized the vital importance of integrated nutrient management to achieve sustainable yields while protecting soil fertility.

Conclusion

In conclusion, the 4R principles serve as scientific guidelines that show the right path to farmers. They do not just increase crop yields, but keep agriculture sustainable by protecting soil health for future generations as well. If farmers implement these principles in their daily farming practices, expenses will decrease, income will increase, and the environment will be protected. Therefore, every farmer must follow the 4R principles to achieve the goal of **"Sustainable Agriculture – Prosperous Farmer."**

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TRUE POTATO SEED (TPS): REVOLUTIONIZING AFFORDABLE AND DISEASE-FREE SEED SYSTEMS FOR SMALLHOLDER POTATO FARMERS

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Introduction

Potato is the world's third most important food crop after rice and wheat and plays a vital role in ensuring food and nutritional security. However, the availability and affordability of quality seed remain major constraints to potato production, particularly for smallholder farmers. Seed alone accounts for nearly 40–50% of the total cost of potato cultivation, and poor-quality planting material is one of the primary reasons for low productivity and yield instability (Buckseth *et al*., 2022).

Traditionally, potatoes are propagated using seed tubers. While this method ensures crop uniformity and ease of cultivation, it also involves several challenges, including high transportation costs, seed degeneration and the accumulation of diseases. In recent years, True Potato Seed (TPS)—the botanical seed produced within potato berries—has emerged as a promising alternative. Although TPS was introduced and evaluated in India during the early 1980s (Almekinders *et al*., 2009), advances in hybrid breeding, nursery management and seed production technologies have renewed interest in its adoption.

This article examines the advantages and limitations of both traditional seed tubers and TPS and discusses how an integrated seed system can benefit resource-constrain potato growers.

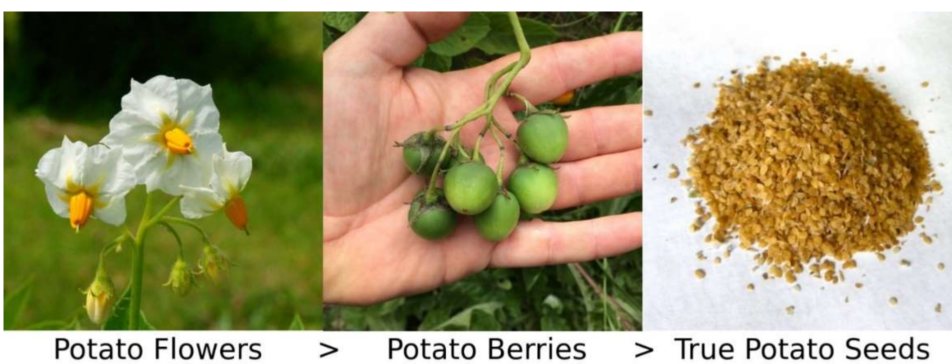

Fig 1: True Potato Seed (Credit: Cultivariable)

Traditional Seed Tubers: Strengths and Limitations

Why Farmers Prefer Seed Tubers

Seed tubers have served farmers reliably because they are:

- Genetically identical clones, ensuring uniformity in field performance.
- Easy to plant without special nursery skills.
- Familiar to farmers, requiring no specialised knowledge.
- Quick to establish, with no transplanting stage.

- Reliable in market-driven production, where uniform tuber size is essential.

For commercial growers supplying processing industries or structured markets, these advantages are critical.

But Seed Tubers Carry Hidden Costs

Why Farmers Prefer Seed Tubers

For generations, seed tubers have been the preferred planting material because they offer several practical advantages:

- Genetic uniformity due to clonal propagation
- Reliable field establishment and crop performance
- Ease of planting without the need for nursery raising
- Familiarity among farmers and extension personnel
- Production of uniform tubers suitable for commercial markets and processing industries

These attributes make seed tubers highly suitable for intensive and market-oriented potato production systems.

Hidden Costs of Seed Tubers

Despite their advantages, seed tubers have several inherent limitations:

- Accumulation of viral diseases over successive generations
- High transportation and storage costs because of their bulky nature
- Requirement for cold storage facilities to maintain seed quality
- Susceptibility to rotting, mechanical damage and pest infestation
- High seed cost per hectare
- Rapid seed degeneration requiring frequent replacement with certified seed

Research indicates that seed degeneration caused primarily by viral infections can reduce potato yields by 20–80%, depending on environmental conditions and seed source quality (Kumar *et al.*, 2024).

Thus, while seed tubers perform well in areas with access to certified seed and storage infrastructure, they often become a major economic burden for smallholders in remote and resource-constrained regions.

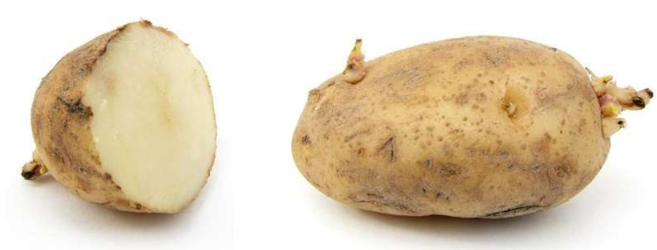

Fig 2: Potato seed tuber (Credit: Feedipedia)

True Potato Seed (TPS)

Why TPS Is Attracting Global Attention

TPS offers several advantages that directly address the challenges associated with conventional seed tubers:

1. Disease-Free Planting Material
As botanical seeds, TPS generally does not transmit most tuber-borne viral diseases, providing a clean starting point for crop establishment.

2. Lower Seed Cost
Only a few grams of TPS are sufficient to plant one hectare, dramatically reducing seed expenditure.

3. Easy Storage and Transportation
Unlike bulky seed tubers, TPS requires minimal storage space and can be transported easily at negligible cost.

4. Enhanced Adaptability
Many TPS populations exhibit greater tolerance to drought, heat stress and certain diseases, making them suitable for challenging production environments.

5. Longer Storage Life
TPS can remain viable for 5–10 years when stored under cool and dry conditions, offering significant advantages for seed security.

Modern TPS Hybrids: Addressing Earlier Limitations
Earlier open-pollinated TPS populations often produced highly variable plants and tubers, limiting their commercial acceptance. However, recent advances in hybrid breeding have resulted in TPS varieties with improved uniformity, higher productivity and better adaptation to diverse agro-climatic conditions.

Several breeding programmes in India, Peru, China and Bangladesh have demonstrated the potential of modern TPS hybrids for sustainable potato production.

Challenges Associated with TPS
Despite its advantages, TPS adoption is not without challenges:

- Requirement for nursery raising and seedling management
- Greater technical skill and labour input
- Longer crop duration, often extending 20–30 days beyond conventional crops
- Initial variability in tuber size and shape during the first generation

These factors may discourage farmers seeking immediate marketable produce. However, TPS-grown seedlings can produce healthy mini-tubers that serve as excellent seed material for subsequent seasons.

Comparative Evaluation of TPS and Seed Tubers
Table 1. Seed Tubers vs TPS: A Comparative Overview

Feature	Traditional Seed Tubers	True Potato Seed (TPS)
Disease load	High	Negligible
Seed cost	Very high	Very low
Transport and storage	Difficult and costly	Easy and economical
Uniformity	Excellent	Moderate to high (hybrids)
Labour requirement	Low	Higher
Shelf life	Short	Long
Suitability for remote areas	Low	High
Seed degeneration	Common	Absent

An Integrated Seed Strategy: The Best of Both Worlds

Increasingly, researchers and development agencies are advocating a two-step seed system that combines the strengths of TPS and seed tubers:

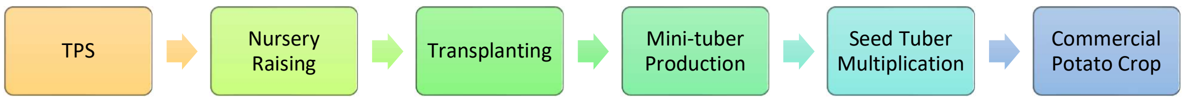

Fig. 3. Integrated TPS-based seed production system for generating disease-free seed tubers and commercial potato crops.

Year 1

Use TPS to produce disease-free mini-tubers.

Years 2–3

Plant the mini-tubers as seed tubers for commercial production.

This approach provides:

- Reduced seed costs
- High crop vigour
- Minimal disease pressure
- Improved seed quality
- Greater yield stability
- Uniform marketable produce

Such an integrated strategy combines the economic advantages of TPS with the agronomic benefits of conventional seed tubers.

Which Option Is Best for Small Farmers?

TPS May Be More Suitable For Farmers Who:

- Face high seed procurement costs
- Live in remote areas with expensive transportation
- Frequently experience virus-related yield losses
- Seek greater seed self-reliance
- Possess the capacity to manage nurseries

Seed Tubers May Be More Suitable For Farmers Who:

- Require immediate and uniform crop establishment
- Produce for commercial or processing markets
- Have reliable access to certified seed sources
- Prefer simpler cultivation practices without nursery management

Conclusion

True Potato Seed should not be viewed as a complete replacement for conventional seed tubers. Rather, it represents a complementary technology capable of overcoming many of the economic and logistical constraints faced by smallholder potato farmers.

By enabling the production of disease-free mini-tubers at a fraction of the cost of conventional seed, TPS offers a pathway toward greater seed security, reduced production costs and improved sustainability. The integration of TPS-derived mini-tubers with traditional seed systems presents a practical and scalable approach for enhancing potato productivity in developing countries.

As breeding programmes continue to develop more uniform, high-yielding and climate-resilient TPS hybrids, this technology is poised to become one of the most transformative innovations in potato cultivation. Sometimes, the smallest seed can create the biggest change in agricultural sustainability and farmer livelihoods.

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GRAFT AND GROW: THE SCIENCE OF STRONGER VEGETABLES

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Abstract
Vegetable grafting is an important horticultural technique in which a desirable scion is joined with a resistant rootstock to improve crop performance. It helps protect vegetable crops from soil borne pathogens such as *Fusarium*, *Verticillium* and root knot nematodes, while also improving tolerance to salinity, drought and temperature stress. The success of grafting depends on proper cambium alignment, callus formation and vascular reconnection between the scion and rootstock. Various grafting methods, including cleft, tube, tongue approach, slant, hole insertion, mechanized and micro grafting, are used commercially. Double harvest plants such as Brimato and Pomato show the innovative potential of grafting. Thus, vegetable grafting supports sustainable production, crop resilience and improved yield.

Keywords: Vegetable grafting, grafting methods, Brimato, Pomato

Introduction
Grafting is an ancient practice that originated centuries ago in perennial fruit orchards but has recently been adapted to fast-growing herbaceous vegetable crops. The practice was first commercialized in East Asia in the 1920s, when watermelon (*Citrulluslanatus*) was grafted onto bottle gourd (*Lagenariasiceraria*) rootstocks in Japan and Korea to control severe soilborne diseases (Kumar *et al*., 2021).While woody perennials takemonths to unite, herbaceous vegetable grafts unite within few days (Colla *et al*., 2018). This demand made to shift the practice from manual work to highly automated industrial setups. Modern facilities use the computervision-guided robotics and they regulated climate chambers to massproduce uniform, high-quality grafted plugs (Kubota *et al*., 2008). The global expansion of vegetable grafting was increaseddue to international environmental regulations.Initially, commercial vegetable farming dependedonthe chemical soil fumigants like methyl bromide to control soilborne pests.Afterthe Prohibition of methyl bromide under the Montreal Protocol, the monoculture cropping fields suffered from yield losses due to the pathogens like *Fusariumoxysporum*and *Ralstoniasolanacearum* (Colla *et al*., 2018).Grafting helps an eco-friendly solution. It allows growers to utilize the natural genetic resilience of wild or non-commercial rootstocks without changing the fruit characteristics of scion varieties (Kubota *et al*., 2008). But now,

large-scale commercial nurseries suppliesmillions of uniform grafted plants annually, making the grafting as a standard global practice for crop security and yield stabilization.

Commercial Grafting Methods

Grafting methods involve such techniques as cleft grafting, tube grafting, whip grafting, tongue grafting, spliced grafting, flat grafting, saddle grafting, bud grafting, hole insertion grafting, and tongue approach grafting etc. These methods of grafting are briefly described as under(Kumar *et al*., 2021).

Cleft grafting: For practicing this method of grafting, seeds of the rootstocks are sown 5-7 days earlier than those of the scion. The stem of the scion (at the four leaf stage) and the rootstock (at the 4-5 leaf stage) are cut at right angles, each with 2-3 leaves remaining on the stem. The stem of the scion is cut into a wedge and the tapered end fitted into a cleft cut in the end of the rootstock. The graft is held firm with a plastic clip.

Tube grafting: This method of grafting makes it possible to graft small plants grown in plug trays two or three times faster than the conventional method and is quite popular among Japanese seedling producers. Plants in small cells must be grafted at earlier growth stages and requires tubes with a smaller inside diameter. First the rootstock is cut at a slant. The scion is cut in the sameway. Elastic tubes with side slit are placed onto the cut end of the rootstock. The cut ends of the scions are inserted into the tube, splicing the cut surfaces of the scions and rootstocks together. While practicing the tube grafting in eggplant, the seeds of *Solanumtorvum* must be sown a few days earlier than those of the other rootstock species.

Tongue approach grafting: Melons and other cucurbitaceous plants are generally grafted by this method. It gives a higher survival ratio because the root of the scion remains until the formation of the graft union. In this method, seeds of cucumber are sown 10-13 days before grafting and pumpkin seeds 7-10 days before grafting, to ensure uniformity in the diameter of the hypocotyl of the scion and rootstock. The shoot apex of the rootstock is removed so that the shoot cannot grow. The hypocotyl of the scion and rootstock are cut in such a way that they tongue into each other and the graft is secured with a plastic clip. The hypocotyl of the scion is left to heal for 3-4 days and then crushed between the fingers. The hypocotyl is cut off with a sharp razor blade three or four days after being crushed.

Slant grafting: Recently this method of grafting has gained popularity. It has been developed for robotic grafting. In this method, it is essential to remove the first leaf and lateral buds when a cotyledon of rootstock is cut on a slant.

Hole-insertion grafting: Theupper stem of rootstock is excised immediately above cotyledons, followed by a 6-8mm deep narrow cone-shaped hole created in the rootstock. Then, the upper part of scion seedling is removed at the cotyledon stage, with an oblique transfer cut. Then, the scion is inserted in the hole of the rootstock stem.

Micro-grafting: Micro or In-vitro grafting is used to eliminate the viruses from infected plants using very small or micro-explants from meristematic tissues. But it is very expensive.

Double harvest(wonder plants) like Brimato&Pomato through grafting

The Brimato

The inter-specific grafting has emerged as a promising tool for increasing the tolerance to biotic and abiotic stresses, besides enhancing the productivity in vegetables. The dual or multiple grafting is a new technological option, wherein, two or more than two scions of the same family are grafted together to harvest more than one vegetable from a single plant.The dual grafting of brinjal and tomato (Brimato) was demonstrated in the field during 2020-21. The brinjal hybrid - Kashi Sandesh and improved cultivar of Tomato - Kashi Aman were successfully grafted into brinjal rootstock - IC 111056.

The Pomato

The "Pomato" represents a tomato (*Solanumlycopersicum*) scion is joined to a potato rootstock, producing a double harvest from a single plant (Islam *et al*., 2019). Careful manipulation of this source-sink balance via structural pruning and canopy management is vital to optimize both top and bottom yields simultaneously without stalling the plant (Islam *et al*., 2019; Ngawang and Rai, 2024).

Table 1. Potential rootstocks with special features of resistance against biotic and abiotic stresses

Crop	Species	Specific Features
Tomato	*Solanumpennelli*	Tolerance to drought
Tomato	*S. chessmanii*	Resistant to salt
Tomato	*S. galapagense*	Tolerance to salt
Tomato	*S. habrochaites*	Resistance to cold as well as insects & diseases (TMV)
Tomato	*S. chilense*	Resistance to drought and diseases (CMV, TYLCV)
Tomato	*S. neorickii*	Resistant to bacterial diseases
Tomato	*S. pimpinellifolium*	Colour, quality, resistance to disease
Tomato	*S. lycopersicum var. cerasiforme*	Tolerance to humidity, resistance to fungi and root rot
Tomato	*S. peruvianum*	Resistance to tomato spotted wilt virus and RKN
Brinjal	*S. macrocarpon; S. gilo*	Tolerant to drought
Brinjal	*S. torvum*	Resistance to Verticillium wilt, Fusarium wilt, RKN and tolerant to abiotic stresses.
Brinjal	*S. khasianum; S. viarum*	Resistant to shoot and fruit borer (BSFB)
Brinjal	*S. xanthocarpum*	Immune to phomopsis blight
Brinjal	*S. sisymbriifolium*	Resistant to little leaf
Brinjal	*S. auriculatum*	Immune to little leaf disease
Brinjal	*S. sisymbriifolium; S. indicum*	Immune to RKN
Chilli	*C. chinensis; C. baccatum*	Anthracnose resistant species
Chilli	*C. pubescens; C. microcarpum*	Powdery mildew resistance species
Potato	*S. desmissum*	Resistant to late blight
Cucumber	*Cucumishystrix*	Resistant to downy mildew, gummy stem blight, virus and nematode
Muskmelon	*Cucumismelo var. momordica*	Resistant to DM and PM
Muskmelon	*Cucumistrigonus*	Resistant to fruit fly
Muskmelon	*C. anguria; C. Ficifolia; C. metuliferus*	Resistant to nematode
Pumpkin	*Cucurbita lundelliana*	Resistant to powdery mildew
Wax gourd	*Benincasahispida*	Resistance to Fusarium wilt

Source: (Kumar *et al*., 2021)

Conclusion

Vegetable grafting is a horticultural technique that helps in sustainable crop production. The intricate cellular choreography of cambial alignment, callus proliferation, and vascular integration demonstrates the remarkable plasticity of herbaceous species. By utilizing the defensive capabilities of specialized rootstocks, modern agriculture can protect crops against destructive soilborne pathogens and environmental stresses without chemical soil fumigants. The development of dual-harvest plantslikeBrimato and Pomato opens new avenues for maximizing food output, vegetable grafting will remain as an essential asset for ensuring global food security, improving crop resilience, and advancing eco-friendly agricultural practices.

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WATER USE EFFICIENCY IN CROPS: PRODUCING MORE WITH LESS WATER

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Abstract

Water is essential for agriculture, but its availability is declining due to climate change, population growth, and increasing pressure on freshwater resources. Water Use Efficiency (WUE) helps crops produce higher yields with less water, improving productivity, drought resilience, and sustainability. Adopting practices such as drought-tolerant varieties, precision irrigation, mulching, conservation agriculture, and digital technologies can help farmers maximize crop production while conserving water resources.

Keywords: Water Use Efficiency, Climate Change, Irrigation, Drought Tolerance, Crop Productivity, Sustainable Agriculture

Introduction

Water is often called the lifeblood of agriculture because it is essential for seed germination, nutrient transport, photosynthesis, and plant growth. However, increasing water scarcity has become a major challenge for agriculture worldwide. Climate change, erratic rainfall, declining groundwater levels, and rising food demand have intensified the need to produce more with less water. In this context, Water Use Efficiency (WUE) has emerged as a key concept in sustainable agriculture. It focuses on maximizing crop yield while minimizing water consumption. Improving WUE is not merely about reducing irrigation but about ensuring that every drop of water contributes effectively to crop production.

Understanding Water Use Efficiency

Water Use Efficiency is commonly defined as the amount of crop yield produced per unit of water used.

$$\text{WUE} = \text{Crop Yield} \div \text{Water Used}$$

A crop with high WUE produces greater biomass or economic yield using the same amount of water compared to a less efficient crop. WUE can be assessed at different levels, including leaf, plant, and field scales. The ultimate goal is to improve productivity without wasting precious water resources.

Why Water Use Efficiency Matters

Water scarcity is becoming one of the biggest constraints to agricultural growth. Improving WUE offers several important benefits:

- Higher productivity under limited water conditions.
- Reduced irrigation costs.
- Improved drought tolerance.
- Better nutrient utilization.

- Conservation of groundwater resources.
- Enhanced sustainability and climate resilience.

As water resources become increasingly scarce, improving WUE will be essential for ensuring future food security.

Water and Plant Growth
Water plays several vital roles in crop growth and development.

Photosynthesis
Water is a raw material for photosynthesis, the process by which plants produce food using sunlight and carbon dioxide. Efficient water availability supports higher photosynthetic activity and better yield formation.

Nutrient Transport
Water acts as a medium for transporting nutrients from the soil to various plant parts. Insufficient water limits nutrient uptake and affects plant growth.

Cell Expansion
Plant growth depends on cell enlargement, which requires adequate water to maintain cell turgor pressure. Water deficiency can restrict leaf development and reduce biomass accumulation.

Temperature Regulation
Plants lose water through transpiration, which helps cool leaves and maintain favorable temperatures, especially during hot weather.

Physiological Basis of Water Use Efficiency
Stomatal Regulation
Stomata are tiny pores on leaf surfaces that regulate the exchange of carbon dioxide and water vapor. Efficient stomatal control enables plants to absorb carbon dioxide for photosynthesis while minimizing excessive water loss.

Photosynthetic Efficiency
Plants capable of maintaining higher photosynthetic rates with lower water consumption generally exhibit superior WUE. Improving photosynthetic efficiency is considered one of the most promising approaches for enhancing crop productivity under water-limited conditions.

Root System Development
Deep and extensive root systems enable crops to access moisture from deeper soil layers. Crops with stronger root systems often perform better during drought and exhibit improved water-use efficiency.

Water Use Efficiency in Different Crop Types
C3 Crops
Rice, wheat, soybean, and potato belong to the C3 group. These crops generally have lower WUE because they experience greater photorespiration, particularly under high temperatures.

C4 Crops
Maize, sorghum, pearl millet, and sugarcane are C4 crops. Their specialized photosynthetic mechanism allows them to use water more efficiently and perform better under hot and dry conditions.

CAM Plants

Plants such as pineapple and cactus exhibit exceptionally high WUE because they open their stomata mainly at night, reducing daytime water loss.

Factors Affecting Water Use Efficiency

Several environmental and management factors influence WUE:

Climate

High temperatures, low humidity, and strong winds increase water loss through transpiration and reduce water-use efficiency.

Soil Health

Soils rich in organic matter retain more moisture and provide a favorable environment for root growth, thereby improving WUE.

Crop Variety

Different varieties vary in rooting depth, drought tolerance, canopy architecture, and stomatal behaviour. Selecting suitable cultivars can significantly improve water productivity.

Nutrient Management

Balanced nutrient application enhances photosynthesis, root growth, and biomass production, resulting in better water-use efficiency.

Practical Strategies to Improve Water Use Efficiency

Drought-Tolerant Varieties

Cultivars with improved root systems and stress tolerance can maintain productivity under water-limited conditions.

Precision Irrigation

Precision irrigation applies water according to crop needs rather than fixed schedules. This approach reduces water wastage and improves irrigation efficiency.

Drip Irrigation

Drip irrigation delivers water directly to the root zone, minimizing evaporation losses and improving water productivity. It is one of the most effective methods for enhancing WUE.

Mulching

Applying organic or synthetic mulch reduces soil evaporation, conserves moisture, suppresses weeds, and improves soil health.

Conservation Agriculture

Practices such as minimum tillage, crop residue retention, and crop rotation improve soil structure and moisture storage, leading to better water-use efficiency.

Rainwater Harvesting

Collecting and storing rainwater provides an additional water source during dry periods and enhances resilience in rainfed farming systems.

Climate Change and Water Use Efficiency

Climate change is expected to intensify water scarcity through rising temperatures and irregular rainfall patterns. Increased evaporative demand will raise crop water requirements, making efficient water management even more important. Climate-smart agricultural practices such as drought-tolerant varieties, precision irrigation, improved soil management, and digital farming technologies will play a crucial role in adapting agriculture to future challenges.

Future Prospects

Advances in crop physiology, genetics, and digital agriculture are improving water use efficiency in crops. Researchers are developing deep-rooted and drought-tolerant varieties while enhancing photosynthetic efficiency through breeding and gene-editing technologies. Additionally, artificial intelligence and remote sensing are helping farmers optimize irrigation and monitor crop water status, leading to higher productivity with reduced water use.

Conclusion

Water Use Efficiency is a cornerstone of sustainable agriculture in an era of increasing water scarcity and climate uncertainty. By understanding the physiological processes governing water use and adopting improved management practices, farmers can produce higher yields with limited water resources. Technologies such as drip irrigation, precision farming, conservation agriculture, and climate-resilient crop varieties provide practical solutions for improving WUE. The future of agriculture will depend not only on increasing production but also on maximizing the productivity of every drop of water, ensuring food security and environmental sustainability for generations to come.

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WHO WILL FEED INDIA? THE VANISHING FARMER AND YOUTH EXODUS FROM AGRICULTURE

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Abstract

The declining participation of youth in Indian agriculture has emerged as a critical challenge for the future of food security, rural livelihoods and sustainable development. This article examines the economic, social and structural factors driving young people away from farming in India. Although agriculture continues to employ over 43 per cent of the workforce, its contribution to India's GDP has declined to nearly 15 per cent, creating a severe imbalance between labour dependence and economic returns. Census and PLFS data reveal a steady decline in cultivators alongside a sharp rise in agricultural labourers, indicating distress-driven transitions within the rural economy. Low and unstable farm incomes, shrinking landholdings, rising production risks, indebtedness and limited access to institutional support have made farming economically unattractive for younger generations. Education, urban exposure and changing aspirations have further encouraged youth to seek non-farm employment, often in informal urban sectors offering greater social status and income security. The article also highlights the feminisation of agriculture, where women increasingly manage farms without adequate ownership rights or institutional support. Despite several government interventions such as PM-KISAN, MSP and crop insurance schemes, structural challenges remain unresolved. The study argues that reversing youth disengagement requires a comprehensive policy approach focused on improving agricultural profitability, land consolidation, infrastructure development, technological innovation and rural non-farm employment opportunities. The future sustainability of Indian agriculture depends on making farming a viable, dignified and aspirational livelihood for the younger generation.

Keywords: Youth Migration, Agricultural workforce, Agrarian crisis, Rural livelihoods, Farm Income, Structural Transformation, Youth Employment, Indian Agriculture

Introduction

The question of who will grow our food in coming decades is the most pressing challenges facing global food security. Agriculture, once the primary employer of humanity, is experiencing a demographic transformation with an aging workforce and declining youth participation threatening food production system world-wide.

In the United States, the average age of farmers reached 58.1 years in the 2022 census of agriculture (USDA NASS, 2022). The situation is more acute in Japan, where the average of farmers is 67 years with projections that 1.3 million hectares could fall out of production by 2035 (MAFF Japan, 2024). In the EU, the farmers over 65 constitutes 31 per cent of the workforce, while those under 35 represent only 5.6 per cent (Eurostat, 2023). Whereas India does not face the acute graying seen in the West and Japan as the average Indian farmer is roughly 20 years younger than the average American farmer and 25+ years younger than Japanese farmer (Narayanan *et al*., 2024). However, the challenge in India is not an aging workforce but attrition of youth as they seek non-farm employment, leaving behind agriculture sector that questions about future succession and viability. The consequences of this demographic shift and farmland consolidation into ever-larger operations threatens the diversity of agricultural systems.

India's relationship with agriculture is deeply rooted in its civilizational memory. For millennia, farming has been more than an economic activity; it has been a way of millennia, farming has been more than an economic activity; it has been a way of life, a cultural identity and the foundation upon which the Indian economy was built. At the time of independence in 1947, agriculture contributed over 50 per cent of the country's Gross Domestic Product (GDP) and employed more than 70 per cent of the workforce. Today, that picture has transformed dramatically. While agriculture's share in GDP has fallen to approximately 15 per cent, it still employs over 43 per cent of the workforce, creating a structural imbalance that has profound implications for productivity, livelihoods and intergenerational mobility (Ministry of Agriculture, 2024).

This disjuncture between output and employment lies at the heart of India's agrarian crisis. The sector has become a reservoir of underemployment, absorbing labour that cannot be productively engaged elsewhere while failing to generate incomes that can sustain dignified livelihoods. For India's youth, who are more educated, more connected and more aspirational than any previous generation, the arithmetic of farming simply does not add up. This article presents an evidence-based analysis of why young people are leaving farming in India, drawing upon official statistics, scholarly research and on-the-ground studies to construct a comprehensive picture of this transformative phenomenon.

Declining agricultural workforce

The data on India's shifting occupational structure tells a compelling story of structural transformation, albeit one marked by distress rather than smooth transition. According to the Census of India, the proportion of the workforce engaged in agriculture (including both cultivators and agricultural labourers) declined from 58.2 per cent in 2001 to 54.6 per cent in 2011. While this may seem like a modest decline, the absolute numbers reveal a more dramatic shift. The total number of cultivators, those who owned or leased land and worked on it as self-employed farmers, fell from 127.6 million in 2001 to 118.7 million in 2011, a decline of 8.9 million, or approximately 7 per cent (Census of India, 2011).

The trend accelerated in the subsequent decade. The Periodic Labour Force Survey (PLFS) 2023-24 estimates indicate that the share of the workforce in agriculture has further declined to approximately 43.5 per cent. This represents a decline of nearly 15 per centage points from 2001 levels, translating to millions of workers shifting out of agriculture over two decades. However, it is critical to note that this decline in the agricultural workforce share has not been accompanied by a proportional decline in the absolute number of agricultural workers, due to overall workforce growth. What has changed is the composition, with new labour force entrants, particularly the youth, choosing non-agricultural occupations in far greater numbers than their predecessors.

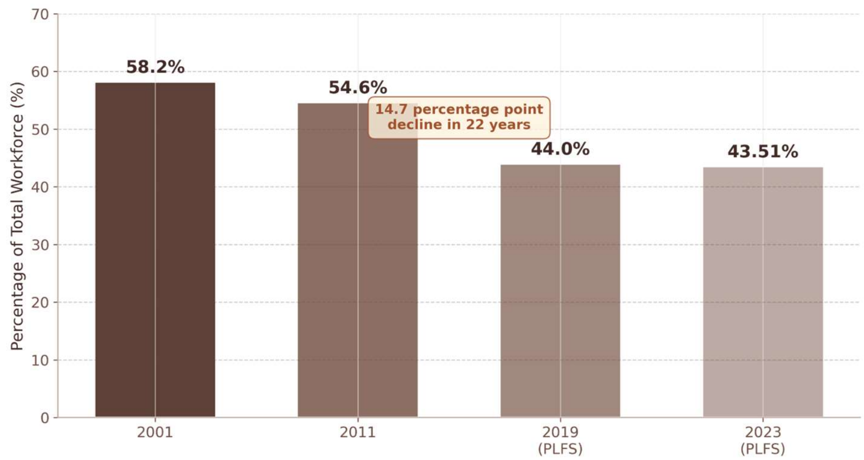

Fig. 1: Decline in Agricultural workforce share in India, 2001-2023.
Source: Census of India (2001, 2011); PLFS (2019,2023).

Cultivators versus Laborers

Perhaps the most significant trend visible in the Census data is the dramatic restructuring within the agricultural workforce itself. While the number of cultivators declined by 8.9 million between 2001 and 2011, the number of agricultural labourers increased by a staggering 36.9 million, from 107.4 million to 144.3 million. For the first time since independence, agricultural labourers outnumbered cultivators, fundamentally altering the social and economic character of the Indian countryside (Srivastava, 2016).

This shift from cultivation to wage labour represents a distress-driven proletarianization rather than a positive structural transformation. Many of those leaving cultivation are not moving to better-paying, more productive employment in manufacturing or services. Instead, they are joining the ranks of agricultural labourers, working on others' farms for subsistence wages. According to analysis by P. Sainath based on Census 2011 data, India was losing approximately 2,000 farmers every day during the 2001-2011 decade. The average size of operational holdings has been declining steadily, with 68 per cent of farmers now owning less than one hectare of land, making farming economically unviable for the vast majority (Sainath, 2013).

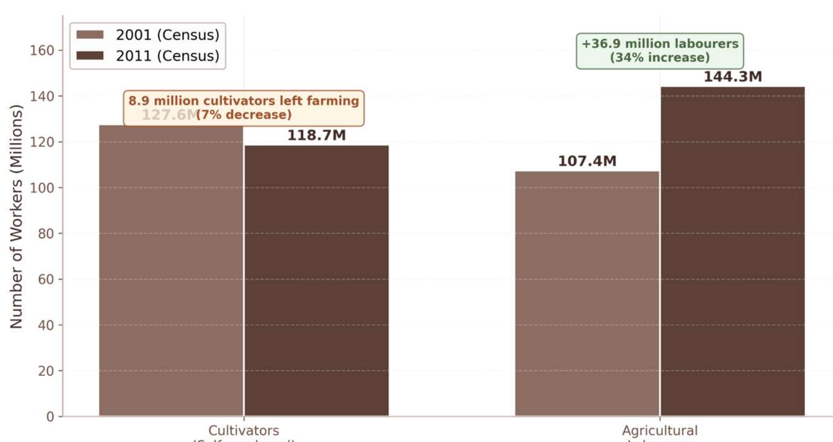

Fig. 2: The changing face of Indian agriculture: Cultivators decline while laborers' surge
Source: Census of India (2001, 2011)

The income crisis

At the core of youth disengagement from agriculture lies a fundamental economic reality: farming in India does not pay enough. The National Sample Survey Office (NSSO) Situation Assessment Survey (SAS) of Agricultural Households provides the most authoritative data on farmer incomes in India. According to the 77th round (January-December 2019), the average monthly income per agricultural household during the agricultural year July 2018-June 2019 was Rs. 10,218 (approximately USD 123 at prevailing exchange rates). While this represented a nominal increase from Rs. 6,426 recorded in the 70th round (2012-13), the real income growth, adjusted for inflation, has been marginal or stagnant for many categories of farmers (NSSO, 2021).

To put this figure in perspective, the average monthly income of an agricultural household in 2018-19 was less than the minimum wage for unskilled labour in most Indian states. The Sasakawa India Leprosy Foundation's annual survey of marginal farmers found that the average income of a farming family in more than half of India's states was a meagre Rs. 20,000 annually, which is not even 10 per cent of India's average per capita income (Birthal *et al*., 2023). The 2016 Economic Survey of India noted that the average income of a farming household was lower than their average consumption expenditure, implying that farmers were sinking into debt merely to survive.

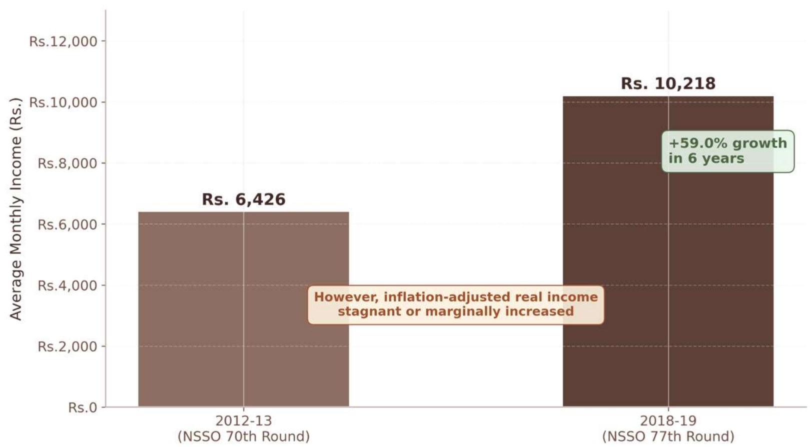

Fig. 3: Average monthly income of agricultural households in India
Source: NSSO, 2020

The income crisis is compounded by extreme volatility. Indian agriculture remains heavily dependent on the monsoon, with nearly 60 per cent of cultivated area still rainfed. Crop failures due to drought, flood, or pest attacks can wipe out an entire season's earnings, pushing farmers into debt. The lack of adequate crop insurance, price volatility and the absence of effective risk mitigation mechanisms make farming an inherently risky proposition. As Agarwal and Agrawal (2022) observe in their study of Indian farmers in transition, older farmers tend to be more satisfied with farming than younger ones, suggesting a generational shift in perception. Being educated above secondary school is linked with greater dissatisfaction and the same holds true for families owning pucca (concrete) houses, indicators of relative prosperity that seem to raise aspirations beyond what farming can fulfil.

Why youth are leaving: Root causes

The economic factors driving youth away from agriculture are multifaceted and deeply structural. First and foremost is the question of land. With India's population growing and land being divided through inheritance across generations, the average farm size has been shrinking continuously. According to the Agriculture Census 2015-16, the average operational holding in India was just 1.08 hectares, down from 2.28 hectares in 1970-71. Small and marginal farmers (those with less than 2 hectares) accounted for 86.2 per cent of all farm holdings but operated only 47.3 per cent of the total cultivated area. For a young person inheriting a fraction of a hectare, the economic viability of full-time farming is questionable at best.

The second economic factor is the widening gap between farm and non-farm incomes. According to research by Pratap S. Birthal at the National Institute of Agricultural Economics and Policy Research, 40 per cent of farmers dislike farming as a profession because of low profits, high risk and lack of social status. The income differential between farm and non-farm work has been widening, particularly with the growth of the services sector and construction industry. Even low-skilled non-farm jobs often offer more predictable incomes, regular wages and some form of social security, however minimal. A young person working at a construction site or a textile factory in a town earns more, with greater certainty, than they would cultivating a marginal plot of land.

Third, the capital intensity of modern agriculture creates barriers to entry for youth. Mechanisation, improved seeds, irrigation and other productivity-enhancing inputs require capital that young farmers typically do not possess. Access to institutional credit remains a persistent challenge, with small and marginal farmers often forced to rely on informal moneylenders who charge exorbitant interest rates. The promise of doubling farmers' income by 2022, announced by the Government of India in 2016, remained largely unfulfilled, further eroding confidence in the sector's economic potential.

Beyond economics, powerful social forces are reshaping young people's relationship with agriculture. Education, once seen as complementary to farming, has become a vehicle for escaping it. As Agarwal and Agrawal (2022) note in their study based on an all-India survey, education is increasingly perceived as a way of escaping agriculture rather than as complementary to good farming. This represents a fundamental shift in social attitudes. Where previous generations viewed farming as an honourable occupation and a familial duty, today's rural youth, exposed to urban lifestyles through television, smartphones and social media, aspire to jobs that offer not just better incomes but also higher social status.

The stigma associated with farming is a recurring theme in qualitative studies. Research across multiple Indian states has found that young people often describe farming as "tiresome work with little or no pay that fits elderly and poor people who have no other job options." The social prestige attached to white-collar or even blue-collar urban employment far exceeds that of farming. A young man working as a security guard or delivery person in a city may earn only marginally more than he would from farming, but the urban job carries a social cachet that farming does not.

Gender dimensions add further complexity to this narrative. Female farmers are found to be more likely to dislike farming than their male counterparts. As men migrate to non-farm employment, women are increasingly left to manage agricultural operations, a phenomenon researcher have termed the “feminisation of agriculture.” However, women rarely have independent control over land, credit, or decision-making and their agricultural involvement is often characterised by greater drudgery and lower returns. The proportion of women participating in farming is consistently less than that of men and gender gaps persist across all age cohorts (Vijayabaskar *et al*., 2018).

The productivity paradox

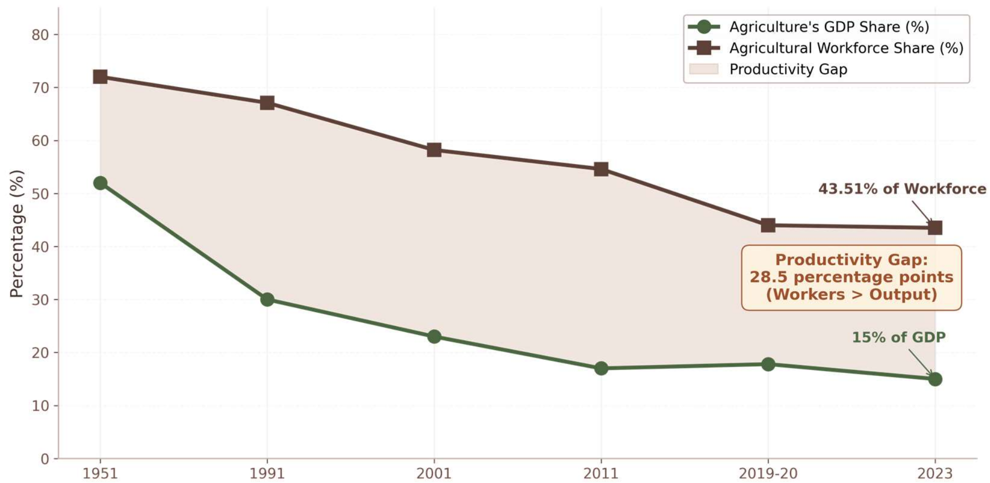

Fig. 4: India's agricultural paradox: GDP contribution versus workforce share (1951-2023)
Source: Ministry of Agriculture; World Bank; PLFS.

India presents a striking paradox in its structural transformation. In most successful developing economies, the movement of labour out of agriculture was accompanied by rising agricultural productivity, enabling fewer farmers to produce more. In India, however, the massive decline in agriculture's share of GDP, from 52 per cent in 1951 to approximately 15 per cent in 2023, has not been matched by a proportional decline in the agricultural workforce. While the GDP share fell by 37 per centage points, the workforce share fell by only about 29 per centage points, leaving a productivity gap of roughly 28 per centage points.

This gap means that agricultural workers in India are significantly less productive than their counterparts in other sectors and in other countries. The large mainly in casual wage work, while the share of regular employment actually declined. This means that even when youth leave agriculture, they often end up in precarious, low-quality employment rather than in productive, formal sector jobs.

The paradox is further deepened by the changing composition within agriculture. The shift from cultivators to labourers noted in Census data is not a positive evolution. Cultivators, despite their small holdings, at least have some autonomy and potential for productivity gains through investment and innovation. Agricultural labourers, by contrast, are among the most vulnerable workers in India, with no job security, no social protection and wages that frequently fall below statutory minimums. The increasing casualisation of agricultural work reflects a deepening distress within the sector rather than a healthy structural transformation.

Policy response and gaps

The Indian government has launched numerous programmes aimed at addressing agrarian distress and making farming more attractive. The Pradhan Mantri Kisan Samman Nidhi (PM-KISAN) provides direct income support of Rs. 6,000 per year to farmer families. The Pradhan Mantri Fasal Bima Yojana (PMFBY) offers crop insurance, while the Minimum Support Price (MSP) mechanism guarantees prices for 23 crops. Subsidised institutional credit, soil health cards and various technology missions are part of the policy architecture.

However, these interventions have had limited success in reversing the youth exodus. The income support from PM-KISAN, while welcome, amounts to only Rs. 500 per month, a fraction of what a young person can earn in even the lowest-paid non-farm job. Crop insurance penetration remains low, with most small farmers either unaware of the schemes or unable to navigate the bureaucratic complexities. The MSP system benefits primarily large farmers in a few states; as Birthal *et al.,* MSP system benefits primarily large farmers in a few states; as Birthal *et al*., (2023) note, only 6 per cent of farmers actually receive guaranteed price support for their crops and more than 90 per cent sell their produce in the open market.

The fundamental policy gap lies in the failure to address structural issues. Land consolidation, investment in irrigation and storage infrastructure, development of farmer producer organisations and most critically, the creation of productive non-farm employment in rural areas, remain largely unaddressed. Without a comprehensive strategy that either makes farming economically viable or creates attractive alternatives for rural youth, the exodus from agriculture is likely to continue.

Conclusion and the way forward

The departure of young people from farming in India is neither a temporary trend nor a simple matter of individual choice. It is the visible manifestation of deep structural crises in the agricultural sector, the rural economy and the broader pattern of India's development. The data tells an unambiguous story: millions of cultivators have left farming, agricultural labourers have surged, farmer incomes remain distressingly low and the gap between agricultural GDP share and workforce share continues to widen. For a generation that is more educated, more connected and more aspirational than any before it, farming has become economically irrational and socially undesirable.

Yet this exodus carries profound risks. A nation that cannot feed itself securely is a nation that cannot claim true sovereignty. The aging of the agricultural workforce, with the average farmer now over 40 years and rising, threatens long-term productivity and innovation in the sector. The feminisation of agriculture without corresponding empowerment of women farmers creates new vulnerabilities. And the absorption of millions of rural youths into precarious urban employment fuels inequality, social tension and environmental stress in already overburdened cities.

Addressing this challenge requires a paradigm shift in agricultural policy. Piecemeal subsidies and income transfers, while providing temporary relief, cannot make farming competitive with non-farm employment. What is needed is a comprehensive approach: investment in irrigation, storage and market infrastructure to reduce risk and increase returns; land reform and consolidation to make holdings viable; investment in agricultural research and extension to raise productivity; and, crucially, the development of a vibrant rural non-farm economy that can absorb young people productively without requiring them to migrate to overcrowded cities.

The question India faces is not whether young people should leave farming, but whether those who remain or choose to enter agriculture can do so with dignity, security and a reasonable hope of prosperity. The answer to that question will determine not just the future of Indian agriculture, but the trajectory of India's development itself.

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STATUS, CHALLENGES, AND FUTURE PROSPECTS OF AGRICULTURE AND ALLIED SECTORS IN WEST GARO HILLS DISTRICT, MEGHALAYA

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Abstract

West Garo Hills district of Meghalaya is predominantly agrarian, with 80% of the population depending on agriculture and allied activities for their livelihood. The district possesses favorable agro climatic conditions, abundant rainfall, diverse farming systems and significant potential for crop and livestock production. However, farmers faced several challenges, including undulating topography, small and fragmented landholdings, low productivity, shifting cultivation, inadequate irrigation facilities, poor market infrastructure, limited adoption of improved technologies, climatic vulnerabilities and unscientific livestock management. These constraints have adversely affected the livelihoods of farmers and hindered sustainable agricultural growth and development of the district. Despite these challenges, the district has a great scope for agricultural development through crop diversification, crop intensification, promotion of high value horticultural crops, adoption of integrated farming systems, expansion area of organic farming, development of mini agro processing units, efficient management of irrigation water, value addition of locally available fruits and vegetables and strengthening of livestock enterprises. Timely supply of quality inputs, scientific production technologies, capacity building programmes, value addition, and market linkages can significantly improve crop productivity and income of the farmers. Research institutions, extension agencies, governmental organizations and local famers of the district should work jointly to transform the agriculture and allied sectors into a productive and sustainable farming system.

Keywords: West Garo Hills, Small and Marginal Farmers, Integrated Farming Systems, Agriculture and Allied Sectors, Sustainable Agriculture

Introduction

West Garo Hills district of Meghalaya lies at a longitude of 89° 40´ to 90°30´E and at a latitude of 25°20' to 26° N which is bordered by districts namely East Garo Hills, South West Garo Hills, South Garo Hills, state Assam and the country Bangladesh. It covers a total area of 281100 ha with net sown area of 67483 ha and forest area of 121876 ha. The district falls under the Sub-tropical humid climatic condition and generally rain starts early of the April and it continues till 1st week of October with a very high speed of wind, thunder and hailstorm and cyclone resulting in crop damage on cashew and others plantation crops every year. The mean annual rainfall ranges from 2000 to 3362 mm and potential evapotranspiration (PET) ranges from 1000 to 1299 mm. The district experiences a water deficit of 300-350 mm due to seasonal dry spells during post-monsoon period. The district shows different types of soil as the provenance differs widely. Red Gravelly Soil and Red Sandy Loam in the hilly slopes and Clayey Loam in the plains are the common soil types. The soils are acidic in nature and comparatively rich in organic matter and nitrogen but poor in phosphorous. The main livelihood occupation for most of the people of the district is agriculture, horticulture and livestock as well as fish farming. The commercial commodities produced in the district are arecanut, cashewnut, paddy, maize, ginger, tuber crops, vegetables and piggery, goatery, dairy and poultry. The major sources of irrigation are through rivers, perennial streams and rainfall**.**

The district is predominantly characterized by small and marginal farmers. The increasing dependence on traditional low output agricultural practices have resulted in economically unviable production systems. Decrease in agricultural productivity due to climatic factors like flood, drought, soil erosion, lack of market opportunities and remoteness; expose them to high production risk as well as low income. Changing climate conditions impeded the continuous water availability in most countries of the world, which further impacted the sustenance of conventional irrigation practices (Du *et al*., 2015). Limited awareness and adoption of modern agricultural technologies, inadequate use of irrigation facilities, high yielding variety (HYV) seeds, fertility management, plant protection measures, and improved crop management practices, have contributed to low agricultural productivity and farm income. These challenges have adversely affected the livelihood of farmers' especially small and marginal farmers of the district. In view of the above facts, the agricultural developmental issues of the district are very complex. Nevertheless, Meghalaya's strong base of indigenous knowledge and traditional ecological practices, coupled with a growing interest in sustainable agriculture, presents significant potential for advancing agro ecological transformation in the region (Borah *et al*., 2024). Therefore, a thorough understanding of challenges faced by local farmers of the district and assessment of future opportunities and prospects is very necessary for achieving sustainable agricultural growth and rural development. The main objective of the paper is to identify the challenges in agriculture and allied sectors and to find out solution for future prospects of the district.

Status of Agriculture and Allied Sectors

The economy of West Garo Hills district is basically agrarian in nature with about 80 percent of the population depends on agriculture. Paddy is the major crop followed by maize. The agro climatic conditions of the district are conducive for various agricultural activities. According to 2011 census, agriculture provides full time employment to 13.56 per cent of total workers. There are about 189544 cultivators and 22472 agricultural labourers in the district. Heterogeneity in cultivation practices and diversity of cropping patterns are the important features of agriculture in the district. The details of land use pattern of the district other than forests are given in Table 1. Percentage of different landuse pattern of the district is depicted in Fig. 1**.**

Table 1. Land use pattern of West Garo Hills District (2022-23)

Classification of Land	Area (ha)
Total geographical Area	281100
Net area sown	67483
Area sown more than once	13060
Total cropped area	80543
Area under non-agricultural uses	14959
Barren and uncultivable land	4232
Land under misc. trees, crops and groves	18142
Cultivable waste lands	12981
Fallow land other than current fallows	22366
Current fallows	7986

Source: *Handbook on area, production and yield of principal crops in Meghalaya, 2025, Directorate of Economics & Statistics, Government of Meghalaya*

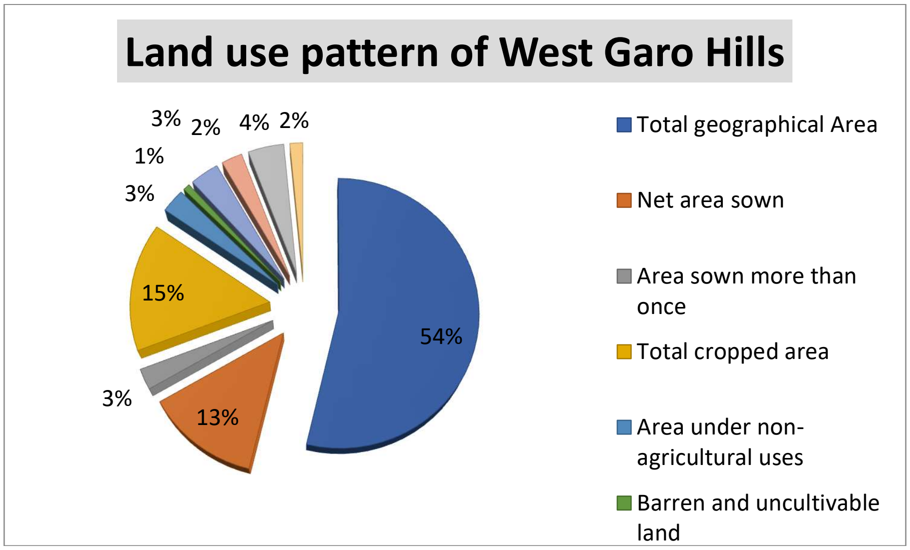

Fig. 1. Landuse pattern of West Garo Hills district, Meghalaya (2022-23)

As per the Agricultural statistics, Government of Meghalaya (2023-24), major area is covered under rice, arecanut, rapeseed & mustard followed by cashewnut, pineapple and maize. Among the horticultural crops, cashewnut, pineapple, ginger, tapioca, and citrus were the dominant crops, accounting for the major proportion of the area under horticultural cultivation in the district as shown in Table 2.

Table 2. Area, production and productivity of principal crops of the district (2023-24)

Sl. No.	Name of Crop	Area(ha)	Prod.(MT)	Yield (kg/ha)
1.	Sali Paddy	14859	38411	2585
2.	Autumn (Ahu) Paddy	5000	9840	1968
3.	Spring Paddy	7493	34298	4577
4.	Wheat	128	236	1844
5.	Maize	2726	4265	1565
6.	Small Millets	1117	733	656
7.	Gram Pulses	766	810	1057
8.	Tur Arhar	598	855	1430
9.	Rabi Pulses	2224	3159	1420
10.	Jute	1885	17236	1646
11.	Mesta	1160	4725.8	733
12.	Cotton	515	506	167
13.	Potato	363	2756	14710.2
14.	Sugarcane	28	99	3536
15.	Tapioca	1168	6745	5775
16.	Arecanut	9542	17763	1862
17.	Cashewnut	4013	5683	1416
18.	Pineapple	2978	28462	9557
19.	Banana	1586	21638	13643

Sl. No.	Name of Crop	Area(ha)	Prod.(MT)	Yield (kg/ha)
20.	Papaya	155	1508	9729
21.	Citrus fruits	2515	6411	2549
22.	Blackpepper	427	287	672
23.	Ginger	2412	11360	4710
24.	Turmeric	407	2487	6111
25.	Chillies	959	790	824
26.	Linseed	80	47	588
27.	Rapeseed & Mustard	5473	5388	984
28.	Sesamum	1100	1034	940
29.	Sweet potato	410	1510	3683
30.	Cabbage	175	2013	11503
31.	Cauliflower	184	1691	9190
32.	Radish	173	2515	14538
33.	Tomato	174	3216	18483
34.	Carrot	96	1403	14615
35.	Cucumber	104	1009	9702
36.	Capsicum	109	1025	9404
37.	Beans	139	1444	10388
38.	Brinjal	194	3748	19320
39.	Pumpkin	170	2538	14929
40.	Ridge Gourd	124	1838	14823
41.	Broccolli	58	597	10293

Source: *Handbook on area, production and yield of principal crops in Meghalaya, 2025, Directorate of Economics & Statistics, Government of Meghalaya*

The majority of farmers in the district practice subsistence agriculture. The crop production is primarily intended for household consumption, leaving little or no marketable surplus for sale. Traditional farming methods are predominantly followed, with no application of chemical fertilizers, pesticides, insecticides, and other agrochemicals. Rice is the principal staple food crop cultivated in the district and occupies the largest share of the cultivated area. The major farming systems prevalent in the district are presented in Table 3.

Table 3. Farming system prevalent in West Garo Hills district, Meghalaya

Farming system	Soil Texture	Principal crops/breeds
Jhum mixed farming system	Sandy loam	Rice, maize, small millets, pulses, vegetables, tuber crops
Agri-horti-pisci-livestock	Sandy clay loam	Paddy, summer & winter vegetables, oilseeds, pulses, Indian major & minor carps, poultry birds, milch cattle, goat, pig, duck etc.
Horti-agri-livestock	Sandy loam	Paddy, summer & winter vegetables, oilseeds,

Farming system	Soil Texture	Principal crops/breeds
		pulses, poultry birds,
Agriculture	Sandy loam	Paddy, vegetables, Paddy-paddy system
Livestock	-	Poultry birds and pig
Horti-pisci-agriculture	Clay loam	Paddy, summer & winter vegetables, Indian major & minor carps
Livestock-agri-horticulture	Sandy clay loam	Pig, goat, poultry birds, paddy, mustard, maize, colocasia, banana, pine apple
Agri-horti-silvi-pastoral-livestock	Sandy clay loam	Rubber, pineapple, banana, teak, karoi, bamboo, citrus
Plantation	Sandy clay loam	Cashew nut, rubber and tea
Plantation-pisci-livestock	Sandy clay loam	Rubber, pig, poultry bird.
Horticulture	Sandy clay loam	Summer and winter vegetables

Livestock is an important sector in the district. Pig is the most preferred animal for the farmers. Pig rearing is a common practice among the villagers, with nearly every household maintaining one or two pigs to meet emergency financial needs. Landless and marginal farmers rear pigs, poultry and goats as their alternate livelihood. Due to food habit, consumption of milk and milk products is less in the district. Very few tribal farmers are engaged in crossbred cows rearing, hence milk production is very less in Garo Hills. There is about 223021 cattle population including 913 only numbers cross bred. Though, over the years the number of cross bred cattle is increasing. The details of livestock and poultry population are furnished in Table 4 and 5.

Table 4. Livestock population in the district

Sl. No.	Name of livestock	Cross	Indigenous	Total (in nos.)
1	Cattle	913	222108	223021
2	Buffalo	-	937	937
3	Sheep	-	10687	10687
4	Goats	-	94962	94962
5	Pigs	114571	3108	117679

Table 5. Poultry population in the district

Sl. No.	Name	Desi	Improved	Total
1	Chicken	1017792	3816	1021608
2	Duck	38505	6715	45220

Source: *20th Livestock Census, Animal Husbandry & Veterinary Department, Meghalaya*

The average yield of different animals in the district is very low as compared to the other parts of the country which is shown in Table 6.

Table 6. Average yield of various animals and bird in the district

Sl. No.	Animal/bird	Average nos. possessed	Average yield (specific units)
1	Cow	6 (Local)	0.5 litre / cow / day
2	Pig	2 (Local)	48 kg body wt. at market age
3	Goat	3 (Local)	2 kids /goat/yr
4	Chicken	8 (Improved)	112 eggs / chicken / year
5	Duck	4 (Local)	80 eggs / duck / year

Major Challenges

Despite of favourable natural resources of the district, farmers faced several constraints that hinder agricultural productivity and income generation. The problem is compounded by unscientific agricultural practices such as shifting cultivation on steep slopes, deforestation, burning etc., which has resulted in soil and water resources degradation. The farmers of the district are mostly small and marginal and mainly practice monocropping, thus neglecting the concept of intercropping and multiple cropping systems leading to low agricultural productivity and insufficient production. The main issues of agriculture faced by farmers are low productivity, inadequate access to appropriate technologies and other external inputs, increased natural calamities. In addition, the high cost of production due to undulating topography is also one of the major constraints in crop cultivation. The low adoption of improved agricultural technologies by local farmers is primarily attributed to inadequate technical knowledge and poor infrastructural support. There exist large variations of organic manures, biofertilizers and biopesticides usage in the district leading to uneven and low crop productivity. Balanced application of these organic manures is necessary to ensure optimum utilization by plants and thereby reducing wastage and loss due to leaching and volatilization. Organic manures like farm Yard Manure (FYM), green manuring crops and compost is widely practiced by farmers, but the use of farmyard manure is much below the desired level. Use of biofertilizers like Rhizobium, Azotobacter, Azospirrillum, Azolla is not widespread and this practice needs to be popularized. Most farmers cultivate crops on leased land systems and do not have the freedom to independently adopt new farming technologies and practices, as the land is owned by others. Irrigation has so far played only a minimal role in agriculture in the district. The topography itself makes alignment and construction of channels difficult and comparatively costly. Lack of proper marketing channels is also a major challenge which leads the farmers of rural areas to face challenges of selling their produce timely and get minimum monetary return from their farm produce. The lack of technical expertise in scientific rearing of livestock among farmers contributes to suboptimal production performance and lower economic returns. The widespread rearing of inferior, nondescript pig breeds by farmers in the district is a major limitation to improving pig production and profitability. Non availability of feed and fodder is also another major problem in livestock production. The feed resources used by farmers in the district are not balanced in terms of protein and energy to meet the nutrient requirement of the animals leading to poor performance. The present scenario of shrinking farm sizes and fragmented landholdings are major constraints to agricultural development, as they hinder efficient resource utilization, mechanization, and adoption of improved farming practices. After harvest, farmers faced difficulty in accessing timely credit flow, poor and inadequate marketing facilities, post harvest losses, and limited opportunities for value addition. Inability to purchase agricultural machineries, scarcity of farm labour due to migration to urban areas, continuous practice of shifting cultivation which degrades soil properties, lack of cold storage facilities and unavailability of land for fodder development are also some problems affecting the growth of agriculture and allied sectors.

Prospects

Prospects and future potentialities of agriculture and allied activities in the district are very vast. Despite many challenges, the district possesses immense opportunities for agricultural development. Crop diversification through introduction of improved variety of high value fruits such as pineapple, dragon fruit, passion fruit, litchi and spices, vegetables and plantation crops can significantly enhance income, employment opportunities, nutritional and livelihood security. Crop diversification will reduce dependence on traditional low return crops, minimizes production risks, and promotes sustainable agricultural development in the district. The promotion and establishment of Integrated Farming System (IFS) models is also one most effective technology especially for small and marginal farmers of the district. The introduction of Horticulture-based IFS models integrating fruit crops, vegetables, duckery and fisheries would enhance farm income, improve household nutrition and increase resilience to climate variability. The farmers of the district can expand more areas under 'boro' paddy wherever feasible, in order to productively utilize cultivable fallow land. Promotion of organic farming practices through the increased use of organic manures, biofertilizers, and biopesticides should be prioritized in the district. In line with the Meghalaya State ongoing transition towards organic agriculture under the 'Mission Organic' programme, the district has considerable potential for expanding organic cultivation in suitable crops across different locations. The district has immense potential for the establishment of small and medium scale processing units for locally available crops such as pineapple, ginger, turmeric, citrus, banana, arecanut and cashewnut. Strengthening processing infrastructure, including grading, packaging, storage, and marketing facilities with promotion of agri entrepreneurship and farmer producer organizations can further support rural employment generation and economic growth in the district. Interventions on development and management of micro watersheds can help mitigate water scarcity during the post monsoon season improve agricultural productivity; improve soil and water conservation, and efficient natural resource management. More emphasis should be given on cultivation of rapeseed, mustard and pulse crops in cultivable fallow lands after the harvest of paddy. In addition, related Government organizations in the district should conduct more awareness and capacity building programmes to enhance farmers' knowledge and skills regarding improved agricultural technologies, sustainable farming practices, and market opportunities. The district obtains feasible climatic conditions for fodder planting in the field of sustainable livestock farming. There is a great scope for expansion of piggery, poultry, goat rearing, and dairy farming under the integrated farming system models. Popularization of improved and disease resistant breeds of cattle, pigs, goat and poultry will contribute to employment generation to rural youths of the district. Further, establishment of collection centers, livestock markets, slaughter facilities, cold chains and value addition units would improve market access and profitability in the district.

Conclusion

West Garo Hills district, Meghalaya is predominantly agrarian and majority of the workforce are engaged in agriculture and allied sector for their livelihood. The district is endowed with favorable agro climatic conditions, abundant rainfall, diverse farming systems, and considerable scope for crop and livestock production. However, agricultural development is constrained by several factors such as undulating topography, inadequate irrigation facilities, low productivity, fragmented landholdings, shifting cultivation, poor market infrastructure, limited adoption of improved technologies, and deficiencies in livestock management and fodder resources. Despite these challenges, the district possesses immense potential for sustainable agricultural growth through diversification towards cultivation of high value crops, promotion of organic farming practices, adoption of integrated farming systems, development of mini agro processing units, efficient irrigation water management, and strengthening of livestock enterprises. Improved access to quality inputs, scientific production technologies, capacity building programmes, value addition, and market linkages can significantly enhance farm productivity, income, and employment opportunities. With collaborative efforts from farmers, research institutions, extension agencies, and government organizations, the agriculture and allied sectors of West Garo Hills district can be transformed into a more productive and sustainable, thereby improving the livelihood and nutritional security of Garo Hills farming community.

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RAISING A HEALTHY PADDY NURSERY: KEY PRECAUTIONS FOR HIGHER *KHARIF* YIELDS

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Introduction

Rice contributes more than 40% of India's total food grain production and plays a similarly vital role in ensuring food security across South and Southeast Asia. Despite its importance, substantial yield gaps continue to persist on millions of smallholder farms. A significant portion of these losses can often be traced back to the nursery stage, where poor germination, weak root development, pest infestation, and disease-prone seedlings limit the crop's productive potential from the very beginning. A successful paddy crop therefore starts long before the seedlings are transplanted into the puddled field it begins with a healthy nursery. For *Kharif* rice growers, the nursery serves as the foundation for uniform crop establishment, efficient nutrient uptake, vigorous growth and greater resilience to biotic and abiotic stresses. Careful attention and timely management during this critical stage can yield substantial benefits later in the season, including higher tillering, uniform crop maturity, reduced need for gap filling, and increased grain yield. This article highlights practical and field-tested precautions for raising robust paddy nurseries that lay the groundwork for a productive and profitable *Kharif* rice harvest.

Site selection and land preparation

- Choose a well-drained, level site near the main field to reduce seedling handling and transplanting shock. Proximity saves time and avoids root damage.
- Prepare nursery beds (or mats) on raised, levelled soil. Smooth the surface to ensure uniform water spread and even seedling growth.
- If using seedbeds, make them 4-6 m long and 1.0-1.2 m wide for easier management and access.

Seed quality and treatment

- Use certified, disease-free seed of recommended high-yielding varieties or hybrids suited to your ecology and market. Seed vigor matters as much as variety.
- Treat seed to reduce fungal and bacterial problems: recommended treatments include hot water treatment (detailed by local extension) or seed-soaking with approved fungicides/biologicals following label instructions.
- If seed-borne pests are known locally, consider nursery-stage treatments like Trichoderma or appropriate seed dressings that are permitted and safe.

Sowing methods and seed rate

- Choose method based on labour and desired transplanting age: line sowing for easier thinning and monitoring, or broadcasting for large, small-seeded varieties.

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- For transplanted rice, aim for 18–25 kg/ha of seed for well-timed single transplanting (adjust for variety and sowing method). Over-seeding increases competition and weakens seedlings.
- Ensure even distribution; mix seed with sand for uniform spread when broadcasting.

Water management

- Maintain a thin film of water (3–5 mm) for the first few days to ensure good germination. Avoid waterlogging that causes oxygen stress and fungal growth.
- After emergence, allow the surface to dry slightly between irrigations to toughen seedlings and reduce incidence of sheath blight and fungal pests.
- For mat nurseries, manage water level so that seedlings develop strong root systems without being submerged continuously.

Nutrition and soil fertility

- Apply basal manure or compost during bed preparation: 2–3 kg of well-decomposed farmyard manure per square meter helps root growth.
- Use starter doses of balanced NPK as per local recommendations too much nitrogen in the nursery results in spindly, weak seedlings. For many *Kharif* nurseries a light N application (e.g., 10–15 kg N/ha equivalent) combined with P and K as needed is adequate.
- Consider foliar micronutrient sprays (zinc, boron) if soils are deficient; these improve seedling vigour and reduce later deficiency risks.

Pest, disease and weed precautions

- Monitor daily, especially in warm, humid *Kharif* conditions that favour diseases and insect pests.
- Preventive measures: maintain good spacing, avoid excessive nitrogen, and ensure adequate drainage to reduce sheath blight and blast risk.
- Use sticky yellow traps or light monitoring to detect early pest presence. For severe infestations, follow recommended integrated pest management (IPM) measures biocontrols first, pesticides only when economic thresholds are reached.
- Keep the nursery weed-free through hand weeding early; weeds compete strongly with tender seedlings.

Seedling age and hardening

- Transplant seedlings at the recommended age for the variety (commonly 20-30 days old or at 4-5 leaf stage for many types). Younger seedlings may tiller well but increase transplanting shock; older seedlings become root-bound and lose yield potential.
- Harden seedlings 7-10 days before transplanting by reducing water slightly and, if possible, avoiding heavy fertilizers. Hardening improves resistance to transplant shock, drought and pests. (Kapur *et al.,* 2020)

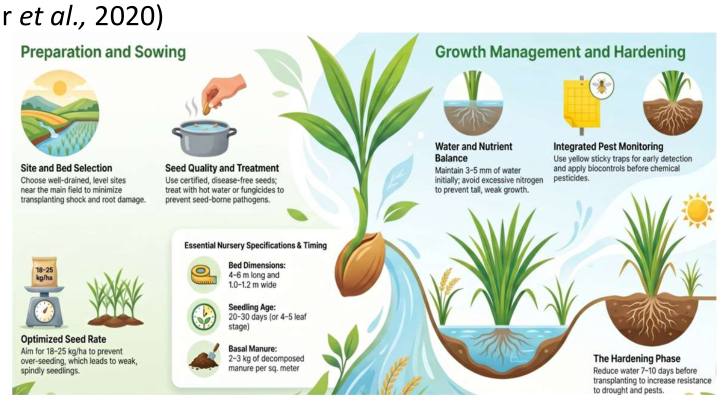

Fig1. Diagram Showing the Stages of Raising Healthy Nursery

Sanitation and hygiene

- Clean tools, and avoid bringing infected straw, hay or soggy debris into the nursery area to reduce disease spread.
- If using trays or mats repeatedly, sanitize or sun-heat them between crops. Rotate nursery location if disease pressure persists.

Transplanting tips

- Transplant during cooler parts of the day (morning or late afternoon) to reduce shock.
- Maintain uniform spacing in the main field to ensure equal resource distribution; this depends on the seedling age and variety.
- Avoid piling or trampling seedlings during transport carry trays with care and transplant as soon as possible.

Small-scale innovations and cost-saving options

- Use mat nurseries or floating nurseries where waterlogged fields are common; mats reduce root damage and facilitate rapid establishment.
- For smallholders, paper or straw trays and raised beds conserve seed and space while producing uniform seedlings.
- Employ low-cost biostimulants (based on local evidence and extension recommendations) to boost vigor; test them on a small scale before widespread use.

Common mistakes to avoid

- Over-applying nitrogen in nursery beds, creating tall, weak seedlings.
- Delayed transplanting leaving seedlings root-bound and reducing tillering potential.
- Ignoring early disease signs and failing to act until the problem spreads to the main crop.
- Using low-quality seed or untested seed sources.

Conclusion

A well-managed nursery is a high-return investment for *Kharif* rice growers. By selecting quality seed, preparing a level nursery site, managing water and nutrients carefully and watching vigilantly for pests and diseases, you create seedlings that transplant well and reach their yield potential. Small changes timely hardening, correct seed rates, simple sanitation and record-keeping combine to deliver more uniform stands, reduced crop failures and better grain yields.

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SHRIMP HEAD WASTE: A VALUABLE FOOD INGREDIENT AND SUSTAINABLE APPROACH TO SEAFOOD INNOVATION

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Abstract

The industrial seafood processing sector generates massive quantities of shrimp by-products, primarily consisting of heads and shells. Although traditionally discarded as environmental pollutants, recent scientific investigations reveal that these processing residues are actually rich reservoirs of essential proteins, amino acids, bioactive carotenoids, and chitin. Driven by advanced bio-processing technologies, researchers and food scientists are now converting these marine by-products into high-value functional ingredients, including natural flavour powders and protein concentrates. Integrating these nutrient-dense extracts into commercial food formulations—such as fortified noodles, snacks, and crackers—significantly enhances their nutritional profiles and sensory characteristics. Ultimately, this circular "waste-to-wealth" strategy mitigates the ecological footprint of seafood disposal, optimises resource efficiency, and unlocks new economic avenues for sustainable food production systems.

Keywords: Shrimp-heads, Shrimp waste, Flavour, Noodles.

Introduction

Seafood is a global dietary cornerstone, supplying essential proteins, lipids, and micronutrients. However, shifting consumer demands toward convenience foods coincide with a critical industrial challenge: the generation of massive volumes of processing waste. In shrimp processing, unutilized heads, shells, and tails constitute up to 50% of the raw biomass. Historically discarded, this mismanagement poses severe ecological liabilities.

Recent bio-resource research redefines these processing residues not as waste, but as dense matrices of structural polymers, carotenoids, minerals, and bioactive proteins. Shrimp cephalothoraxes (heads) and exoskeletons are particularly rich in chitin, chitosan, and astaxanthin, alongside high-value amino acids. Recovering these components offers a dual pathway to mitigate environmental degradation and advance circular economy models within global fisheries.

A prominent innovation in this field is the synthesis of natural seafood flavour powders. Shrimp heads contain high concentrations of endogenous glutamic acid, the primary driver of the savory umami palate. Utilizing advanced processing methodologies—such as targeted enzymatic hydrolysis, thermal dehydration, and spray drying—scientists can convert this volatile biomass into shelf-stable, nutrient-dense flavour concentrates. These powders present a viable, clean-label alternative to synthetic flavour enhancers.

Converting marine processing by-products into functional food ingredients represents a highly efficient closed-loop system. This methodology simultaneously curtails industrial pollution, optimizes resource efficiency, and meets the rising consumer demand for nutrient-fortified, clean-label products. Ultimately, such biotechnological innovations demonstrate how food science can bridge the gap between industrial sustainability and global nutritional security.

Shrimp Waste: An Untapped Resource

The rapid growth of the seafood processing industry has resulted in the generation of substantial quantities of by-products, particularly from shrimp processing. Shrimp heads, shells, and tails can account for nearly 50–60% of the total raw material, posing significant disposal and environmental challenges if not managed properly (Bassig *et al*., 2021; Nirmal *et al.*, 2021). However, recent research has revealed that these by-products are rich sources of proteins, lipids, minerals, carotenoids, chitin, and chitosan, making them valuable raw materials for the development of innovative food and industrial products (Cahu *et al.*, 2012; Kandra *et al.*, 2012).

Instead of being treated as waste, shrimp by-products are increasingly being recognized as a sustainable resource that can contribute to a circular economy. Their utilization not only minimizes environmental pollution but also creates opportunities for generating high-value products from materials that would otherwise be discarded.

Recovery of Valuable Bioactive Compounds

Scientists have made significant progress in extracting valuable compounds from shrimp waste. According to Cahu *et al.*, (2012), shrimp heads can be processed to recover protein hydrolysates, carotenoids, chitin, and chitosan. These compounds possess functional, nutritional, and biological properties that make them useful in food, pharmaceutical, cosmetic, and biotechnology industries.

Similarly, Kandra *et al.*, (2012) emphasized that shrimp waste contains numerous bioactive substances, including amino acids, fatty acids, pigments, and chitin derivatives, which can be utilized in diverse commercial applications. More recently, Nirmal *et al.*, (2021) highlighted emerging uses of shrimp-derived compounds in bioplastics, bioremediation, and eco-friendly energy conversion technologies. These developments demonstrate how seafood processing waste can be transformed into valuable resources while promoting sustainability.

Natural Seafood Flavour Powders

Among the most promising food applications is the production of natural flavour powders from shrimp heads and shells. Shrimp heads possess a characteristic seafood aroma and contain glutamic acid and other flavour-enhancing compounds associated with umami taste. Researchers have developed flavour powders by concentrating shrimp extracts and drying them into stable powdered products. Similar approaches have been applied to tuna processing liquids and other seafood by-products, demonstrating that waste streams can be transformed into ingredients that improve flavour while adding nutritional value.

Studies on shrimp head flavour powders have reported high protein content, good solubility, and favourable sensory acceptance. Different carrier materials such as dextrin, wheat flour, and maltodextrin have been used to optimize powder characteristics, including moisture content, bulk density, and flavour retention. Importantly, these natural flavour powders offer an alternative to excessive reliance on synthetic flavour enhancers and align with consumer demand for cleaner-label food products.

Enhancing Food Products with Shrimp-Derived Ingredients

Seafood-derived flavour powders have been incorporated into a variety of snack foods, including crackers, extruded products, and stick snacks. Research indicates that moderate inclusion levels can enhance aroma, taste, and overall consumer acceptability without negatively affecting product quality. In some formulations, shrimp head extracts have improved crispiness, flavour intensity, and protein content of ready-to-eat snacks. These findings demonstrate that shrimp by-products can serve not only as waste-reduction tools but also as functional ingredients that improve food quality.

Fortification of Noodles: A Nutritious Innovation

Noodles are among the most widely consumed convenience foods worldwide. However, conventional noodles are primarily carbohydrate-based and often deficient in essential amino acids. Researchers have therefore explored the incorporation of seafood-derived ingredients to improve their nutritional profile.

Parvathy *et al.*, (2016) successfully developed fish-fortified noodles with enhanced protein content, while Mahanand *et al.*, (2019) demonstrated that fish protein enrichment improved both nutritional and textural characteristics of extruded noodles. Chowdhury *et al.*, (2020) emphasized that fish-based ingredients provide essential amino acids, omega-3 fatty acids, vitamins, and minerals that are often lacking in cereal-based foods.

Nutritional and Functional Benefits

Beyond flavour enhancement, shrimp-derived ingredients offer significant nutritional benefits. Suparmi *et al.*, (2020) identified seventeen amino acids in shrimp waste flavour powder, including nine essential amino acids and high levels of glutamic acid. Dayakar *et al.*, (2022) reported that caroteno protein powder extracted from shrimp head waste contained more than 86% protein and exhibited strong antioxidant properties, indicating its potential as a functional food ingredient and nutraceutical.

Such products not only improve the nutritional quality of foods but also contribute valuable bioactive compounds that may promote health and well-being.

Towards a Circular and Sustainable Seafood Industry

The conversion of shrimp processing waste into flavour powders, protein concentrates, and fortified food products represents a major advancement in sustainable seafood processing. Studies by Bassig *et al.*, (2021) and Deepika *et al.*, (2022) have demonstrated that many of these products remain stable during storage and possess commercial potential.

As global demand for sustainable and nutritious foods continues to rise, the utilization of shrimp by-products offers a practical solution for reducing waste, conserving resources, and generating economic value. By embracing innovative technologies and value-added product development, the seafood industry can transform an environmental challenge into an opportunity for sustainable growth and food innovation.

Conclusion

Shrimp processing waste, once regarded as a disposal problem, is now emerging as a valuable resource for sustainable food innovation. Research has demonstrated that shrimp heads and shells can be transformed into flavour powders, protein-rich ingredients, and functional food additives with significant nutritional and economic value. The incorporation of these ingredients into products such as snacks and fortified noodles not only enhances flavour and nutrition but also promotes efficient utilization of marine resources. By converting waste into value-added products, the seafood industry can reduce environmental pollution, improve profitability, and support a circular economy. Such innovations highlight the potential of science and technology to create sustainable, nutritious, and environmentally responsible food systems for the future.

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ROLE OF AGROFORESTRY FOR IMPROVING THE SOIL HEALTH AND MAINTAINING THE SUSTAINABILITY

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Introduction

By structurally and functionally diversifying its components, agroforestry promotes more effective resource use than monocropping by integrating woody perennials with arable crops, cattle, or fodder on the same plot of land. Along with providing food, timber, and fodder, this integration of trees also improves the physical, biological, and chemical qualities of the soil and increases fertility, among other soil-related ecological services. Agroforestry can improve biodiversity more than monocropping by offering a specific habitat, refuges for epigenic organisms, microclimate variety, buffering effect, soil moisture, and humidity. Agroforestry's capacity for internal repair has been validated by numerous researches. Agroforestry helps manage erosion by reducing runoff, capturing rainfall, and binding soil particles together.

The integration of trees on farmland is not significantly hampered by the trade-off between crop productivity and other non-cash ecological services; however, there are other significant co-benefits for practitioners. Tree-based systems improve agricultural resilience, yields, and livelihoods, which guarantees food security and nutrition. Through food diversification, soil improvement and protection, and wind erosion reduction, agroforestry can be a cost-effective and climate-smart farming technique that can assist smallholder farmers deal with the climate-related extremes of dryland areas. This review emphasized how agroforestry can increase soil quality, microclimate conditions, and productivity, especially in semi-arid and degraded settings when management approaches are carefully considered.

One of the other approaches to implementing sustainable forest management to improve community welfare is thought to be agroforestry. AF offers agricultural and silvicultural practices and expertise that are intended to increase farmers' resilience in addition to restoring the environment. However, the advantages of agroforestry in terms of soil fertility for maximizing land productivity and managing community livelihood are frequently disregarded and have not received enough attention. The purpose of this paper is to outline the ways that intelligent agroforestry techniques have greatly improved crop yields and maintained soil fertility in different parts of Indonesia and several other nations, all while ensuring financial gains for the local population. In both tropical and non-tropical areas, research has concentrated on the function of AF in maintaining soil fertility and community livelihood. Problems with the Environment and the Need for Sustainable Solutions: Deforestation, soil erosion, biodiversity loss, and falling soil fertility are just a few of the many environmental issues facing the planet today. These problems are frequently made worse by conventional agricultural methods, which rely heavily on monoculture and large land use. Adopting agroforestry techniques is becoming more popular as a potential solution to these problems in a sustainable manner.

The Contributions of Agroforestry to Soil Conservation: Through a number of methods, agroforestry is essential to soil conservation. The strategic integration of trees and shrubs in agricultural landscapes helps control soil erosion by reducing the force of wind and water on the soil surface. Tree roots stabilize the soil, preventing erosion and protecting against landslides in hilly terrains. Moreover, agroforestry systems often include species with deep and extensive root systems, enhancing soil structure and water infiltration capacity, which further minimizes soil erosion. Enhancing Soil Organic Matter and Carbon Sequestration: Agroforestry also contributes significantly to soil organic matter accumulation. The leaf litter, pruned branches, and root exudates from trees and shrubs decompose to form organic matter, enriching the soil with nutrients and improving its overall health. This continuous addition of organic matter enhances soil structure, water-holding capacity, and nutrient retention, thus promoting sustainable crop growth.

Soil Microbial Diversity and Biodiversity: Agroforestry systems' varied vegetation produces microhabitats that sustain a variety of plant and animal species. Bacteria, fungus, and other soil organisms are among the vast community of microorganisms that flourish in the soil environment, demonstrating the extent of biodiversity. The breakdown of organic matter, disease prevention, and nutrient cycling are all made possible by this high microbial variety, which also increases soil fertility. These processes are essential for sustainable crop production.

Soil Fertility and Nutrient Cycling: The addition of nitrogen-fixing plants and shrubs to agroforestry systems improves the soil's nutrient availability. By forming symbiotic interactions with nitrogen-fixing bacteria, these leguminous species transform atmospheric nitrogen into forms that plants can use. A well-balanced nutrient cycling system is also facilitated by the varied flora and organic matter, which guarantees a consistent supply of nutrients for crops and raise soil fertility over all. Agroforestry is a broad category of methods and approaches that combine crops, trees, and shrubs to improve soil conservation. Some of the most important agroforestry methods and strategies for shielding soil from nutrient depletion, erosion, and degradation are examined in this section.

Windbreaks and Shelterbelts: Windbreaks and shelterbelts are common agroforestry practices that involve planting rows of trees or shrubs perpendicular to prevailing winds. These vegetative barriers help reduce wind speed and deflect strong winds away from cultivated areas, mitigating soil erosion caused by wind action. Windbreaks also act as protective shields for crops, preventing wind damage and improving overall crop productivity. Alley Cropping: Alley cropping is a widely adopted agroforestry technique where rows of trees or shrubs are alternated with alleys of annual or perennial crops. The trees provide multiple benefits, including reducing soil erosion, enhancing soil fertility through nutrient cycling, and providing shade and wind protection for the intercropped crops. Alley cropping systems are particularly effective in hilly or sloping landscapes where erosion control is a significant concern.

Silvopasture: Silvopasture is an agroforestry practice that combines trees with livestock grazing. By integrating trees or shrubs into pasturelands, silvopasture systems offer numerous benefits for soil conservation. Tree roots help stabilize the soil, reducing compaction from livestock, while also providing shade and shelter for animals. The presence of trees in silvopasture systems contributes to organic matter input through leaf litter, enhancing soil fertility.

Home gardens and Multistory Cropping: Home gardens and multistory cropping involve the deliberate planting of multiple crops, trees, and shrubs in small plots around homesteads or gardens. These diverse cropping systems provide soil cover throughout the year, reducing soil erosion and maintaining soil moisture levels. The combination of different plant species enhances nutrient cycling and sustains soil health over the long term. Incorporating these agroforestry practices and techniques into agricultural landscapes not only conserves soil but also promotes overall ecosystem health, enhances biodiversity, and supports sustainable crop production.

Agroforestry's Impact on Soil Characteristics and Microbial Diversity

Agroforestry systems contribute to better soil health and long-term agricultural output by having a significant effect on soil characteristics and microbial diversity. The several ways that agroforestry practices affect soil characteristics and promote a variety of microbial communities are examined in this section. Nutrient Content and Organic Matter in Soil: Agroforestry techniques greatly increase the amount of organic matter in the soil because of their varied vegetation and constant supply of organic matter from tree litter and chopped branches. Plant development and nutrient cycling are facilitated by improved soil structure, water-holding capacity, and nutrient retention brought about by increased organic matter. Essential elements like potassium, phosphorus, and nitrogen are released during the breakdown of organic materials, promoting long-term crop development.

Control of Soil Erosion: In agroforestry systems, the presence of trees and shrubs effectively reduces soil erosion. Particularly on slopes, tree roots are essential for anchoring soil and minimizing erosion. By slowing down surface water flow, agroforestry techniques like windbreaks and contour hedgerows reduce soil erosion and sediment loss. By preventing erosion, topsoil is preserved and soil fertility is preserved. Soil Moisture Regulation: By reducing the direct effect of rainfall on the soil surface, agroforestry systems help regulate soil moisture through the tree canopy. Tree shade improves water use efficiency by lowering transpiration and evaporation from the soil and crops.The resulting moderation of soil moisture levels benefits both plants and soil microorganisms. Soil pH and Nutrient Availability: The litter and organic matter derived from trees and shrubs in agroforestry systems can influence soil pH and nutrient availability. The decomposition of organic matter can create mild acidification, which may affect nutrient availability in the short term. However, in the long term, the continuous input of organic matter promotes nutrient cycling and enhances overall soil fertility.

Microbial Activity and Diversity: Agroforestry systems promote a variety of microbial communities in the soil, which has a beneficial impact on the breakdown of organic matter and the cycling of nutrients. varied microorganisms have varied niches created by the presence of different plant species, each of which has its own organic inputs and root exudates. Soil resistance to environmental shocks is increased and nitrogen cycle efficiency is improved by this variety. Mycorrhizal Partnerships: Mycorrhizal relationships between beneficial fungi and tree roots are frequently promoted by agroforestry techniques. By developing symbiotic associations with tree roots, mycorrhizal fungi help the host plant absorb nutrients, especially phosphorus, in return for carbon molecules. These mycorrhizal relationships promote the availability of nutrients for crops and trees, which benefits plant growth and soil health.

Improving Soil Fertility through Agroforestry: Because they make it easier for nutrients to be efficiently absorbed, recycled, and redistributed in the soil, agroforestry systems are essential to nutrient cycling. Agroforestry techniques produce a dynamic and varied ecosystem that increases soil fertility and nutrient availability by integrating trees, shrubs, and crops. The role that agroforestry plays in improving soil fertility and nutrient cycling is examined in this section. Fixation of Nitrogen by Biology: In many agroforestry systems, nitrogen-fixing tree species—like legumes—form symbiotic relationships with bacteria that fix nitrogen in their root nodules. These trees feed the soil with nitrogen by converting atmospheric nitrogen into forms that plants can use.

As a result, nitrogen-fixing trees not only support their growth but also enhance nitrogen availability for associated crops, promoting healthier plant growth and reducing the need for external nitrogen fertilizers.

Decomposition of Leaf Litter and Organic Matter: Trees and shrubs in agroforestry systems produce clipped branches and shed leaves, which adds organic matter to the soil continuously. With the help of soil microbes, this organic waste breaks down, releasing vital minerals including potassium, phosphorus, nitrogen, and micronutrients. The slow decomposition of organic matter enhances soil structure and enriches the soil with nutrients, increasing crop yield and soil fertility.

Conclusion

These case studies and insights show that agroforestry systems offer a viable way to boost crop output and encourage sustainable land management techniques. There are several advantages to integrating trees with crops, ranging from enhanced resilience and climate change adaptation to better soil fertility and nutrient cycling. These observations offer important information that helps farmers, researchers, and policymakers embrace and advance agroforestry techniques to meet the demands of sustainable agriculture and food security in a changing global environment.

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AGROMETEOROLOGICAL INSIGHTS INTO POLLINATOR DECLINE AMID SHIFTING SEASONS IN INDIA

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Abstract

India's agricultural economy depends heavily on pollinator services, with 84% of food crops relying on animal pollination. Rising temperatures and monsoon variability have created phenological mismatches between pollinators and flowering crops, reducing agricultural productivity. This article examines how agrometeorological changes—temperature increases of 0.24°C per decade and declining monsoon precipitation—have disrupted Indian pollinator populations and presents region-specific adaptation strategies.

Keywords: Agrometeorology, Pollinator decline, India, Phenological mismatch, Climate change

Introduction

Pollinators are critical to Indian agriculture. Over 84% of Indian cultivated crops—including mustard, sunflower, mango, and cashew—depend partially on animal pollination (Mishra & Yadav, 2012). Honeybee pollination services are valued at ₹27,961 crores annually. However, Indian honeybee (*Apis cerana indica*) and European honeybee (*Apis mellifera*) populations have declined 35-55% over the past two decades. India's temperature has increased 0.24°C per decade since 1901, accelerating since 1975. The Indian monsoon has become increasingly erratic, with post-monsoon precipitation declining 23% in Northwestern India over 50 years. These agrometeorological shifts create phenological mismatches—temporal disconnections between pollinator emergence and crop flowering—directly threatening food security for 1.4 billion people.

Temperature Effects and Phenological Mismatch

Temperature increases have advanced crop flowering significantly. Studies from the Indo-Gangetic plains show mustard (*Brassica juncea*) flowering advanced 2-3 weeks over 30 years, while Indian honeybee emergence remained relatively constant due to photoperiod dependence. This creates critical food gaps where honeybees emerge before adequate flowers bloom, forcing colonies into starvation conditions (Choudhury *et al*., 2016). Similarly, mango flowering in Western India (Rajasthan, Gujarat, Karnataka) advanced 10-15 days since the 1990s, while native bee emergence showed minimal shifts. This mismatch reduced mango fruit set by 15-25% in affected regions during 2014-2018 (Sharma *et al*., 2019). In cotton-growing regions, temperature increases extended the pest breeding season, requiring 7-9 pesticide applications annually instead of 4-5, directly harming pollinator populations.

Monsoon Variability and Documented Declines

Southwest Monsoon rainfall declined -0.29 mm/year since 1981, severely impacting flowering plants' nectar and pollen production. During drought years, mustard and sunflower nectar production declined 30-40%, while extended dry conditions forced pollinators to travel greater distances, increasing mortality by 25-35% (Jat *et al*., 2019). Conversely, erratic heavy rainfall during critical flowering periods prevents bee foraging for 5-8 continuous days. In Punjab's cotton belt, unseasonable rains in October 2017 reduced cotton pollination by 45%, lowering seed-cotton yields by 20-30%.

Documented population declines across India are severe:

- **Indian Honeybees:** Declined 35% between 1990-2020; summer colony losses averaged 22-28% annually during 2010-2020 versus 8-12% during 1990-2000.
- **European Honeybees:** Managed colonies declined 18% nationally between 2016-2021, with winter losses in Himalayan regions exceeding 40%.
- **Native Wild Bees:** Populations declined 40-60% in Southern Indian agricultural regions (Karnataka, Maharashtra, Tamil Nadu) during 1995-2020 (Hegde *et al*., 2015).

Western India experienced steeper declines (45-55%) than Eastern India (30-40%), reflecting differential climate stress patterns.

Climate-Driven Pests and Adaptation Strategies

Warming temperatures have expanded honeybee pests. *Varroa destructor* (parasitic mite) infestation rates increased from 8-12% of colonies (2010-2015) to 35-45% (2018-2022). *Nosema ceranae* (fungal pathogen) prevalence in Indian honeybee colonies increased from 5-8% (2008-2012) to 22-28% (2018-2022), particularly in rice-growing regions.

Regional Impacts and Solutions

Indo-Gangetic Plains: Mustard flowering advanced 2-3 weeks, creating temporal gaps reducing mustard seed set and oilseed yields.

Western India: Declining precipitation reduces nectar production by 30-40%, while high temperatures (>40°C) and low humidity reduce pollinator foraging activity by 50-60%.

Coastal Regions: Mango fruit set declined from 25-30% (1990-2000) to 15-20% (2015-2020).

Evidence-Based Adaptations

Crop Diversification: Cultivating crops with staggered phenology extends the flowering season, providing continuous nectar availability and buffering against phenological mismatches.

Improved Beekeeping: Promoting *Apis cerana indica* apiary management adapted to local climates with temperature-humidity monitoring increases colony survival by 20-30% during stress years (Sharma *et al*., 2021).

Precision Irrigation: Strategic irrigation during drought periods maintains nectar production, increasing nectar yield by 35-40% and improving pollination efficiency (Jat *et al*., 2019).

Monsoon-Based Crop Scheduling: Adjusting sowing dates using monsoon forecasts (available 2-4 weeks in advance) aligns flowering with optimal pollinator availability.

Habitat Conservation: Maintaining hedgerows and wildflower patches provides diverse floral resources across seasons. Agroforestry systems with 40-60% landscape diversity support higher native pollinator populations than monocultures.

Conclusion

India's pollinator crisis—evidenced by 35-55% population declines driven by agrometeorology—threatens food security for 1.4 billion people. Temperature increases and monsoon variability have created phenological mismatches reducing pollination efficiency and yields. Region-specific agrometeorological monitoring integrated with precision agriculture, habitat conservation, and indigenous knowledge can sustain pollinator populations and agricultural productivity. National initiatives must prioritize climate-informed adaptive management across India's diverse agroecological zones**.**

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THE WATER WE NEVER SEE: HOW GLOBAL TRADE IS QUIETLY MOVING THE WORLD'S FRESHWATER

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Abstract
Virtual water trade refers to the movement of water embedded in agricultural and industrial commodities through international trade. As freshwater resources face increasing pressure from population growth, urbanization, climate change and rising food demand, virtual water trade has emerged as an important framework for understanding the relationship between water resources, agriculture and economic development. India is one of the world's largest exporters of virtual water through commodities such as rice, cotton, sugar, tea and spices. While these exports contribute significantly to foreign exchange earnings, rural employment and economic growth, they also involve the transfer of substantial volumes of freshwater, much of which is sourced from stressed groundwater reserves. This article examines the concept and significance of virtual water trade, India's role in the global virtual water economy and the associated challenges of groundwater depletion, environmental degradation and rising irrigation costs. It further highlights the importance of water valuation, sustainable export strategies, crop diversification, efficient irrigation technologies and improved water governance. The study concludes that integrating water resource considerations into agricultural and trade policies is essential for ensuring long-term water security, economic resilience and environmental sustainability in India.

Keywords: Virtual Water Trade, Water Footprint, Groundwater Depletion, Agricultural Exports, Water Valuation, Sustainable Water Management and Food Security.

Introduction

When we think about international trade, we usually picture ships carrying containers filled with rice, cotton, coffee, or electronics across oceans. What we rarely imagine is water traveling alongside these products. Yet hidden within every grain of rice, cotton shirt, or cup of coffee is a significant amount of water used during production. This invisible movement of water through global trade is known as virtual water trade, a concept that is becoming increasingly important in a world facing growing water scarcity. Although water covers about 71 percent of the Earth's surface, only a small fraction is available as freshwater for human use. Rapid population growth, urbanization, industrial expansion, and climate change are putting immense pressure on these limited freshwater resources. As concerns about water security intensify, researchers and policymakers are looking beyond rivers, reservoirs, and groundwater to understand how water is being exchanged through global markets. The concept of virtual water was introduced by British geographer Professor Tony Allan in the early 1990s. It refers to the amount of water required to produce a commodity or service. For example, producing one kilogram of rice may require more than 2,500 liters of water while a cotton T-shirt can consume thousands of liters during cultivation and manufacturing. When such products are exported, the water used in their production is effectively transferred from the exporting country to the importing country. This hidden flow of water has significant implications for global resource management. Water-scarce countries often import water-intensive commodities rather than producing them domestically thereby conserving their limited freshwater supplies. Many nations in the Middle East, for instance, rely heavily on imported food to meet domestic demand while preserving local water resources. In this way, virtual water trade contributes to food security and helps balance global water availability. However, the concept also raises important concerns. Countries that export large quantities of water-intensive crops may experience groundwater depletion, environmental degradation, and increased vulnerability to climate change. In some regions, economic gains from exports come at the cost of long-term water sustainability. This has led to growing discussions about whether the true value of water is adequately reflected in international trade. Today, virtual water trade is reshaping how we think about water, agriculture, and economic development. It highlights the interconnected nature of global resource use and demonstrates that every product carries a hidden environmental footprint. As freshwater becomes an increasingly valuable resource in the twenty-first century, understanding virtual water trade will be essential for building sustainable economies, ensuring food security, and managing the world's limited water resources more effectively.

Understanding Virtual Water Trade and India's Role in the Global Water Economy

Understanding Virtual Water Trade

Concept of Virtual Water

Water is often viewed as a resource that flows through rivers, reservoirs, and underground aquifers. However, a significant portion of the world's water also moves invisibly through trade. This hidden water is known as virtual water; the total volume of water consumed during the production of a commodity or service.

Virtual water can be categorized into three types. Green water refers to rainwater stored in the soil and used by plants during growth. Blue water includes water withdrawn from rivers, lakes, and groundwater sources for irrigation and industrial processes. Grey water represents the amount of freshwater required to dilute pollutants generated during production to acceptable environmental standards.

The amount of virtual water embedded in everyday products is often surprising. Producing one kilogram of wheat requires approximately 1,300 liters of water, while one kilogram of rice may require between 2,500 and 3,500 liters. Cotton is even more water-intensive, with around 10,000 liters needed to produce one kilogram. The production of one kilogram of beef can consume as much as 15,000 liters of water. Even a simple cup of coffee carries a hidden water footprint of about 140 liters. These figures illustrate that when countries export agricultural or industrial products, they are effectively exporting the water used in their production. Similarly, importing countries gain access not only to the product itself but also to the water resources embedded within it. This invisible exchange forms the foundation of virtual water trade.

Significance of Virtual Water Trade

Water Conservation

One of the most important benefits of virtual water trade is its contribution to water conservation. Countries facing water scarcity can reduce pressure on their domestic water resources by importing water-intensive products instead of producing them locally. For example, growing rice or wheat in arid regions often requires extensive irrigation, which can rapidly deplete groundwater reserves. By importing these crops from water-rich regions, countries can conserve valuable freshwater resources for essential uses such as drinking water, sanitation, and industrial development.

Food Security

Virtual water trade plays a crucial role in enhancing food security, particularly in regions where climatic conditions limit agricultural production. Many countries in the Middle East and North Africa face chronic water shortages and cannot produce sufficient food to meet the needs of their populations. Through imports of grains, fruits, and other agricultural commodities, these nations can secure stable food supplies without exhausting their already limited water resources. In this sense, virtual water trade acts as a mechanism that links global water resources with global food systems.

Global Resource Optimization

From a global perspective, virtual water trade promotes more efficient use of water resources. Agricultural production can be concentrated in regions where water availability is relatively abundant and climatic conditions are favorable. This allows crops to be produced with lower water consumption and higher productivity. Consequently, virtual water trade contributes to the optimal allocation of scarce water resources across countries, improving overall efficiency in food production and resource management.

Scenario of India in Virtual Water Trade

India as a Major Virtual Water Exporter

India occupies a significant position in global virtual water trade due to its status as one of the world's largest agricultural producers and exporters. The country's diverse agro-climatic conditions enable the cultivation of a wide range of crops that are exported to markets around the world. As a result, India exports substantial volumes of virtual water embedded in agricultural commodities.

Rice

Rice is India's most significant virtual water export. The crop requires large quantities of water throughout its growing season, particularly in irrigated farming systems. India is among the largest exporters of rice globally, supplying major markets in Asia, Africa, and the Middle East. While rice exports generate considerable foreign exchange earnings, they also involve the transfer of enormous amounts of water from India's freshwater reserves to importing nations.

Cotton

Cotton is another major contributor to India's virtual water exports. The textile industry, which forms a vital part of the Indian economy, depends heavily on cotton cultivation. However, cotton is highly water-intensive, particularly in regions where rainfall is insufficient and irrigation is required. The export of cotton and cotton-based products therefore represents a significant export of virtual water.

Sugar

Sugarcane cultivation is particularly demanding in terms of water use. Despite recurring concerns regarding water scarcity, India remains one of the largest producers and exporters of sugar. The export of sugar effectively transfers large quantities of freshwater resources to international markets, raising important questions about sustainability and resource management.

Wheat and Other Agricultural Products

In addition to rice, cotton, and sugar, India exports substantial quantities of wheat, fruits, vegetables, tea, coffee, and spices. Collectively, these products contribute significantly to the country's virtual water exports and strengthen its position in global agricultural trade.

Water Stress Challenges

Groundwater Depletion

One of the most pressing concerns associated with India's virtual water exports is groundwater depletion. States such as Punjab, Haryana, Rajasthan, and Uttar Pradesh rely heavily on groundwater for irrigation. Decades of intensive agricultural production have resulted in extraction rates that often exceed natural recharge levels. As groundwater tables continue to decline, farmers are forced to drill deeper wells and incur higher pumping costs, threatening the long-term sustainability of agricultural production.

Regional Imbalances

A major challenge lies in the mismatch between crop patterns and water availability. Water-intensive crops such as rice and sugarcane are frequently cultivated in regions that already face water stress. Punjab, for example, has become a major rice-producing state despite its limited natural water resources. This imbalance has accelerated groundwater depletion and placed additional pressure on local ecosystems.

Climate Change Impacts

Climate change is expected to exacerbate existing water challenges. Rising temperatures increase evapotranspiration rates, while changing rainfall patterns contribute to more frequent droughts and extreme weather events. These factors can reduce water availability and negatively affect agricultural productivity, making the management of virtual water exports increasingly complex.

Environmental Consequences

Excessive irrigation and overexploitation of water resources have several environmental impacts. Declining groundwater levels threaten the availability of freshwater for future generations. Soil degradation caused by intensive irrigation can reduce agricultural productivity over time. Reduced river flows affect aquatic ecosystems and biodiversity, while ecosystem disruption can undermine the natural services that support agriculture and human well-being.

Opportunities for India

Crop Diversification

One of the most effective strategies for reducing virtual water exports is crop diversification. Encouraging farmers to cultivate less water-intensive crops such as millets, pulses, and oilseeds can significantly reduce pressure on freshwater resources. These crops are better suited to India's semi-arid conditions and often provide greater resilience to climate variability. The growing recognition of millets as climate-smart crops presents an opportunity to align agricultural production with sustainable water management.

Improved Irrigation Efficiency

Improving irrigation efficiency offers substantial potential for water conservation. Technologies such as drip irrigation deliver water directly to plant roots, minimizing evaporation and runoff losses. Sprinkler irrigation systems provide more controlled water distribution compared to traditional flood irrigation methods. Meanwhile, precision farming techniques use sensors, satellite imagery, and data analytics to optimize irrigation schedules based on crop needs and soil moisture conditions. Together, these innovations can significantly reduce water consumption while maintaining or even increasing agricultural productivity.

India's future role in virtual water trade will depend on its ability to balance economic benefits from agricultural exports with the sustainable management of its precious water resources. By adopting water-efficient technologies, promoting crop diversification, and strengthening water governance, India can continue to participate in global agricultural markets while safeguarding its long-term water security.

Export Strategy Reform: Aligning Trade with Water Sustainability

As water scarcity becomes an increasingly serious challenge, India must reconsider its agricultural export strategy. Traditionally, export policies have focused on maximizing production and foreign exchange earnings, often overlooking the enormous quantities of water embedded in exported commodities. This has encouraged the large-scale export of water-intensive crops such as rice, sugar, and cotton, despite growing concerns over the depletion of the country's freshwater resources.

India relies heavily on groundwater for irrigation, with nearly two-thirds of irrigated agriculture dependent on aquifers. However, excessive extraction in states such as Punjab, Haryana, Rajasthan, and Uttar Pradesh has led to alarming declines in groundwater levels. Surface water resources are also under stress due to erratic monsoons, climate change, urbanization, and industrial demand. As a result, the availability of water for crop production is steadily decreasing, threatening long-term agricultural sustainability. A more sustainable approach would promote the export of high-value, low-water-intensive commodities such as spices, horticultural crops, medicinal plants, pulses, and processed foods. These products generate higher economic returns while consuming significantly less water. Such a shift would reduce pressure on groundwater reserves without compromising export earnings. Another important consideration is the inclusion of virtual water costs in export pricing. Current market prices rarely account for the economic value of the water used in production. Incorporating this hidden cost would provide a more realistic measure of profitability and encourage water-efficient crop choices. Furthermore, rising fuel and electricity prices are making irrigation increasingly expensive. As groundwater levels decline, farmers must pump water from greater depths, increasing energy consumption and production costs. Therefore, future export policies should focus on maximizing economic returns per unit of water used, ensuring both economic growth and long-term water security for India.

Monetary Returns in Virtual Water Trade

Export Earnings

Virtual water trade generates substantial economic benefits for India through its agricultural exports. India is among the world's leading exporters of rice, cotton, sugar, tea and spices, commodities that collectively carry enormous quantities of embedded water. According to the Department of Commerce, Government of India (2024), agricultural and allied exports were valued at approximately USD 48.8 billion in 2023–24, making agriculture a significant contributor to foreign exchange earnings and national economic growth. Rice represents India's largest virtual water export. India exported approximately 17.8 million metric tonnes of rice in 2023–24, maintaining its position as the world's largest rice exporter (APEDA, 2024). Since the production of one kilogram of rice requires roughly 2,500–3,500 liters of water, these exports represent the transfer of enormous quantities of virtual water to importing countries (Hoekstra & Hung, 2003; Water Footprint Network, 2024). Cotton is another major contributor to India's virtual water exports. Studies estimate that producing one kilogram of cotton requires approximately 10,000 liters of water, highlighting the significant water footprint associated with India's textile supply chain (Water Footprint Network, 2024). The economic benefits of these exports extend far beyond foreign exchange earnings. Agriculture and allied sectors employ approximately 45–46% of India's workforce, making export-oriented agriculture a critical source of livelihoods for millions of farmers, labourers, traders and workers involved in processing and transportation (Periodic Labour Force Survey, 2024). India's spice exports alone generated a record USD 4.46 billion in 2023–24, demonstrating the growing importance of high-value agricultural products in international markets (Spices Board India, 2024). Similarly, tea exports continue to contribute substantially to export revenues and rural employment. However, these monetary gains are accompanied by significant hidden environmental costs. Research on global virtual water flows indicates that India is one of the world's largest exporters of virtual water, particularly through rice, cotton and sugar exports (Mekonnen et al., 2024; Tamea et al., 2021). While these exports generate valuable revenue, they also involve the transfer of tens of billions of cubic meters of freshwater annually, much of it sourced from already stressed groundwater reserves (Hoekstra & Hung, 2003). This is particularly concerning because groundwater levels in major agricultural states such as Punjab, Haryana and Rajasthan have been declining steadily due to intensive irrigation practices. Therefore, although virtual water trade contributes significantly to India's export earnings, employment generation and economic growth, its long-term sustainability depends on balancing financial returns with responsible water resource management. Future trade policies must recognize that water is not merely an agricultural input but a strategic natural asset whose value should be reflected in production and export decisions (Allan, 1998; Mekonnen *et al*., 2024).

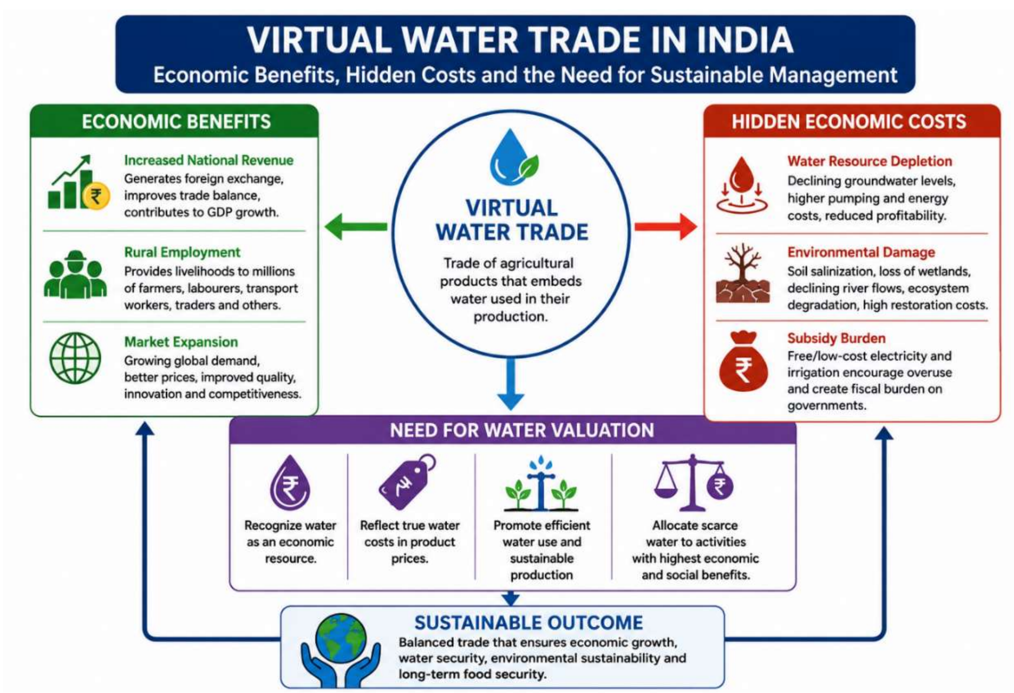

Fig 1: Virtual water trade in India

Increased National Revenue

Agricultural exports are an important component of India's economy. Revenue generated through exports improves the country's trade balance, contributes to GDP growth and supports investments in infrastructure, technology, and rural development. Export earnings also provide governments with additional fiscal resources that can be directed toward social and economic development programs.

Rural Employment

The benefits of agricultural exports extend beyond national income. Millions of farmers, labourers, transport workers, traders and processing industry employees depend on export-oriented agriculture for their livelihoods. The cultivation, harvesting, processing, packaging, and transportation of export commodities create employment opportunities across rural and semi-urban regions. In many areas, agricultural exports serve as a major source of economic activity and income generation.

Market Expansion

Global demand for Indian agricultural products has continued to grow, opening new opportunities for diversification and market expansion. Export-oriented agriculture encourages innovation, improves product quality and enhances competitiveness in international markets. Access to global consumers also allows farmers and agribusinesses to benefit from higher-value markets and premium pricing opportunities.

Hidden Economic Costs

While virtual water exports generate substantial monetary returns, they also impose hidden costs that are often overlooked in traditional economic assessments.

Water Resource Depletion

Groundwater depletion represents one of the most significant hidden costs associated with virtual water exports. As water tables decline, farmers must invest in deeper wells, more powerful pumps, and higher energy consumption to access groundwater. These additional costs reduce profitability and increase financial risks for agricultural producers. In the long run, excessive groundwater extraction can undermine agricultural productivity and threaten food security.

Environmental Damage

Unsustainable water use can lead to environmental degradation, including soil salinization, loss of wetlands, declining river flows, and ecosystem disruption. Restoring damaged ecosystems often requires substantial public investment. Governments may need to allocate significant resources toward environmental rehabilitation, watershed management, and conservation programs, creating additional economic burdens.

Subsidy Burden

In many agricultural regions, water use is indirectly subsidized through free or low-cost electricity for groundwater pumping and subsidized irrigation infrastructure. While these measures support farmers in the short term, they can encourage inefficient water use and excessive extraction. The resulting fiscal burden on governments can be substantial, diverting public funds away from other critical development priorities.

Need for Water Valuation

One of the major shortcomings of current agricultural markets is that water is often treated as a free or underpriced resource. Unlike land, labor, or fertilizers, the actual value of water consumed during production is rarely reflected in commodity prices. As a result, water-intensive crops such as rice, sugarcane, and cotton may appear profitable even though they consume enormous quantities of freshwater and contribute to groundwater depletion. In India, a significant portion of irrigation water is supported through subsidized electricity and irrigation infrastructure. While this reduces production costs for farmers, the environmental costs associated with declining groundwater levels, reduced river flows, and ecosystem degradation are not accounted for in market prices. Consequently, society bears the long-term costs of water scarcity and resource depletion. Water valuation aims to recognize water as an economically valuable resource. By incorporating the cost of water into production and trade decisions, commodities with high water footprints would better reflect their true resource costs. This would encourage farmers to adopt water-efficient technologies and shift toward less water-intensive crops. Water valuation can also improve resource allocation by directing scarce freshwater toward activities that generate higher economic returns per unit of water used. Furthermore, incorporating virtual water costs into export pricing would help policymakers assess whether export revenues adequately compensate for the water resources consumed. Ultimately, valuing water appropriately is essential for promoting sustainable agriculture, conserving groundwater resources, and ensuring long-term water security.

Way Forward

Sustainable Agricultural Practices

Precision Agriculture

Modern farming technologies offer significant opportunities to improve water-use efficiency. Precision agriculture uses sensors, drones, satellite imagery, and data analytics to monitor crop health and soil moisture levels. Farmers can apply water only where and when it is needed, reducing wastage while maintaining crop productivity. Such technologies can significantly improve irrigation efficiency and reduce pressure on freshwater resources.

Conservation Agriculture

Conservation agriculture focuses on maintaining soil health and improving water retention. Practices such as minimum tillage reduce soil disturbance and help preserve soil structure. Crop rotation improves soil fertility and reduces pest pressures, while mulching minimizes evaporation and conserves soil moisture. Together, these practices enhance water-use efficiency and improve resilience to drought conditions.

Water Governance Reforms

Groundwater Regulation

Effective groundwater management is essential for sustainable virtual water trade. Governments need to establish stronger regulatory frameworks that limit excessive groundwater extraction and encourage sustainable usage. Licensing systems, groundwater monitoring, and community-based water management can help ensure that extraction remains within sustainable limits.

Water Accounting

Accurate measurement and reporting of water use are critical for informed decision-making. Water accounting systems can track water consumption across sectors, identify inefficiencies, and provide valuable information for policy development. Improved transparency can support better resource allocation and encourage responsible water management practices.

Technological Innovation

Artificial Intelligence

Artificial intelligence has the potential to revolutionize water management in agriculture. AI-powered systems can analyse weather forecasts, crop growth patterns, and soil conditions to predict irrigation requirements with high accuracy. This enables farmers to optimize water use while maximizing productivity.

Remote Sensing

Satellite-based remote sensing technologies provide real-time information on crop conditions, soil moisture levels, and water use patterns. These tools enable policymakers and researchers to monitor water consumption across large geographic areas and identify regions experiencing water stress.

Smart Irrigation Systems

Automated irrigation systems equipped with sensors and digital controls can adjust water delivery according to crop requirements. Such systems minimize water losses due to over-irrigation and improve overall efficiency, making them an important component of sustainable agriculture.

International Cooperation

Water scarcity is a global challenge that transcends national boundaries. Countries should integrate virtual water considerations into international trade agreements, climate adaptation strategies, and sustainable development initiatives. Collaborative research, technology transfer, and knowledge sharing can help nations improve water management practices and strengthen global water security.

Future of Virtual Water Trade

Rising Importance of Water Security

As the global population approaches 10 billion by 2050, demand for food, fiber, and agricultural products is expected to increase dramatically. This growth will place additional pressure on freshwater resources and elevate the importance of virtual water trade as a mechanism for balancing water availability and food production across regions.

Climate Change Adaptation Tool

Virtual water trade can serve as an effective adaptation strategy in a changing climate. Countries experiencing droughts or declining water availability may increasingly rely on imports of water-intensive products from regions with more favourable climatic conditions. This flexibility can help reduce vulnerability to climate-related disruptions.

Expansion of Data-Driven Decision Making

Advances in digital technologies are transforming the way virtual water flows are measured and managed. Comprehensive water footprint databases, satellite monitoring systems, and advanced analytical tools will enable governments and businesses to make more informed decisions regarding production, trade, and resource management.

Sustainable Trade Networks

Future trade systems are likely to place greater emphasis on sustainability. Consumers, investors, and policymakers are increasingly demanding products that are produced using environmentally responsible practices. Water-efficient production methods, sustainable sourcing strategies, and environmental certification programs may become key factors influencing global trade patterns.

Strategic Resource Management

Water-rich countries may gain strategic advantages as global demand for food and agricultural products increases. Access to abundant freshwater resources could become an increasingly important determinant of agricultural competitiveness and economic influence in international markets.

Future of Monetary Trade in Virtual Water

Water Footprint-Based Pricing

Future markets may increasingly incorporate water footprints into product pricing mechanisms. Products that require excessive water consumption could become more expensive, while water-efficient products may receive price incentives. Such pricing systems would encourage producers to adopt sustainable practices and help consumers make more environmentally informed choices.

Water Credit Markets

Inspired by carbon trading systems, water credit markets could emerge as a tool for promoting water conservation. Organizations and farmers that successfully reduce water consumption may earn tradable credits that can be sold to other entities seeking to offset their water usage. These markets could create financial incentives for efficient water management and innovation.

Sustainable Investment Opportunities

Water scarcity is creating new investment opportunities in sectors focused on improving water efficiency and sustainability. Investors are increasingly directing capital toward water-efficient agriculture, smart irrigation technologies, water recycling infrastructure, and sustainable supply chains. These industries are expected to experience significant growth as governments and businesses prioritize resource conservation.

Eco-Labelling and Consumer Awareness

Consumers are becoming more aware of the environmental impacts associated with production and consumption. In the future, products may carry labels indicating their water footprint, sustainability certifications, or water-efficiency ratings. Such information can influence purchasing decisions and encourage companies to adopt more sustainable production practices.

Integration with ESG Frameworks

Environmental, Social, and Governance (ESG) criteria are becoming central to corporate and investment strategies worldwide. Companies that demonstrate responsible water management practices are likely to attract investors, gain better access to capital, enhance their brand reputation, and achieve higher market valuations. Water stewardship is increasingly being recognized as a key indicator of long-term business resilience and sustainability. As water emerges as one of the defining resources of the twenty-first century, the economic significance of virtual water trade will continue to grow. The challenge for countries such as India will be to harness the financial benefits of trade while ensuring that water resources are managed responsibly for future generations.

Conclusion

Virtual water trade highlights the hidden flow of water through agricultural commodities traded across the world. For India, it has become an important source of foreign exchange earnings, rural employment, and economic growth through exports of rice, cotton, sugar, tea, and spices. However, these benefits come at a significant environmental cost, as many of these crops require large quantities of water and contribute to groundwater depletion in already water-stressed regions. With declining groundwater levels, increasing irrigation costs, climate change impacts, and growing competition for water resources, the sustainability of exporting water-intensive commodities is becoming a major concern. Therefore, future agricultural and trade policies must balance economic gains with responsible water management.

Promoting high-value, low-water-intensive crops, improving irrigation efficiency, strengthening groundwater governance, and incorporating virtual water costs into export pricing can help achieve this balance. By recognizing water as a strategic and valuable resource, India can ensure that its agricultural exports continue to generate economic benefits while safeguarding long-term water security and environmental sustainability for future generations.

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ENVIRONMENTAL DNA (eDNA) FOR AQUATIC BIODIVERSITY MONITORING

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Abstract

Aquatic ecosystems support a wide range of biodiversity, including fish, microorganisms, plankton, crustaceans, molluscs, and aquatic plants. However, monitoring these organisms is challenging due to their hidden nature and the limitations of traditional sampling methods. Environmental DNA (eDNA) has emerged as a revolutionary molecular tool that enables the detection of aquatic organisms by analyzing DNA traces released into the environment through skin cells, mucus, faeces, urine, and other biological materials. Compared with conventional methods like netting, electrofishing, and visual surveys, eDNA reduces disturbance to organisms while providing broader biodiversity information. This non-invasive approach provides a rapid, sensitive, and cost-effective method for biodiversity assessment, conservation, and ecosystem management.

Keywords : Environmental DNA (eDNA), Aquatic biodiversity, Species detection, Fisheries management, Invasive species detection.

Introduction

Environmental DNA (eDNA) is organismal DNA that can be detected in the environment and is derived from cellular material of organisms shed into aquatic or terrestrial environments. It can be sampled and monitored using molecular methods, which is important for the early detection of invasive and native species as well as the discovery of rare and cryptic species (Huang et al., 2022).

Need For Biodiversity Monitoring

Aquatic ecosystems contain enormous biodiversity including fish, plankton, amphibians, molluscs, crustaceans, microbes, and aquatic plants.

Monitoring this biodiversity is essential for:

- Ecosystem management
- Fisheries conservation
- Pollution assessment
- Invasive species detection
- Restoration planning

Concept of eDNA

- The concept of eDNA originated in microbiology (Ogram et al., 1987) and refers to genomic DNA in the environment (e.g., soil, water, or air). eDNA has been widely used to reveal microbial communities in animals and humans (Karygianni et al., 2020).
- In the past decade, eDNA was widely used to detect aquatic organisms, with researchers worldwide collecting water samples to detect taxa.

- eDNA was first used in 2008 to track the presence of a frog (*Rana catesbeiana*) in controlled environments and natural wetlands, which opened a new perspective for detecting aquatic species in ecological and environmental studies (Ficetola et al., 2008). In 2012, the first eDNA metabarcoding analysis was used to record marine fish biodiversity (Thomsen *et al*., 2012a).

TYPES OF ENVIRONMENTAL DNA (eDNA)

Environmental DNA (eDNA) can be broadly divided into two major types based on the source from which the DNA originates:

1. **Organismal eDNA:** Organismal eDNA refers to DNA obtained directly from whole living microorganisms or tiny organisms such as bacteria and phytoplankton that are naturally present in environmental samples such as water, sediment, or soil.

- In this type, the entire organism itself is collected along with its intact genetic material.

2. **Extra-organismal eDNA:** Extra-organismal eDNA refers to DNA that is released into the environment from larger organisms through body materials, secretions, or waste products. In this case, the organism itself is not collected; only traces of its DNA are obtained from the environment.

Methodology of eDNA Analysis

Step 1: Sample Collection

- **Common Samples includes:** Water, Sediment, Soil, Biofilms. These samples are collected from lakes, rivers, lagoons, estuaries, oceans, wetlands.
- Environmental DNA begins to decay immediately after shedding (Thomsen et al. 2012a); Therefore, samples should be preserved using a standardized protocol as soon as possible after collection (Pilliod et al. 2013).

Fig.1 Sample collection

Step 2: Filtration: Water samples contain very dilute DNA, therefore, filtration is used to concentrate eDNA. Filtration is performed usually within 24 h of sample collection to reduce the amount of eDNA degradation. Common Filter Sizes: 0.22 µm, 0.45 µm, 0.7 µm.

- Samples of eDNA can be effectively collected with cellulose nitrate (Goldberg et al. 2011), glass fibre, polycarbonate, nylon, polyether sulfon and cellulose acetate filters.
- Filters (and collected materials) can then be preserved by freezing (Jerde et al. 2011), immersion in ethanol (Goldberg et al. 2011), drying, or immersion in cell lysis buffer (Renshaw et al. 2015).

Fig.2 Filtration

Step 3: DNA Extraction

Procedure

For DNA Extraction commercial kits, such as the Qiagen DNeasy Kit
or FastDNA SPIN Kit or PowerWater DNA Isolation Kit are used that are optimized for water samples.

1. Lysis (Breaking the Cells): Add a lysis buffer (containing detergents like SDS to break cell membranes) and Proteinase K (to digest proteins). Incubate at $56^0$for 1-2 hours or until the filter is completely dissolved, on a rotary shaker.
2. DNA Binding: Add a binding buffer and ethanol to the lysate. This creates conditions where DNA binds to a silica membrane (in spin columns). Transfer the mixture to a spin column and centrifuge. The DNA binds to the column, and impurities pass through.
3. Washing: Wash the spin column with wash buffers (typically containing ethanol) to remove residual lysis buffer. (e.g., humic acid).
4. Elution: Add elution buffer (e.g., TE buffer or nuclease-free water) directly to the center of the column membrane. Incubate at room temperature for 1–5 minutes. Centrifuge to collect the purified DNA in a clean tube.

Storage: Store the extracted eDNA at -20^0 for short-term or -80^0 for long-term storage until amplification.

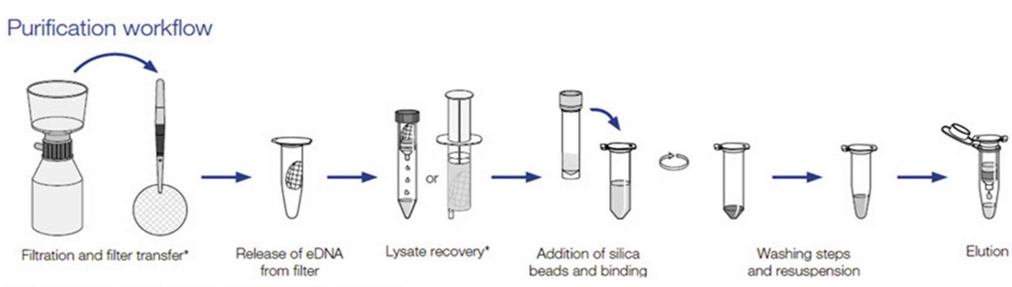

Fig.3 Showing DNA Extraction process

Step 4: PCR Amplification (eDNA)

Procedure

1. **Preparation of PCR reaction mixture**: A PCR reaction mixture is prepared in sterile PCR tubes under aseptic conditions.

The reaction mixture generally contains:

- Template DNA (extracted eDNA), Forward primer, Reverse primer, PCR master mix(contains DNA polymerase, dNTPs, $MgCl_2$, and buffer), Nuclease-free water

All these components are mixed gently and placed in a PCR tube. This tube is then inserted into a PCR machine (thermal cycler).

2. Selection of primers for target organisms: Specific primers are selected based on the target aquatic organisms.

- For aquatic biodiversity studies, common primers target: 12S rRNA → fish and vertebrates. These primers bind to conserved regions of the DNA and allow amplification of species-specific fragments.

3. Thermal cycling: The PCR tubes are placed in a thermal cycler such as Veriti Thermal Cycler, where the amplification process takes place through repeated temperature cycles.
4. Repeat for multiple cycles: These three steps(Denaturation, Annealing and Extension) are repeated 35–40 times (cycles). Each cycle doubles the DNA amount. So even very small amounts of eDNA become detectable.
5. Final extension: After all cycles, Keep it at 72°C for 5–10 minutes. This ensures all DNA strands are completely extended.
6. Hold stage : The machine cools to 4°C. The amplified samples are preserved until further analysis.

Step 5: Sequencing: It is the process of determining the nucleotide sequence (A, T, G, and C) of amplified DNA fragments, in order to identify which organism released the DNA into the aquatic environment, without directly capturing or observing them.

Procedure

- After PCR amplification, the amplified eDNA (called PCR Amplicons)is checked using gel electrophoresis to confirm successful amplification. The PCR products are then purified to remove unwanted primers and chemicals.

The library is loaded into a sequencing platform such as Illumina MiSeq, where the DNA fragments are sequenced to obtain millions of reads (large number of short DNA sequences).

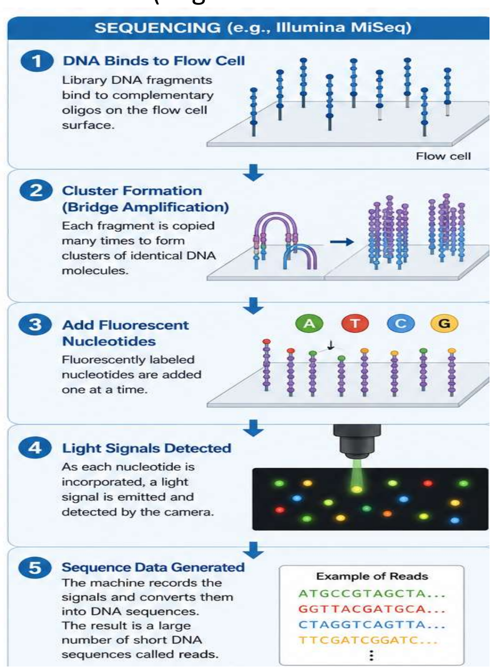

Fig.4 Showing the Nucleotide sequence

Step 6: Bioinformatics analysis: The sequence reads obtained from the machine are analyzed using computer software. Common databases: NCBI GenBank, BOLD Systems.

By matching the obtained sequences with these databases, scientists identify the species present in the water body.

Step 7: Data Interpretation: The identified species data is then interpreted to: Evaluate biodiversity, Detect rare species, Monitor invasive species, Study seasonal changes, Assess ecosystem health.

Conclusion

Environmental DNA (eDNA) has emerged as a powerful and innovative tool for aquatic biodiversity monitoring. It allows the detection of organisms from genetic material present in water without the need for direct capture or observation. eDNA has wide applications in biodiversity assessment, fisheries management, and ecosystem monitoring, making it highly valuable for aquatic environment management. Despite certain limitations, recent advances in molecular techniques like PCR and metabarcoding have improved its accuracy and usefulness. Therefore, eDNA has great potential as a future tool for sustainable monitoring and conservation of aquatic ecosystems.

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POTATO APHID: DAMAGE SYMPTOMS AND A SMART WAY TO PROTECT CROPS

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Abstract

The Potato Aphid (*Macrosiphum euphorbiae*) is a globally significant pest of numerous crops, most notably potato, tomato, and various ornamentals. Its primary impact stems not only from direct feeding damage but, more critically, from its role as an efficient vector for numerous devastating plant viruses, including Potato Virus Y (PVY) and Potato Leafroll Virus (PLRV). This dual threat necessitates a highly refined and sustainable control strategy. This article advocates for Integrated Pest Management (IPM) as the most effective, economical, and environmentally sound strategy for managing the Potato Aphid. IPM for M. euphorbiae emphasizes rigorous monitoring (particularly of aphid migration), conservation and augmentation of natural enemies, the use of resistant cultivars, and the highly judicious application of selective insecticides only when action thresholds are met. We explore the essential components, practical methodologies, tangible positive outcomes, and future technological prospects of leveraging IPM to secure crop health and ensure the quality of essential food crops.

Keywords: Integrated Pest Management (IPM), Potato Aphid (*Macrosiphum euphorbiae*), Virus Vector, Potato Virus Y (PVY), Potato Leafroll Virus (PLRV), Monitoring, Biological Control, Resistant Cultivars, Selective Insecticides, Crop Protection.

Introduction and Background

The potato (*Solanum tuberosum*) is the world's fourth largest food crop, providing essential nutrition and economic stability across the globe. However, its productivity is severely constrained by insect pests, with aphids being the most consequential. The Potato Aphid (*Macrosiphum euphorbiae*) is a large, cosmopolitan aphid species, typically green or pink, that infests hundreds of plant species, making it a persistent threat in many cropping systems.

While direct feeding by large populations of *M. euphorbiae* can cause leaf curling, yellowing, stunting, and the excretion of sticky honeydew (which promotes the growth of sooty mold), the aphid's role as a disease vector is its most economically damaging characteristic. The Potato Aphid is one of the most efficient transmitters of non-persistent viruses like Potato Virus Y (PVY) and persistent viruses like Potato Leafroll Virus (PLRV). These viruses are difficult to manage and, once established, can cause severe degeneration of seed stock, leading to significant yield and quality loss in subsequent plantings.

Traditional control strategies relied heavily on blanket application of systemic insecticides, often applied preventively. This approach is facing increasing challenges:

Insecticide Resistance: Aphids reproduce quickly and have developed resistance to multiple classes of insecticides (e.g., neonicotinoids, pyrethroids).

Vector Inefficiency of Chemicals: Non-persistent viruses (like PVY) can be transmitted instantly upon probing, often before the systemic insecticide can kill the aphid, rendering insecticides ineffective for stopping the spread of the most damaging diseases.

Environmental and Health Concerns: High pesticide use poses risks to human health, aquatic life, and crucially, decimates the populations of natural aphid predators and parasitoids.

These factors necessitate the adoption of Integrated Pest Management (IPM)—a sophisticated, knowledge-based approach that combines biological, cultural, physical, and highly targeted chemical tactics. IPM is essential for managing a highly mobile vector pest like the Potato Aphid, where the goal is not merely reducing the population, but specifically preventing virus spread.

Life Cycle and Damage Dynamics

The life cycle of the Potato Aphid is characterized by high reproductive capacity and mobility, which underlies its vectoring efficiency.

Life Cycle Summary

The Potato Aphid exhibits a complex life cycle, often involving both sexual and asexual (parthenogenetic) reproduction, depending on climate.

Asexual (Parthenogenetic) Reproduction: In most agricultural areas, reproduction is asexual. Females give birth to live nymphs without mating. This rapid, continuous reproduction is the source of population explosions.

Nymphs: Nymphs are smaller versions of the adults and progress through four instars (molting stages) in a week or two, depending on temperature.

Apterous (Wingless) Adults: The majority of aphids are wingless, which concentrates them on the initial host plant.

Alate (Winged) Adults: When the host plant quality declines, or crowding occurs, winged forms are produced. These alate individuals are responsible for migrating to new plants and fields, driving the primary spread of viruses across the landscape.

Damage Dynamics and Symptoms

The dual nature of the damage makes the Potato Aphid exceptionally destructive:

Direct Feeding Damage: Aphids pierce the phloem tissue and suck sap, leading to:

Leaf Distortion: Curling, crinkling, and yellowing (chlorosis) of leaves.

Honeydew and Sooty Mold: The excretion of excess sugar (honeydew) coats the leaves, providing a substrate for black sooty mold fungus, which reduces photosynthesis and fruit quality.

Indirect Virus Transmission (The Major Threat):

Non-Persistent Viruses (e.g., PVY): The aphid acquires the virus almost instantly upon probing an infected plant and transmits it immediately upon probing a healthy one. Control of PVY focuses on reducing the rate of aphid visits, as killing the aphid is often too slow to prevent transmission.

Persistent Viruses (e.g., PLRV): The aphid requires a longer acquisition feeding time, and the virus circulates within the aphid's body before transmission. Control of PLRV focuses on killing the aphid before it can transmit the virus to a healthy plant.

Methodologies and Key Features of IPM

IPM for the Potato Aphid is a sophisticated strategy that focuses heavily on preventing virus transmission, not just eliminating the pests.

1. Monitoring and Thresholds (The Intelligence Phase)

Monitoring must track both population density and migration activity to inform intervention timing. Key Features: Trap-based Surveillance and Virus Forecasting.

Materials Used:

Yellow Water Pan Traps: These shallow yellow containers filled with water and a small amount of soap (to break surface tension) attract winged aphids. They are crucial for tracking the timing and density of aphid migration into the crop.

Suction Traps: Large, standardized traps used across regions to provide essential data for regional aphid forecasts.

Field Scouting: Regular visual inspection of plants, focusing on the undersides of leaves and growing points, to estimate the percentage of infested plants and track population density.

Methodology: Action Thresholds for aphid control are typically based on vector potential (number of winged aphids caught in traps) rather than just population density, especially for seed potato production where virus spread is critical. The threshold might be as low as one winged aphid per trap per week.

2. Cultural and Physical Control (Risk Reduction)

These methods manipulate the environment to reduce aphid attraction and virus spread.
Key Features: Barrier Crops and Mulches.

Methodology:

Mineral Oil Sprays: Applying light horticultural mineral oil sprays to the foliage. The oil does not kill the aphids but inhibits the aphid's ability to transmit non-persistent viruses like PVY by interfering with virus attachment to the aphid's mouthparts. Must be applied frequently.

Reflective Mulches: Placing silver or reflective plastic mulch on the soil surface in the early season. The reflection confuses the incoming winged aphids, deterring them from landing on the plants and significantly reducing the initial introduction of viruses.

Roguing: Physically removing and destroying (bagging and burying) any plants showing symptoms of aphid-transmitted viruses to eliminate the virus source from the field.

3. Biological Control (Ecological Leverage)

Conserving and augmenting natural enemies is foundational to long-term aphid management.
Key Features: Conservation and Augmentation.

Natural Enemies:

Parasitoid Wasps: Especially Aphidius species, which lay eggs inside the aphid. The dead, parasitized aphid swells up and turns a characteristic bronze color, forming an "aphid mummy."

Predators: Lady beetles (ladybugs), lacewing larvae, and hoverfly larvae are highly effective, voracious aphid predators.

Methodology: Avoiding broad-spectrum insecticides is the most critical step to conserve existing beneficial populations. When natural populations are low, controlled release (augmentation) of commercially reared Aphidius wasps or lady beetles can be used, particularly in greenhouse or high-value crops.

4. Host-Plant Resistance (Genetic Control)
Key Features: Breeding for Resistance.

Methodology: Using potato cultivars that possess natural resistance or tolerance to aphid feeding (antixenosis or antibiosis) or, critically, genetic resistance to the viruses (e.g., R-genes providing extreme resistance to PVY). Planting certified, virus-free seed stock is the most fundamental protective step.

5. Judicious Chemical Control (The Last Resort)
Chemical intervention is highly selective, targeted, and used only when monitoring data confirms the need to prevent significant population buildup or virus spread.

Key Features: Selective and Systemic Application.

Materials Used:
Selective Insecticides: Using aphid-specific chemicals like flonicamid or pyropene, which have a low impact on natural enemies.

Systemic Insecticides: Applying systemic neonicotinoids or related chemistries as seed treatments or in-furrow treatments at planting. This provides localized protection for the initial, most vulnerable growth stage while minimizing exposure to beneficial insects on the foliage later in the season.

Methodology: Treatment decisions are strictly based on economic injury levels (EIL) and action thresholds derived from trap catches, ensuring that chemicals are used only when the IPM program's other components are insufficient.

Outcomes and Future Prospects
Outcomes of IPM
Reduced Virus Incidence: By focusing on the vectoring activity (through oil sprays, reflective mulches, and timely targeted sprays), IPM dramatically reduces the introduction and spread of debilitating viruses like PVY and PLRV, leading to higher-quality seed and ware potatoes.

Sustainable Pest Suppression: Relying heavily on natural enemies and cultural controls provides stable, long-term aphid suppression, reducing the need for constant chemical intervention.

Preservation of Efficacy: The selective use of insecticides minimizes selection pressure, slowing the development of aphid resistance and extending the useful life of effective chemical tools.

Enhanced Food Safety: Reduced reliance on chemical sprays meets consumer and regulatory demands for lower pesticide residues in food.

Future Prospects for IPM
The future of Potato Aphid control lies in the synergy of genetics, data science, and novel delivery systems:

AI and Predictive Modeling: Integrating regional aphid trap data, weather data (temperature, wind), and host availability into Artificial Intelligence (AI) models to create highly accurate, real-time forecasts of aphid migration and virus risk. This will allow growers to time applications of oil or insecticides with unprecedented precision.

RNA Interference (RNAi): Developing topical or transgenic RNAi technologies. This involves delivering or expressing molecules that specifically silence essential genes in the aphid, offering a highly specific, non-toxic control mechanism that poses no risk to beneficial insects.

Autonomous Monitoring and Scouting: Utilizing drones equipped with multispectral cameras to quickly scan large fields for early signs of virus infection (often visible as color changes before symptoms are clear to the naked eye) or for the presence of honeydew, flagging specific areas for immediate spot treatment or roguing.

Novel Delivery Systems: Developing encapsulated or micro-dosed systemic treatments that release the active ingredient precisely when the plant is most vulnerable to aphid colonization, maximizing efficacy while minimizing environmental release.

Conclusion

The Potato Aphid (*Macrosiphum euphorbiae*) represents a multifaceted threat to crop production, driven by its high reproductive rate and, crucially, its efficiency as a viral vector. The traditional, chemical-heavy approach is ecologically and economically bankrupt. Integrated Pest Management (IPM) is the necessary and intelligent solution, providing a sustainable framework that prioritizes prevention, biological controls, host resistance, and risk-based decision-making derived from systematic monitoring. By focusing on mitigating virus spread rather than merely aphid numbers, IPM stabilizes potato yields, safeguards seed stock integrity, and ensures the long-term health and sustainability of food systems worldwide.

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MICROPLASTICS AND EMERGING POLLUTANTS IN AQUACULTURE: RISKS, DETECTION, AND MITIGATION STRATEGIES

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Abstract

Aquaculture plays a vital role in global food security and economic development; however, increasing contamination of aquatic ecosystems by microplastics and emerging pollutants has become a major challenge to sustainable aquaculture production. Microplastics, originating from plastic degradation, fishing activities, aquaculture infrastructure, and wastewater discharge, are now widely distributed in aquatic environments. Similarly, emerging pollutants such as pharmaceuticals, antibiotics, pesticides, endocrine-disrupting chemicals, heavy metals, and personal care products are continuously introduced into aquaculture systems through agricultural runoff, industrial effluents, sewage discharge, and intensive farming practices. These contaminants adversely affect aquatic organisms by inducing oxidative stress, tissue damage, immune suppression, reproductive dysfunction, metabolic disorders, and behavioral abnormalities. Moreover, bioaccumulation and trophic transfer of pollutants through the aquatic food chain pose significant risks to human health and seafood safety. Advanced analytical tools including Fourier Transform Infrared Spectroscopy (FTIR), Raman spectroscopy, chromatography, mass spectrometry, biosensors, and molecular techniques have improved pollutant detection and environmental monitoring. Sustainable mitigation strategies such as biofloc technology, recirculating aquaculture systems (RAS), integrated multi-trophic aquaculture (IMTA), bioremediation, and eco-friendly waste management practices provide promising approaches for reducing pollutant loads in aquaculture environments. Furthermore, the integration of artificial intelligence, IoT-based monitoring systems, and nanotechnology may enhance real-time pollution surveillance and sustainable aquaculture management. Therefore, effective monitoring, regulatory frameworks, and advanced remediation technologies are essential to minimize environmental contamination and ensure safe and sustainable aquaculture production.

Introduction

Aquaculture has emerged as one of the most rapidly expanding food production sectors worldwide and currently contributes more than half of the fish consumed globally (FAO, 2022). The increasing demand for seafood products has intensified aquaculture production systems, thereby improving food security and economic growth. However, rapid industrialization, urbanization, and agricultural expansion have simultaneously increased environmental pollution in aquatic ecosystems, posing serious challenges to sustainable aquaculture development. Among aquatic pollutants, microplastics and emerging contaminants have received substantial scientific attention due to their persistence, toxicity, and widespread distribution in freshwater and marine environments (Cole *et* *al*., 2011). Microplastics are plastic particles smaller than 5 mm and are categorized into primary and secondary microplastics. Primary microplastics are intentionally manufactured in microscopic sizes for industrial and cosmetic applications, whereas secondary microplastics result from the degradation of larger plastic materials through physical, chemical, and biological processes (GESAMP, 2015). Emerging pollutants include pharmaceuticals, antibiotics, pesticides, endocrine-disrupting compounds, heavy metals, nanomaterials, and personal care products that are not routinely monitored but may cause adverse environmental and health effects (Barbosa *et al*., 2016). These pollutants are introduced into aquatic environments through multiple pathways including industrial effluents, agricultural runoff, sewage discharge, hospital wastewater, and aquaculture activities (Carvalho, 2017). Aquaculture systems are highly vulnerable to contamination because various plastic materials such as fishing nets, cages, feed bags, ropes, and tanks continuously release plastic particles into water bodies (Auta *et al*., 2017). Additionally, the extensive use of antibiotics and chemicals in aquaculture for disease prevention and growth promotion contributes to environmental contamination and antimicrobial resistance (Cabello, 2006). Pollutants accumulated in water and sediments can be ingested by aquatic organisms and transferred through the food chain. Microplastics and emerging pollutants negatively affect fish health by inducing oxidative stress, tissue damage, inflammation, metabolic disorders, reproductive dysfunction, and immune suppression (Wright *et al*., 2013; Rochman *et al*., 2013). Furthermore, contaminants accumulated in seafood products may pose significant risks to human health through dietary exposure (Rist *et al*., 2018). Therefore, effective monitoring, detection, and mitigation strategies are urgently required to minimize pollution risks and ensure sustainable aquaculture practices.

Microplastics in Aquaculture Systems

Definition and Classification

Microplastics are defined as plastic particles smaller than 5 mm in diameter and are broadly categorized into primary and secondary microplastics (GESAMP, 2015). Primary microplastics are manufactured intentionally for industrial products, cosmetics, and pharmaceuticals, whereas secondary microplastics are generated from fragmentation of larger plastic debris due to ultraviolet radiation, mechanical abrasion, and biological degradation (Cole *et al*., 2011). Based on size, plastics may further be classified into macroplastics, mesoplastics, microplastics, and nanoplastics.

Sources in Aquaculture

Aquaculture activities contribute significantly to microplastic pollution through the use of synthetic nets, plastic tanks, ropes, cages, and feed packaging materials (Auta *et al*., 2017). Fishing gear degradation and improper disposal of plastic waste further increase contamination levels in aquatic systems. In addition, urban runoff, industrial discharge, and wastewater effluents introduce substantial quantities of microplastics into ponds, rivers, lakes, and coastal aquaculture environments (Li *et al*., 2018).

Environmental Distribution

Microplastics are widely distributed in water columns, sediments, aquatic plants, and fish tissues (Li *et al*., 2018). Due to their small size and buoyancy, microplastics can be easily ingested by plankton, mollusks, crustaceans, and fish species. These particles can subsequently transfer through trophic levels and accumulate in higher organisms, including humans (Lusher *et al*., 2017).

Biological Impacts

Several studies have reported that microplastics induce oxidative stress, inflammatory responses, gut blockage, tissue damage, and behavioral abnormalities in fish (Wright *et al*., 2013). Chronic exposure may impair feeding efficiency, reproductive performance, growth, and immune responses.

Rochman *et al*. (2013) demonstrated that ingestion of plastic-associated contaminants caused hepatic stress and physiological disturbances in fish. Furthermore, microplastics may act as vectors for toxic chemicals and pathogenic microorganisms, thereby increasing ecological and health risks.

Emerging Pollutants in Aquaculture

Types of Emerging Pollutants

Emerging pollutants in aquaculture include pharmaceuticals, antibiotics, heavy metals, pesticides, endocrine-disrupting chemicals, personal care products, and engineered nanomaterials (Barbosa *et al*., 2016). Antibiotics are frequently used in intensive aquaculture systems to prevent bacterial infections and enhance productivity, while pesticides and herbicides often originate from nearby agricultural activities (Cabello, 2006).

Sources and Pathways

These pollutants enter aquaculture systems through agricultural runoff, industrial effluents, municipal wastewater, hospital discharge, and aquaculture chemicals (Carvalho, 2017). Untreated sewage and pharmaceutical residues are major contributors to aquatic contamination in many developing countries.

Effects on Aquatic Organisms

Emerging pollutants can adversely affect aquatic organisms even at low concentrations. Exposure to endocrine-disrupting chemicals may alter hormonal regulation, reproductive development, and metabolism in fish species (Barbosa *et al*., 2016). Heavy metals and pesticides may accumulate in tissues and induce oxidative stress, neurotoxicity, and organ damage (van der Oost *et al*., 2003). Furthermore, prolonged exposure to antibiotics promotes antimicrobial resistance among aquatic microbial communities, posing severe environmental and public health concerns (Miranda & Zemelman, 2002).

Risks Associated with Microplastics and Emerging Pollutants

Risks to Fish Health

Microplastics and emerging pollutants significantly affect fish physiology and survival. Pollutant exposure may result in liver toxicity, intestinal damage, altered swimming behavior, reduced growth, reproductive impairment, and immune suppression (Wright *et al*., 2013). Chronic contamination also increases susceptibility to infectious diseases and metabolic disorders.

Human Health Risks

Contaminants accumulated in fish tissues can transfer to humans through seafood consumption. Toxic additives associated with plastics, including bisphenol A and phthalates, may cause endocrine disruption, carcinogenicity, and developmental abnormalities in humans (Rist *et al*., 2018). In addition, antibiotic residues and antimicrobial-resistant bacteria represent major food safety concerns (Ahmed *et al*., 2017).

Environmental Risks

The accumulation of pollutants in aquatic ecosystems may reduce biodiversity and disturb ecological balance. Sediment contamination can affect benthic organisms and alter microbial communities involved in nutrient cycling (Auta *et al*., 2017). Persistent pollutants may remain in aquatic environments for extended periods and continuously affect aquatic organisms.

Economic Impacts

Environmental pollution in aquaculture systems may reduce fish productivity, increase mortality rates, and compromise seafood quality. Contaminated seafood products may fail export standards, leading to substantial economic losses for aquaculture industries and associated stakeholders.

Detection and Monitoring Technologies

Detection Methods for Microplastics

Various analytical techniques are used for the identification and characterization of microplastics. Microscopy methods enable visual examination of particle shape and size, while FTIR and Raman spectroscopy provide detailed polymer composition analysis. Scanning Electron Microscopy (SEM) is also widely employed for surface morphology studies.

Detection of Emerging Pollutants

High-Performance Liquid Chromatography (HPLC), Gas Chromatography-Mass Spectrometry (GC-MS), and Liquid Chromatography-Mass Spectrometry (LC-MS) are commonly used for detecting pharmaceuticals, pesticides, and chemical contaminants in aquatic systems (Barbosa *et al.*, 2016). Biosensors and molecular approaches are increasingly being developed for rapid and sensitive pollutant monitoring.

Advanced Monitoring Approaches

Modern monitoring technologies including remote sensing, artificial intelligence, smart sensors, and IoT-based systems allow real-time water quality monitoring and pollutant detection. These advanced approaches improve environmental surveillance and facilitate early warning systems in aquaculture operations.

Mitigation and Management Strategies

Pollution Prevention

Reducing plastic waste generation and improving waste management practices are essential for minimizing microplastic contamination. The use of biodegradable materials and effective wastewater treatment technologies can significantly reduce pollutant discharge into aquatic ecosystems.

Sustainable Aquaculture Practices

Biofloc systems, recirculating aquaculture systems (RAS), and integrated multi-trophic aquaculture (IMTA) improve water quality and reduce waste accumulation in aquaculture systems (Boyd & Tucker, 2012). These systems promote nutrient recycling and environmental sustainability.

Bioremediation Approaches

Microbial degradation and algal remediation have shown considerable potential for removing pollutants from aquatic environments. Certain microorganisms possess the ability to degrade plastics and absorb toxic compounds. Nanotechnology-based adsorbents are also increasingly explored for pollutant removal and water purification.

Policy and Regulatory Measures

Strict environmental regulations regarding plastic disposal, industrial effluent management, and antibiotic usage are necessary for sustainable aquaculture development. International monitoring guidelines and public awareness programs should be strengthened to reduce aquatic pollution.

Role of Advanced Technologies

Advanced technologies are revolutionizing pollution management in aquaculture systems. Artificial intelligence and machine learning algorithms can predict pollution patterns and optimize water quality management. IoT-based smart sensors enable continuous monitoring of dissolved oxygen, pH, temperature, turbidity, and contaminant concentrations in real time. Nanotechnology offers innovative methods for pollutant adsorption, filtration, and remediation, while biosensors provide rapid and highly sensitive detection of toxic chemicals and pathogens. Precision aquaculture systems integrating automation, big data analytics, and environmental monitoring tools may significantly improve sustainability and productivity.

Challenges and Future Perspectives

Despite significant progress in pollution research, several challenges remain in managing microplastics and emerging pollutants in aquaculture systems. One of the major limitations is the absence of standardized protocols for sampling, extraction, and quantification of microplastics and chemical contaminants, leading to variability among studies (Li *et al*., 2018). High operational and analytical costs associated with advanced monitoring technologies further limit their application, particularly in developing countries. Limited awareness among farmers and stakeholders regarding pollutant impacts and management practices also hinders effective mitigation efforts. In addition, existing environmental regulations are often insufficient to address emerging contaminants such as pharmaceuticals, nanomaterials, and microplastics. Interactions between different pollutants and their combined toxicological effects require further interdisciplinary investigation.

Future research should focus on developing affordable, rapid, and highly sensitive detection technologies for real-time environmental monitoring. Artificial intelligence, biosensors, and IoT-based systems may significantly improve pollution surveillance and early warning capabilities. Furthermore, the development of biodegradable aquaculture materials and sustainable bioremediation strategies could reduce environmental contamination and improve ecosystem resilience. Strong international collaboration, policy implementation, and public awareness programs will be essential for achieving sustainable and environmentally safe aquaculture systems.

Conclusion

Microplastics and emerging pollutants have become major threats to aquaculture sustainability, aquatic biodiversity, and seafood safety. These contaminants originate from multiple anthropogenic activities including plastic waste disposal, industrial discharge, pharmaceutical usage, and agricultural runoff. Their accumulation in aquatic environments can adversely affect fish health by causing oxidative stress, tissue damage, reproductive dysfunction, and immune suppression. Furthermore, contaminants may bioaccumulate and transfer through the food chain, posing serious risks to human health. Advanced detection technologies such as FTIR, Raman spectroscopy, chromatography, biosensors, and AI-based monitoring systems are improving pollutant detection and environmental surveillance. Sustainable mitigation strategies including biofloc technology, recirculating aquaculture systems, integrated multi-trophic aquaculture, and bioremediation approaches provide promising solutions for minimizing pollution impacts. Effective management of microplastics and emerging pollutants requires coordinated efforts among researchers, policymakers, industries, and aquaculture stakeholders. Strengthening environmental regulations, promoting sustainable aquaculture practices, and investing in advanced technologies will be essential for ensuring long-term environmental sustainability and safe aquatic food production.

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THE SILENT SABOTEUR: SAW-TOOTHED GRAIN BEETLE – D AMAGE SYMPTOMS, LIFE CYCLE, AND A SMART WAY TO PROTECT CROPS

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Abstract

The Saw-Toothed Grain Beetle (*Oryzaephilus surinamensis*) is a pervasive, cosmopolitan secondary pest severely impacting the quality and commercial viability of stored agricultural products worldwide. This article advocates for the adoption of Integrated Pest Management (IPM) as the most effective, sustainable, and intelligent strategy for its control. IPM offers a comprehensive, knowledge-based alternative to reliance on chemical treatments by integrating rigorous sanitation, effective monitoring using pheromone and pitfall traps, non-chemical controls like thermal disinfestation, and the judicious application of targeted chemical control as a last resort. We detail the essential IPM features, practical methodologies, tangible positive outcomes, and future technological advancements necessary to secure the global grain supply chain against this persistent threat.

Keywords: Integrated Pest Management (IPM), Saw-Toothed Grain Beetle (*Oryzaephilus surinamensis*), Stored-Product Pests, Grain Storage, Sanitation, Monitoring, Pheromone Traps, Thermal Disinfestation, Chemical Control and Food Security.

Introduction and Background

The preservation of harvested grains and processed food commodities is a critical component of global food security. Post-harvest losses due to insect infestation are staggering, often leading to millions of tons of food being contaminated, damaged, or entirely wasted annually. Among the most challenging pests to manage in food processing and storage environments is the Saw-Toothed Grain Beetle (*Oryzaephilus surinamensis*).

This minute, flat, reddish-brown beetle, typically 2.5–3.0 mm long, is readily identified by the distinctive row of six saw-like teeth projections on each side of its pronotum (the shield behind its head). Its flat morphology allows it to easily penetrate common packaging and hide in minute cracks and crevices, making eradication difficult. While primarily a secondary pest—feeding on processed, broken, or damaged goods—its rapid reproduction and longevity (adults can live for several months) allow populations to explode quickly under favorable conditions (25∘C to 35∘C and 70%–90% relative humidity), leading to massive contamination of flours, cereals, nuts, and dry pet foods.

Historically, the control of O. surinamensis relied heavily on broad-spectrum fumigants, primarily phosphine. However, the excessive and often poorly executed use of these chemicals has spurred the development of widespread insecticide resistance in beetle populations, rendering chemical treatments increasingly unreliable. Furthermore, growing regulatory restrictions and consumer demand for food products free of chemical residues have necessitated a paradigm shift. This has established Integrated Pest Management (IPM) as the standard for effective and sustainable stored-product protection.

IPM is an ecological approach that utilizes a diverse array of tactics to manage pests below economically damaging thresholds while minimizing environmental and health risks. It is a strategic, continuous process rather than a single application, prioritizing prevention and non-chemical controls over reactive chemical intervention.

Methodologies and Key Features of IPM

The success of IPM against the Saw-Toothed Grain Beetle rests on four interdependent and crucial components

1. Prevention and Sanitation (The Foundation)

Sanitation is the single most important control tactic. It directly removes the pest's food source, harborage, and breeding sites.

Key Features: Exclusion and Housekeeping.

Methodology:

Thorough Cleaning: All storage structures, including silos, bins, conveyor systems, and processing equipment, must be completely emptied and meticulously cleaned. High-suction vacuums with crevice tools are essential for removing all spilled grain, dust, and food fines that harbor the beetles.

Structural Repair: Sealing all potential entry and hiding points—cracks in walls and floors, gaps around pipes, and unsealed equipment—using appropriate sealants (caulk, concrete) prevents infestation establishment and movement.

Stock Rotation (First-In, First-Out or FIFO): Ensuring that older stocks are used first prevents commodities from sitting idle for long periods, which allows pest populations to build up.

2. Monitoring and Inspection (The Intelligence Gathering)

Accurate and early detection is the IPM linchpin, enabling targeted, cost-effective intervention.
Key Features: Trap-based Surveillance and Threshold Determination.

Materials Used:

Pheromone and Food-Bait Traps: Pitfall traps (e.g., dome traps) or sticky traps are strategically placed in a grid pattern. They are typically baited with a synthetic aggregation pheromone unique to *O. surinamensis* combined with a food lure.

Sieving and Sampling: Regular manual samples of grain or flour are collected and passed through a series of sieves to physically extract and count insects.

Methodology: Trap counts and sample analyses are performed weekly or bi-weekly. Results are compared against predetermined action thresholds (e.g., 5 beetles per trap per week) to decide if and when control measures are necessary, avoiding unnecessary treatment.

3. Non-Chemical/Physical Control (The Sustainable Tactics)

These methods manipulate the environment to directly kill pests without introducing chemical residues.

Key Features: Thermal and Atmospheric Manipulation.

Methodology:

Thermal Disinfestation: Exploiting the beetle's intolerance to extreme temperatures.

Heat: Heating empty mills, warehouses, or equipment to a sustained temperature of 55∘C to 60∘C for a minimum of 24 hours achieves high mortality across all life stages.

Cold: Freezing infested commodities or empty spaces at −18∘C (0∘F) or lower for 3 to 7 days is highly effective for smaller batches.

Modified Atmosphere (MA): Sealing storage bins and injecting inert gases (CO2 or N2) to reduce the oxygen level below 1% is an effective, non-residual method for bulk commodities.

Diatomaceous Earth (DE): Applying finely ground fossilized diatoms acts as a physical control. The sharp particles abrade the insect's cuticle, leading to desiccation. It is used as a dust application in empty structures or sometimes mixed into grain.

4. Judicious Chemical Control (The Last Resort)

Chemicals are used selectively and only when non-chemical methods have failed to keep pest populations below the action threshold.

Key Features: Targeted, Low-Residue Application.

Methodology:

Targeted Residual Sprays: Applying EPA-approved liquid residual insecticides (e.g., synthetic pyrethroids) only to treated areas like cracks, crevices, or perimeter walls after cleaning and before new product is introduced, ensuring no direct contact with food.

Insect Growth Regulators (IGRs): Compounds like methoprene, which interfere with the beetle's development, are applied as highly selective residual treatments.

Fumigation: This is reserved as a last resort for heavy, widespread infestations in sealed storage facilities. It relies on highly regulated chemicals like phosphine (PH3), and its use must be carefully managed to prevent further development of resistance.

Outcomes and Future Prospects

Outcomes of IPM

Sustainable Control: IPM delivers long-term, stable control by breaking the pest cycle through sanitation, rather than merely treating the symptoms, significantly reducing reliance on chemicals.

Enhanced Food Quality and Safety: Minimizing chemical use reduces the risk of pesticide residues in the final product, meeting strict international safety standards and consumer expectations.

Economic Efficiency: Early detection through monitoring allows for targeted, small-scale treatments, avoiding the costly necessity of discarding large, contaminated batches of product or the high expense of emergency fumigation.

Reduced Insecticide Resistance: The use of multiple, non-chemical control modalities reduces the selection pressure on the beetle population, helping to preserve the effectiveness of the limited available chemical tools.

Future Prospects for IPM

The future of O. surinamensis control lies in the convergence of biology, engineering, and data science:

Precision Pest Management (PPM): Integrating Internet of Things (IoT) sensors for real-time monitoring of temperature, moisture, and pest movement within grain mass. This data, coupled with Artificial Intelligence (AI) and image recognition technology, will allow for automated, instantaneous identification of infestation hotspots and the ability to apply control measures with micro-precision.

Advanced Biological Control: Increased research into the mass production and strategic deployment of natural enemies, particularly specialized parasitoid wasps and predatory mites, will enhance the use of biological controls within storage ecosystems. This involves developing methods to integrate them with "soft chemistry" that minimizes harm to beneficial organisms.

Novel Green Technologies: Continued development of innovative, non-toxic control agents, such as highly effective inert dusts (like advanced formulations of Diatomaceous Earth) and the synthesis of botanical extracts with specific insecticidal and repellent properties, will further broaden the non-chemical IPM toolkit.

Conclusion

The Saw-Toothed Grain Beetle remains a persistent and formidable adversary in the world of stored product protection. The era of relying solely on blanket chemical applications is over, having proven environmentally detrimental and biologically unsustainable due to the prevalence of insecticide resistance. Integrated Pest Management (IPM) represents the smart, essential, and responsible way forward. By prioritizing prevention, information (monitoring), and non-chemical tactics, and reserving targeted chemical intervention only when justified by economic thresholds, IPM effectively secures crop quality and safety, ensures economic viability for stakeholders, and upholds global food security mandates. The continuous integration of technology and biological solutions promises to make future IPM programs even more precise and powerful.

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UNVEILING THE HIDDEN WORLD OF PLANT VIROMES THROUGH METAGENOMICS

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Abstract

Plant viromes comprise the complete assemblage of viruses associated with plants, including pathogenic, asymptomatic, and beneficial viruses. Advances in metagenomics and next-generation sequencing (NGS) have revolutionized plant virology by enabling the unbiased detection and characterization of viral communities without prior knowledge of their identity. These technologies have revealed extensive viral diversity in agricultural and natural ecosystems, leading to the discovery of numerous novel viruses and improving our understanding of virus evolution, ecology, and plant–virus interactions. Key approaches for plant virome analysis include total RNA sequencing, small RNA sequencing, DNA virome sequencing, and bioinformatics-based data analysis. Virome studies have significantly enhanced disease diagnostics, surveillance, and the early detection of emerging viral threats, thereby supporting crop protection and biosecurity efforts. Future developments in long-read sequencing, artificial intelligence, and advanced bioinformatics are expected to further accelerate virus discovery and enable precision disease management. Overall, metagenomics is transforming our understanding of plant health and ecosystem dynamics.

Key words: Virome, NGS, Metagenomics, Diagnostics

Introduction

Plants harbour a diverse community of viruses, collectively known as the plant virome, which includes both pathogenic and asymptomatic viruses. Traditional diagnostic methods are often limited to detecting known viruses, leaving much of this viral diversity unexplored. The advent of metagenomics and next-generation sequencing (NGS) has transformed plant virology by enabling the unbiased detection and characterization of all viral genomes present in a sample.

Metagenomic approaches have revealed an unprecedented diversity of plant-associated viruses in crops, wild plants, and natural ecosystems, leading to the discovery of numerous novel viral species and insights into virus evolution, ecology, and transmission. Beyond disease diagnosis, plant virome studies contribute to surveillance of emerging viral threats, understanding plant–virus interactions, and developing sustainable disease management strategies. As sequencing technologies continue to advance, metagenomics is playing a pivotal role in uncovering the hidden viral world associated with plants and expanding our understanding of plant health and ecosystem dynamics.

Importance of plant viromes in agriculture and ecosystems

Plant viromes, comprising all viruses associated with plants, play a significant role in both agricultural systems and natural ecosystems. While many plant viruses are recognized as important pathogens causing substantial yield and quality losses in crops, a large proportion of plant-associated viruses remain asymptomatic and may influence plant physiology, adaptation, and ecological interactions (Roossinck, 2015; Roossinck *et al*., 2015). Understanding plant viromes is therefore essential for effective disease monitoring, early detection of emerging viral threats, and the development of sustainable crop protection strategies (Prasad *et al.*, 2020). In agricultural ecosystems, virome studies facilitate the identification of known and novel viruses, reveal mixed infections, and improve our understanding of virus epidemiology and evolution (Roossinck *et al.*, 2015; Massart *et al.*, 2017). Such knowledge supports the development of accurate diagnostics and informed disease management practices. In natural ecosystems, plant viromes contribute to shaping plant community dynamics, biodiversity, and plant–microbe interactions. Wild plants frequently act as reservoirs of viral diversity, serving as sources of virus emergence in cultivated crops (Roossinck, 2015). Moreover, certain persistent and mutualistic viruses may enhance plant tolerance to abiotic stresses such as drought, heat, and salinity, highlighting the complex and multifaceted roles of viruses in plant biology (Roossinck, 2015). Recent advances in metagenomics and high-throughput sequencing have greatly expanded our understanding of plant viromes, uncovering numerous previously unknown viruses and enabling comprehensive studies of viral diversity, ecology, and evolution (Simmonds *et al.*, 2017; Prasad *et al.*, 2020). These insights are increasingly contributing to agricultural sustainability, biosecurity, and ecosystem health (Zhan *et al.*, 2022).

Approaches for plant virome analysis

Plant virome analysis relies on several metagenomic approaches for the comprehensive detection and characterization of plant viruses. Total RNA sequencing is widely used because it enables the simultaneous detection of RNA viruses, DNA virus transcripts, and viroids without prior knowledge of the pathogens present (Roossinck *et al.*, 2015; Massart *et al.*, 2017).

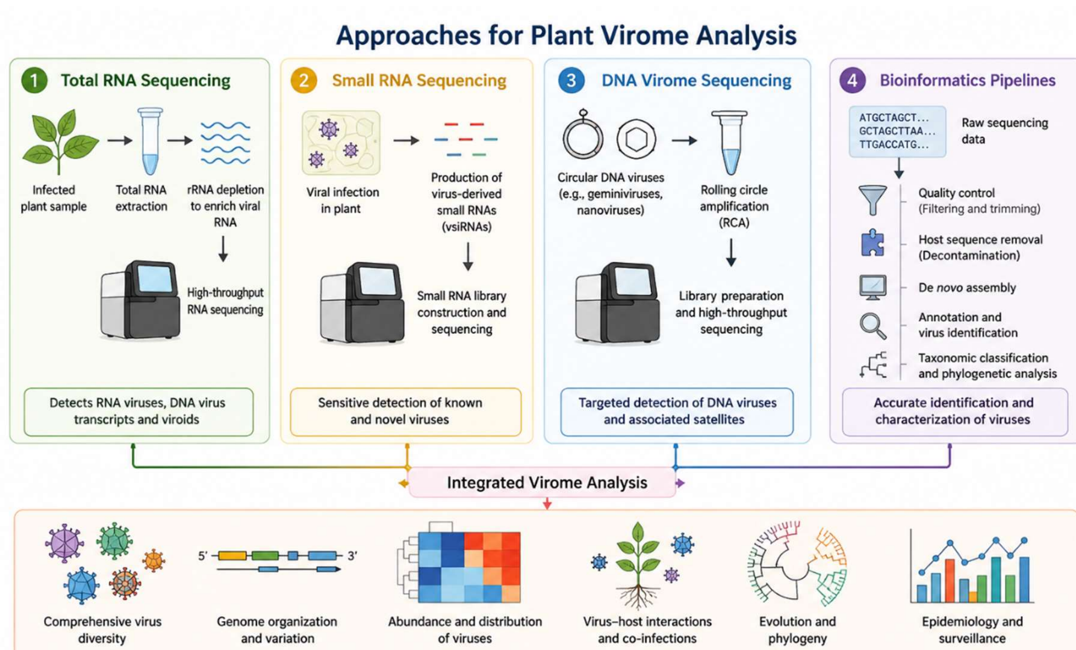

Figure 1. Integrated approaches for plant virome analysis, including total RNA sequencing, small RNA sequencing, DNA virome sequencing, and bioinformatics pipelines for virus detection, characterization, and epidemiological studies.

Small RNA sequencing exploits the plant antiviral RNA silencing mechanism by sequencing virus-derived small interfering RNAs (vsiRNAs), making it highly effective for identifying both known and novel viruses (Kreuze *et al*., 2009; Massart *et al*., 2017). DNA virome sequencing, often combined with rolling circle amplification, specifically targets DNA viruses such as geminiviruses and nanoviruses, facilitating studies on their diversity and evolution (Jeske, 2009; Bernardo *et al*., 2018). The large volume of sequencing data generated by these approaches is analyzed using bioinformatics pipelines, which perform quality control, sequence assembly, annotation, taxonomic classification, and phylogenetic analysis to accurately identify viruses and assess their diversity (Prasad *et al*., 2020; Kutnjak *et al*., 2021). Together, these approaches have revolutionized plant virus discovery and expanded our understanding of plant viromes.

Applications of plant virome studies

Disease Diagnostics and Surveillance

Plant virome studies have transformed disease diagnostics by enabling the simultaneous detection of multiple viruses, including those present at low titers or in mixed infections. High-throughput sequencing (HTS)-based virome analysis provides an unbiased and comprehensive assessment of viral communities in plant samples, facilitating accurate identification of known and novel pathogens. These approaches enhance disease surveillance by monitoring virus distribution, prevalence, and evolution across regions, thereby supporting early intervention, quarantine measures, and informed disease management strategies (Roossinck *et al*., 2015; Massart *et al*., 2017; Hadidi *et al*., 2016).

Early Detection of Emerging Viruses

Virome studies play a critical role in the early detection of emerging and previously unknown plant viruses. Metagenomic sequencing allows the identification of novel viral species, variants, and recombinant strains without requiring prior sequence information. Such early detection is essential for assessing potential threats to crop production, implementing containment measures, and developing targeted diagnostic tools before widespread disease outbreaks occur. Consequently, virome-based surveillance contributes significantly to global plant biosecurity and sustainable agriculture (Roossinck *et al*., 2015; Villamor *et al*., 2019; Massart *et al*., 2022).

Future Perspectives

The future of plant virome research will be driven by advances in third-generation sequencing technologies, such as long-read sequencing platforms, which enable rapid, real-time, and more accurate characterization of complete viral genomes and complex virome populations. The integration of artificial intelligence (AI), machine learning, and advanced bioinformatics tools will further enhance virus detection, genome assembly, taxonomic classification, and prediction of virus–host interactions from large-scale sequencing datasets. Furthermore, virome-informed disease management strategies, combining genomic surveillance with epidemiological and ecological data, will facilitate early warning systems, precision disease forecasting, and the development of sustainable approaches for protecting crop health and ensuring global food security (Rhoads & Au, 2015; Villamor *et al*., 2019; Massart *et al*., 2022).

Conclusion

Plant virome studies have greatly advanced our understanding of the diversity, ecology, and evolution of plant-associated viruses. The integration of metagenomics and high-throughput sequencing has enabled the comprehensive detection of known and novel viruses, improving disease diagnostics, surveillance, and biosecurity. As sequencing technologies and bioinformatics tools continue to evolve, plant virome research will play an increasingly important role in sustainable crop protection, early disease warning systems, and the maintenance of agricultural and ecosystem health.

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YELLOW STEM BORER: DAMAGE, BIOLOGY, AND SMART CROP PROTECTION

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Abstract

The Yellow Stem Borer (YSB), *Scirpophaga incertulas*, is one of the most destructive insect pests of rice across Asia, causing significant yield losses through its characteristic damage symptoms known as 'dead hearts' and 'white ears'. The hidden, internal feeding habits of its larvae make chemical control challenging and often ineffective. This article details the life cycle and damaging phases of the YSB and advocates for Integrated Pest Management (IPM) as the most effective, sustainable, and intelligent strategy for its control. IPM for YSB integrates rigorous monitoring using pheromone traps, targeted cultural practices, strategic deployment of natural enemies, and the judicious use of selective chemical control. We explore the essential components, practical methodologies, tangible positive outcomes, and future technological prospects of leveraging IPM to stabilize rice production and ensure global food security.

Keywords: Integrated Pest Management (IPM), Yellow Stem Borer (YSB), *Scirpophaga incertulas*, Rice Pest, Dead Heart, White Ear, Pheromone Traps, Cultural Control, Biological Control, Selective Insecticides and Crop Protection.

Introduction and Background

Rice (*Oryza sativa*) is the staple food for more than half of the world's population, making the security of its production paramount. Among the many threats to rice cultivation, the Yellow Stem Borer (YSB), *Scirpophaga incertulas*, is consistently ranked as a primary cause of economic loss across major rice-growing regions, particularly in South and Southeast Asia. Infestations can lead to yield reductions ranging from 10% to 30% and, in severe cases, total crop failure.

The damage is caused exclusively by the larva (caterpillar) stage, which bores into the rice stem (tiller) and feeds internally on the tissues, severing the plant's vascular system. This internal feeding makes the pest difficult to reach with conventional contact insecticides, contributing to the persistent nature of the problem.

For decades, the response to YSB outbreaks was characterized by the frequent and often indiscriminate application of broad-spectrum granular and foliar insecticides. This approach resulted in several negative consequences:

Ineffectiveness: The pest's concealed location inside the stem reduced insecticide efficacy.

Environmental Harm: High chemical loads poisoned non-target organisms, including fish, aquatic life in the paddies, and beneficial natural enemies.

Pest Resurgence: The killing of natural enemies led to rapid resurgence of YSB and the proliferation of secondary pests, necessitating even more chemical use—a destructive cycle.

These failures established the critical need for a more nuanced, sustainable, and scientifically grounded strategy: Integrated Pest Management (IPM). IPM for YSB is a holistic, knowledge-intensive approach that focuses on prevention, leveraging ecological processes, and utilizing targeted control tactics only when the pest population reaches a predefined economic threshold.

Life Cycle and Damage Dynamics

Effective control hinges on understanding the YSB's life cycle and the symptoms that indicate its destructive presence.

Life Cycle Summary

The YSB completes its life cycle in approximately 30 to 45 days, allowing for multiple generations (up to five or six) within a single rice-growing season.

Egg: The female moth lays masses of creamy-yellow, overlapping eggs, typically near the tips of the leaves, covering the egg mass with a protective layer of buff-colored hairs from her abdomen. Egg clusters hatch in 4–10 days.

Larva (Caterpillar): This is the destructive stage. The newly hatched larvae disperse, enter the stem, and feed internally. The larva is yellowish-white with a distinct orange-yellow head. It undergoes 4–6 molts. The larval stage lasts 25–35 days and is the target of most control measures.

Pupa: The mature larva pupates inside the stem near the base.

Adult Moth: The adult female is characterized by bright yellow forewings with a conspicuous black spot on each. The adult male is smaller and paler. Moths emerge at night, are attracted to light, and are responsible for mating and egg deposition.

Dynamics and Symptoms

The larval boring and feeding cause two distinct and debilitating symptoms, depending on the crop growth stage:

'Dead Heart' (Vegetative Phase): When the tiller is infested during the vegetative stage (before flowering), the central shoot is cut off from its vascular supply, withers, and dries up. This symptom, called a dead heart, is easily recognized as a pale yellow, shriveled central shoot that can be pulled out easily from the base. Although the plant can produce compensatory tillers, the affected tiller is lost, resulting in reduced plant vigor and density.

'White Ear' or 'White Head' (Reproductive Phase): When infestation occurs after flowering (the reproductive stage), the developing panicle (rice head) is prevented from filling. The entire panicle turns white, erect, and chaffy (empty), as it contains no grain. This symptom is known as a white ear and represents a direct loss of yield, as the panicle is completely barren.

Methodologies and Key Features of IPM

IPM for YSB is a synchronized, multi-tactic approach designed to disrupt the pest's life cycle at its most vulnerable points (egg and early larva) and minimize the use of internal, systemic chemicals.

1. Monitoring and Surveillance (The Intelligence Phase)

Accurate and timely monitoring is the bedrock for deciding when and where to apply control measures.

Key Features: Pheromone Trapping and Field Scouting.

Materials Used:
Pheromone Traps: Traps baited with the synthetic sex pheromone of the female YSB are deployed to specifically catch the adult male moths. Traps are placed in the field (3–5 per acre) before the transplanting season.

Light Traps: Although less specific, light traps are used during the adult emergence peak to monitor population density and provide an early warning of an imminent egg-laying period.

Methodology: The number of moths captured in pheromone traps is counted daily or every two days to determine the Moth Trap Catch and track population trends. An Economic Threshold Level (ETL), often set at 5% dead hearts or a certain pheromone trap catch, is used to justify intervention.

2. Cultural Control (Preventive Management)
These are simple, low-cost farming practices that reduce pest survival and multiplication.
Key Features: Sanitation and Planting Strategy.

Methodology:
Stubble Plowing/Flooding: After harvest, the stubble often harbors diapausing (overwintering) YSB larvae. Plowing the field and flooding it immediately after harvest destroys these larvae, reducing the initial infestation source for the next season.

Clipping Seedlings: Before transplanting, the tips of the rice seedlings are clipped. This removes any eggs laid by the YSB female on the tips, thus preventing their transfer to the main field.

Synchronous Planting: Coordinating planting dates over a wide area reduces the availability of vulnerable young crops over an extended period, diluting the pest pressure across all fields.

3. Biological Control (Ecological Leverage)
Conserving and augmenting natural enemies is crucial to maintaining long-term population stability.
Key Features: Natural Enemy Conservation and Augmentation.

Materials Used:
Parasitoids: The YSB is attacked by several key natural enemies, most notably egg parasitoids (*Telenomus spp.* and *Trichogramma spp.*) and larval/pupal parasitoids (Ichneumonidae wasps). Augmentation involves controlled release of laboratory-reared Trichogramma wasps (typically three releases at weekly intervals during the egg-laying peak).

Predators: Conserving general predators like spiders, dragonflies, and predatory beetles that feed on the adult moths or early-stage larvae is achieved by avoiding broad-spectrum insecticides.

4. Judicious Chemical Control (The Last Resort)
Chemical intervention is highly targeted, selective, and used only when the ETL is crossed.
Key Features: Selective and Granular Application.

Materials Used:
Selective Insecticides: Newer, selective chemicals (e.g., Fipronil, Chlorantraniliprole) that are safer for natural enemies and aquatic life are preferred over older organophosphates.

Granular Insecticides: These are applied to the water in the paddy field. The chemical is absorbed by the roots and translocated systemically to the stems, directly reaching the borer. This method reduces drift and contact hazard but requires careful dosage.

Methodology: Chemical application is precisely timed to target the peak egg-hatching period (first and second larval instars) before they bore deep into the stem, maximizing efficacy.

Outcomes and Future Prospects

Outcomes of IPM

Sustained Yield Stability: By strategically intervening at the most vulnerable stages and reducing the initial pest inoculum through sanitation, IPM provides stable, long-term control, minimizing the incidence of dead hearts and white ears.

Reduced Environmental Load: The shift from blanket spraying to selective chemicals and the reliance on biological and cultural controls drastically reduces the volume of toxic chemicals entering the paddy ecosystem, protecting beneficial fauna.

Economic Advantage: Although monitoring requires effort, the prevention of crop loss and the reduced expenditure on costly, repeated broad-spectrum sprays offer a higher return on investment than conventional chemical-only approaches.

Preservation of Efficacy: By rotating control tactics, IPM minimizes the selection pressure on the YSB population, slowing the development of insecticide resistance, thus preserving the effectiveness of chemical tools.

Future Prospects for IPM

The future of YSB control lies in the integration of cutting-edge technology and genetics:

Precision Agriculture and IoT: Deployment of Internet of Things (IoT) sensors and drone-based imaging to remotely monitor crop health and pest damage (e.g., recognizing dead hearts from the air). This data, integrated with AI models, will create predictive risk maps, allowing farmers to apply treatments with centimeter-level precision.

Genetic Host-Plant Resistance: Developing and deploying rice varieties that possess genetic resistance or tolerance to YSB feeding is the most sustainable long-term solution. Advances in gene editing (CRISPR) are accelerating the ability to introduce specific resistance genes into high-yielding rice cultivars.

Advanced Semiochemicals: Further development of highly effective, slow-release formulations of YSB pheromones for mass trapping or mating disruption techniques. Mating disruption involves saturating the air with synthetic pheromone to confuse the males, preventing them from locating females.

Molecular Diagnostics: Developing rapid, field-based molecular tools to quickly diagnose the infestation level and the presence of specific parasitoid species will enable faster, evidence-based IPM decisions.

Conclusion

The Yellow Stem Borer (*Scirpophaga incertulas*) is an enduring threat to global rice production, and its internal feeding habit demands a sophisticated control strategy. The failure of chemical-only approaches has clearly demonstrated the necessity of a paradigm shift. Integrated Pest Management (IPM) is the intelligent, modern solution. By effectively integrating cultural methods to reduce the larval source, intensive monitoring with pheromone traps, biological augmentation to leverage natural enemies, and highly targeted chemical applications only when required, IPM secures the rice crop against the YSB. This sustainable framework is essential not only for optimizing farmer profitability but also for upholding the food security of billions.

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CHITOSAN: A SUSTAINABLE SOLUTION TO COMBAT TRANSPIRATION LOSS IN AGRICULTURE

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Introduction

Chitosan is a natural biopolymer obtained by the deacetylation of chitin, which is found in the shells of crustaceans (shrimp, crab), insects, and fungal cell walls. It is a biodegradable, biocompatible and non-toxic polymer, making it highly suitable for sustainable agriculture. Due to its unique cationic (positively charged) nature, chitosan interacts with negatively charged biological surfaces, which contributes to its antimicrobial and plant growth-promoting properties.

Chitosan acts as an effective antitranspirant by forming a thin, semi-permeable film on the leaf surface, which helps reduce excessive water loss through transpiration without significantly affecting gas exchange. This protective layer minimizes stomatal water loss and improves plant water-use efficiency, especially under drought or water deficit conditions. As a result, plants treated with chitosan are better able to maintain leaf water status, sustain physiological processes like photosynthesis and tolerate environmental stress. Additionally, chitosan enhances root growth and water uptake, further supporting moisture balance in plants. Due to these properties, chitosan is widely recognized as a promising eco-friendly antitranspirant for improving crop performance under stress conditions (Fauda and Sarah, 2022).

Properties of Chitosan Relevant to Agriculture

1. Biodegradable and eco-friendly
2. Antimicrobial activity (against fungi, bacteria)
3. Film-forming ability
4. Elicitor of plant defence responses
5. Chelating agent (binds nutrients and metals)
6. These properties make chitosan a strong alternative to synthetic agrochemicals (Arnaz and Inmaculada, 2021).

Mechanism of Chitosan as an antitranspirant

Chitosan acts as an effective antitranspirant primarily through the formation of a thin, semi-permeable film on the leaf surface, which reduces excessive water loss without severely affecting gas exchange. When applied to plant foliage, chitosan creates a protective coating that partially blocks stomatal openings, thereby decreasing transpiration rate. This film modifies the diffusion gradient of water vapor from the leaf to the atmosphere, helping plants retain moisture under stress conditions such as drought or high temperature.

In addition to its physical barrier effect, chitosan also induces physiological responses in plants. It stimulates the production of abscisic acid (ABA), a plant hormone responsible for stomatal closure. Increased ABA levels lead to reduced stomatal aperture, further limiting water loss. Moreover, chitosan enhances antioxidant enzyme activity and osmolyte accumulation, which improves plant water use efficiency and stress tolerance.

Chitosan also strengthens the plant's cuticular layer and improves cell membrane stability, reducing water permeability. Its biopolymeric nature allows it to interact with negatively charged components of plant cell walls, forming a cohesive matrix that minimizes dehydration. Overall, the combined physical (film formation) and biochemical (hormonal and metabolic regulation) effects make chitosan a promising eco-friendly antitranspirant for improving plant performance under water limited conditions.

Uses of Chitosan in Agriculture

1. Plant Growth Promoter

- Enhances seed germination and root development
- Improves photosynthesis and nutrient uptake
- Increases crop yield
- Chitosan is widely used as a biostimulant in crops like soybean, wheat, and vegetables.

2. Disease Control (Biopesticide)

Effective against fungal pathogens such as *Fusarium*, *Alternaria*, *Rhizoctonia* etc.

3. Induction of Plant Immunity

- Chitosan acts as an elicitor, meaning it stimulates plant defence systems by activating systemic acquired resistance (SAR)
- Enhances enzyme activity like peroxidase, chitinase, polyphenol oxidase

4. Seed Treatment

- Improves germination rate and seed vigour
- Protects seeds from soil-borne pathogens
- Enhances early seedling growth

5. Soil Amendment

- Improves soil microbial activity
- Enhances beneficial microorganisms
- Helps in nutrient availability

6. Antitranspirant

- Forms a thin film on leaves
- Reduces water loss through transpiration
- Helps plants tolerate drought conditions

7. Nanochitosan in Agriculture

Recent advancements include nanochitosan, which improves nutrient delivery efficiency, reduces chemical fertilizer use and supports sustainable agriculture systems

Limitations

- Limited solubility at neutral pH
- Efficiency depends on molecular weight and concentration

- Cost can be higher than conventional chemicals

Conclusion

Chitosan is a promising natural polymer that plays a vital role in sustainable agriculture. Its ability to enhance plant growth, induce resistance and reduce chemical inputs makes it an important tool for future eco-friendly farming practices.

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CLIMATE SMART AGRICULTURE THROUGH BENEFICIAL MICROBES: A SUSTAINABLE PATHWAY FOR FUTURE FARMING

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Abstract

Climate change presents major challenges to global agriculture through rising temperatures, irregular rainfall, soil degradation and increased greenhouse gas emissions. Climate-smart agriculture (CSA) has emerged as an integrated approach to enhance productivity, strengthen resilience and reduce environmental impacts. Beneficial microorganisms play an important role in achieving these goals by improving nutrient availability, enhancing soil fertility, increasing plant tolerance to abiotic stress and reducing dependence on chemical inputs. Microbial groups including plant growth-promoting rhizobacteria, cyanobacteria, mycorrhizal fungi and decomposer microorganisms contribute to sustainable crop production and ecosystem stability. Integrating microbial technologies into agricultural systems offers a practical pathway toward resilient, productive and environmentally sustainable future farming. This article highlights the importance of beneficial microbes for a sustainable agriculture.

Key words: Climate smart agriculture, Beneficial microbes, Soil fertility, Sustainable agriculture

Introduction

Agriculture today faces unprecedented challenges as climate change continues to alter environmental conditions worldwide. Rising temperatures, irregular rainfall patterns, increasing soil degradation and frequent extreme weather events threaten global food production and agricultural sustainability. The increase in the world's population has led to a sharp increase in the need for food, and the challenge is rapidly becoming more pressing than before. The issue still exists, despite the fact that these pressing demands have increased agricultural output, 10–12% of the world's anthropogenic emissions of greenhouse gases (GHGs) come from agriculture, which includes both crop and livestock production. Non-CO_2 emissions, which include GHGs other than CO_2, total 5.2–5.8 Carbon dioxide equivalent (GTCO2) annually (Purohit et al., 2024). Therefore, it is necessary to adopt a more sustainable agricultural strategy. Supporting sustainable agriculture globally depends on the idea of Climate Smart Agriculture (CSA), an integrative strategy that attempts to lessen the impact of a changing climate on soils and agro-ecosystems. It has emerged as a transformative approach that aims to increase agricultural productivity, strengthen adaptation to climate variability, and reduce greenhouse gas emissions. Among the various strategies proposed under CSA, the use of beneficial microorganisms has gained considerable attention due to their eco-friendly and multifunctional roles in farming systems. Beneficial microbes form natural associations with plants and contribute to nutrient cycling, soil fertility, stress tolerance and disease suppression.

Research over the past decade has demonstrated that these microbial communities act as natural biofertilizers and biostimulants, enhancing crop growth under conditions of drought, salinity and nutrient limitation. As agriculture moves toward environmentally responsible production systems, harnessing beneficial microbes represents a promising pathway for building climate-resilient farming. Integrating microbial technologies into modern agricultural practices offers an opportunity to produce more food with fewer environmental costs, making beneficial microbes an important component of future climate-smart farming systems.

What is climate smart agriculture?

The term "climate-smart agriculture" describes farming methods that concurrently accomplish three goals: sustainably raise farm income and production. Boost climate change adaptability and resilience. Wherever possible, cut back on greenhouse gas emissions. The idea is to minimize the negative environmental effects of agricultural operations while ensuring food security. In order to accomplish all three objectives, beneficial bacteria are crucial.

Beneficial microbes: Nature's hidden workforce

Beneficial microorganisms, which include various kinds of bacteria, fungus and actinomycetes, are essential to sustainable agriculture because of their multifunctional abilities in increasing crop productivity and environmental resilience. These bacteria boost plant function through a variety of processes, including pathogen suppression, nutrient solubilization, nitrogen fixation, phytohormone synthesis, and stress reduction.

Plant Growth-Promoting Rhizobacteria (PGPR)

Plant Growth-Promoting Rhizobacteria are a diverse group of beneficial soil bacteria that colonize the rhizosphere the narrow region of soil surrounding plant roots and enhance plant growth through direct and indirect mechanisms. These microorganisms have gained major attention in climate-smart agriculture because they improve crop productivity while reducing dependence on chemical fertilizers. PGPR support plant growth directly by increasing nutrient availability and stimulating physiological processes. Certain species such as *Azospirillum* and *Rhizobium* fix atmospheric nitrogen into forms plants can absorb, thereby reducing nitrogen fertilizer requirements. Others, including *Bacillus* and *Pseudomonas* solubilize insoluble phosphorus and mobilize micronutrients such as iron and zinc, making them more accessible to plants. Many PGPR also produce phytohormones including indole-3-acetic acid, gibberellins and cytokinins, which stimulate root elongation, improve nutrient absorption and promote overall plant vigour. In addition to direct growth promotion, PGPR protect plants against environmental stresses and pathogens. These bacteria can induce systemic resistance, allowing plants to activate defense mechanisms against diseases. They produce antimicrobial compounds, siderophores, antibiotics and enzymes that suppress harmful microorganisms. Under climate stress conditions such as drought, salinity, and heat, PGPR help plants maintain water balance and reduce oxidative damage. The application of PGPR has shown positive outcomes in crops including wheat, rice, maize, legumes, and vegetables, contributing to sustainable agricultural intensification and improved soil health.

Cyanobacteria

Cyanobacteria, traditionally referred to as blue-green algae, are ancient photosynthetic microorganisms that play an essential role in sustainable agriculture. These microorganisms possess the unique ability to perform oxygenic photosynthesis and fix atmospheric nitrogen, making them valuable biological inputs for improving soil fertility and reducing synthetic fertilizer use.

Cyanobacterial genera such as *Nostoc*, *Anabaena*, *Cylindrospermum* and *Calothrix* contribute significantly to nutrient enrichment in cropping systems, especially flooded rice ecosystems. Through specialized cells called heterocyst, many cyanobacteria convert atmospheric nitrogen into ammonia, which becomes available to plants. This natural nitrogen-fixing capacity improves crop nutrition and decreases environmental pollution associated with chemical nitrogen fertilizers. Beyond nitrogen fixation, cyanobacteria produce extracellular polymeric substances (EPS) that improve soil aggregation, increase water-holding capacity, and enhance soil structure. Cyanobacterial inoculation has also been associated with improved seed germination, increased biomass accumulation and enhanced tolerance to drought and salinity. Recent studies highlight the growing importance of cyanobacteria in climate-smart agriculture due to their role in carbon sequestration, restoration of degraded soils, and development of biofertilizers.

Mycorrhizal fungi

Mycorrhizal fungi form one of the most widespread and ecologically significant symbiotic relationships in terrestrial ecosystems. These fungi establish mutualistic associations with plant roots, where the plant supplies carbohydrates to the fungus, and in return, the fungus improves the plant's access to soil nutrients and water. Among the different types, arbuscular mycorrhizal fungi (AMF) are particularly important in agriculture. These fungi extend their hyphal networks far beyond the root zone, greatly increasing the effective surface area for nutrient absorption. This enhanced nutrient acquisition is especially important for phosphorus, which often exists in forms unavailable to plants. Mycorrhizal associations also improve uptake of zinc, copper, nitrogen, and other essential nutrients. Apart from nutritional benefits, mycorrhizal fungi enhance plant resilience under environmental stress conditions. Their extensive hyphal networks improve water acquisition during drought and help plants maintain physiological functions under water scarcity. Mycorrhizal colonization can also improve soil aggregation through the production of compounds such as glomalin, contributing to carbon storage and soil stability. Additionally, these fungi enhance plant defense mechanisms against root pathogens and improve nutrient-use efficiency making them highly relevant to sustainable and low-input agriculture. Their use in climate-smart farming supports increased crop productivity while preserving ecosystem health.

Decomposer microorganisms

Decomposer microorganisms, primarily consisting of fungi and bacteria, play a fundamental role in maintaining soil fertility and ecosystem functioning. These organisms break down dead organic matter, crop residues, and agricultural waste into simpler compounds that can be recycled within the soil ecosystem. Bacterial decomposers such as *Bacillus* and *Pseudomonas*, along with fungal decomposers including *Aspergillus*, *Trichoderma* and *Penicillium*, produce extracellular enzymes such as cellulases, ligninases, proteases and amylases. These enzymes degrade complex organic materials into nutrients readily available for plant uptake. The decomposition process contributes to humus formation, improves soil structure, enhances water retention and supports microbial diversity. In climate smart agriculture, efficient decomposition systems improve nutrient recycling, support soil carbon accumulation and promote long-term agricultural sustainability. Together, these beneficial microbial groups create healthier soils, enhance crop resilience and provide environmentally sustainable solutions for future food production systems.

Table 1. Benefits of beneficial microbes in climate smart agriculture

Microbe	Key functions	Crop examples	Benefits for climate smart agriculture	References
Rhizobia	Biological N2 fixation, enhances nodulation and nutrient uptake	Soyabean, chickpea, groundnut	Reduces synthetic nitrogen fertilizer use and N2O emissions	Tamang *et al.,* (2026)
Arbuscular mycorrhizal fungi	Enhances phosphorus and micronutrients uptake, improve soil structure and function	Maize, wheat, rice and vegetables	Improves drought tolerance, enhances soil carbon sequestration and reduces fertilizer dependency	Fasusi *et al.,* (2023)
Cyanobacteria	Biological N2 fixation, improves soil fertility, produces growth promoting substances	Rice, wheat and millets	Improves soil health and productivity in low input systems, reduces carbon footprint	Bhardwaj *et al.,* (2014)
Plant growth promoting rhizobacteria	Phytohormone production, solubilizes nutrients, induces systemic stress tolerance, supresses pathogen	Rice, tomato, wheat and cotton	Enhances plant growth and resilience to heat, drought and salinity, reduces chemical input	Bhattacharyya *et al.,* 2016

Conclusion

Climate change poses serious challenges to global agriculture, but beneficial microorganisms offer sustainable and practical solutions. By improving soil fertility, enhancing nutrient use efficiency, increasing stress tolerance, reducing greenhouse gas emissions and suppressing plant diseases, these microscopic allies contribute significantly to climate-smart agriculture. The adoption of microbial technologies can help farmers achieve higher productivity with lower environmental impact, ensuring food security and sustainable agricultural development for future generations. Harnessing the power of beneficial microbes is not merely an alternative approach it is an essential step toward building resilient and sustainable farming systems in the face of climate change.

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SMART DAIRYING: INTEGRATING BIOSENSORS AND AUTOMATION FOR LIVESTOCK MANAGEMENT

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Abstract

The transition toward intensive dairy production demands innovative management to ensure economic viability, environmental sustainability and animal welfare. This article explores "Smart Dairying" which is the specialized application of Precision Livestock Farming (PLF) tailored for dairy production. By integrating advanced Internet of Things (IoT) biosensors with automated mechanical infrastructure, such as robotic milking and precision feeding, smart dairying empowers farmers with real-time, individualized animal data. This powerful convergence of continuous data acquisition and automated execution addresses critical labor scarcities, optimizes herd health and shifts farm management from traditional intuition to a highly efficient, data-driven approach.

Keywords: Automation, Dairy, PLF, Production, Sensors

Introduction

Traditional agriculture has evolved beyond mere mechanization, officially entering the era of intelligent agriculture. Smart Dairying represents the powerful convergence of PLF principles and automated mechanical systems. This automation continuously collects vast amounts of physiological and environmental data and empowers farmers to make highly accurate management decisions, ensuring optimal udder health and farm efficiency (Niloofar *et al*., 2021) by using machines, control systems and information technologies. By combining farm management with technologies like IoT, 5G and Artificial Intelligence, smart dairying seamlessly integrates biometric sensors with automated infrastructure, such as robotic milking and precision feeding. Although currently optimized primarily for cattle, these data-driven principles are rapidly expanding to buffalo, caprine, swine and ovine species, driving a profound global transformation in livestock management.

The Shift to Precision Livestock Farming (PLF)

As global demand surges, expanding herd sizes and labor scarcities make traditional, intuition-based husbandry obsolete. To address this, the industry is embracing Smart Dairying, built upon PLF to optimize economic and environmental performance. PLF empowers data-driven decisions through four key stages: data acquisition, interpretation, integration and execution. This paradigm operates on two core pillars: biosensors, acting as the "eyes and ears" to continuously monitor animal parameters, and automation, serving as the "muscle" to perform physical tasks. Together, they mitigate management complexity, significantly enhancing farm efficiency and animal welfare.

Biosensors used in smart dairying

Sensors for Activity/ oestrous monitoring

Pedometers and accelerometers are vital biosensors used to automate oestrus detection in dairy cows. Pedometers, secured to the leg, continuously record the animal's step count. This data, alongside the cow's identification code, is transmitted to a barn receiver. If activity exceeds a set threshold, the system alerts the farmer that the optimal time for artificial insemination has arrived. Additionally, neck-mounted accelerometers track head and neck movements associated with walking and herding. Implementing these automatic oestrus detection systems significantly improves heat detection rates and overall fertility indices in dairy herds (Valenza *et al*., 2012).

Sensors for lameness detection

Lameness can also be detected through a pressure-sensor mat, which is capable of detecting alterations in footfall and weight distribution, crucial indicators of potential foot-related issues (Van Nuffel *et al*., 2016). The advent of lameness sensors represents a substantial advancement in the sustainable and holistic management of dairy herds. The sensors transmit real-time data to farmers, enabling prompt intervention when necessary.

Bioacoustic sensors

Vocalisation detector sensors for animals often called bioacoustic sensors or animal-borne acoustic biologgers capture, process and analyze sounds to monitor or track livestock health and welfare. By combining sensitive microphones with artificial intelligence, these sensors automatically identify stress, disease and emotional states in animals.

Calving monitoring sensors

Accurate prediction of calving time is of paramount importance for dairy animals reared in extensive grazing areas especially for primiparous animals. Difficult delivery can decrease milk production, cause uterine infection, increase veterinary expenses and potentially cause infertility, followed by premature culling. Intravaginal sensor, which is placed near the cervix detects changes in temperature and light, triggering an alarm to the farmer (Szenci *et al*., 2022) thereby reducing potential health risks to the calf and dam.

Sensors for mastitis detection

Mastitis severely impacts cow health and farm economics, causing reduced yields and high veterinary costs (Kunes *et al*., 2021). Because infected udders have altered ion balances, a spike in electric conductivity (EC) often indicates mastitis and modern digital dairies integrate it with complementary technologies like color sensors to spot blood or infection and biosensors detecting specific enzymes like lactate dehydrogenase. Furthermore, advanced Near-Infrared Spectroscopy (NIRS) analyzers evaluate fat, protein and lactose. By combining these multi-sensor inputs, farmers can catch mastitis earlier, safeguarding both animal welfare and farm profitability.

Sensors for disease detection

Biosensors have played an increasingly important role in diagnosing key pathogens of livestock (Chen *et al*., 2012) such as *Brucella*, *Toxoplasma gondii* and *African Swine Fever* infections. A recently developed biosensor used for detecting African swine fever virus is NanoBit. A G-quadruplex-based Aptasensor has been developed for the specific detection of Bovine Viral Diarrhea virus. Electronic rumen bolus like SmaXtec, Moonsyst, BGT Hydromet measures core temperature, pH and movement directly inside the reticulum. This real-time data allows farmers to detect illnesses days before visible symptoms appear. The bolus minimizes animal handling and ensures a quieter, healthier and more comfort for dairy animals.

Automation in dairying

Automated Cattle identification and tracking

Traditional identification methods, such as RFID systems and ear tags, are often inefficient and can cause stress to the animals. Smart farming addresses this by using advanced systems like

Convolutional Neural Networks to analyze facial features, coat patterns and body shapes for highly accurate, non-invasive cattle identification. Advanced object detection models, such as YOLOv8 and ByteTrack, allow for markerless tracking of animals within the herd. A 360 ° camera systems map spatial patterns to track cow behavior and detect anomalies that might indicate stress.

Automated Milking Systems (AMS)

Often referred to as robotic milkers, AMS units allow animals to be milked voluntarily without human intervention. AMS uses lasers or 3D cameras for teat mapping, the robotic arm cleans the udder, attaches the milking cups and applies post-milking teat dips, significantly reducing the labor while simultaneously collecting individualized yield data. AMS represent a fundamental breakthrough in modern dairy management, replacing conventional parlors (De Koning and Rodenburg, 2004). AMS significantly increases milk production and enhances overall animal welfare and offers unprecedented flexibility, real-time monitoring and operational efficiency.

Automated Feeding Systems (AFS)

Feeding is the most expensive and second most time-consuming task on dairy farms, accounting for up to 50% of operating costs. AFS revolutionize this process using robotic pushers, calf self-feeders and computerized dispensers to provide constant access to precise rations. By integrating AFS with RFID tags, farmers can deliver individualized nutrition based on an animal's lactation stage, metabolic needs and milk yield. Additionally, Near-Infrared (NIR) and optical cameras monitor mixing to guarantee ideal fiber length and homogeneity and significantly reduceing labor, feed waste and enhances overall herd health and productivity.

Automated Climate Control

Environmental conditions heavily impact milk yield and animal welfare. Maintaining an animal within its thermoneutral zone is critical for optimizing the production and welfare. When environmental sensors detect that the temperature has exceeded critical thresholds, the system automatically triggers automated ventilation fans, high-pressure foggers or sprinkler systems. This is particularly vital for mitigating heat stress in dairy buffaloes which are highly susceptible to thermal loads.

Automated waste and effluent management

Robotic manure scrapers autonomously maintain barn hygiene, reducing ammonia emissions. Furthermore, effluent holding facilities equipped with capacity and pH sensors ensure the optimal timing for the application of manure as fertilizer, preventing nutrient runoff and groundwater contamination.

Robotic or automated shearing

Robotic sheep shearing is an emerging technology that automates the difficult wool harvesting process, addressing a severe global shortage of skilled human shearers. These advanced systems utilize three main components: automated restraints to safely hold the animal, 3D machine vision to map its body shape and robotic arms equipped with specialized clippers. Additionally, force feedback sensors adjust to the animal's breathing and skin folds, preventing cuts and enhancing animal welfare.

Conclusion

The integration of PLF, IoT biosensors and advanced automation can transform real-time physiological data into actionable, individualized care. The primary purpose of adopting these integrated technologies is to maximize economic profitability while simultaneously safeguarding animal welfare and environmental sustainability. Looking forward, as artificial intelligence and predictive algorithms continue to evolve, the dairy industry will likely achieve fully autonomous management systems, establishing precision, data-driven interventions as the global standard for sustainable agriculture.

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ENSURING FOOD QUALITY: MONITORING AND MANAGING PESTICIDE RESIDUES

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Abstract

Food quality and safety have become increasingly important due to concerns about pesticide residues in agricultural products. Although pesticides enhance crop productivity and food security, improper use may result in residue accumulation and potential risks to human health and food quality. Effective monitoring and management are essential to ensure compliance with Maximum Residue Limits (MRLs), protect consumers, and support sustainable agriculture. Advances in analytical technologies, including GC-MS/MS, LC-MS/MS, QuEChERS, biosensors, and AI-based systems have significantly improved residue detection and food safety assessment. Integrated approach involving responsible pesticide use, Good Agricultural Practices (GAP), Integrated Pest Management (IPM), precision agriculture, improved post-harvest practices, advanced residue reduction technologies further strengthen food safety systems. Overall, continuous monitoring and effective residue management remain essential for delivering safe, high-quality food and promoting sustainable agricultural development.

Keywords : Food quality, Pesticide residues, Residue detection, Residue monitoring, Sustainable agriculture.

Introduction

Food quality and safety have become increasingly important concerns in modern agriculture as consumers demand food products that are nutritious, safe, and free from harmful contaminants. Agricultural production systems rely heavily on pesticides to protect crops from insect pests, diseases, and weeds. The use of pesticides has contributed significantly to enhancing productivity, minimizing crop losses, and supporting global food security and economic stability (Aktar *et al*., 2009).

However, despite their agricultural benefits, pesticide application may lead to chemical residues in food products, raising concerns regarding food quality and human health (Stachniuk and Fornal, 2016). Pesticide residues including their metabolites and degradation products may persist throughout harvesting, storage, processing, and distribution stages. Improper pesticide use, excessive application rates, and failure to follow recommended pre-harvest intervals can result in residue accumulation above permissible limits (WHO, 2025). Prolonged exposure to elevated levels of pesticide residues through dietary intake has been recognized as a potential risk factor for adverse health outcomes. To minimize these risks, pesticide residue management has become an essential component of global food safety systems. Monitoring programs and regulatory frameworks are implemented to ensure that food products comply with established Maximum Residue Limits

(MRLs) and international safety standards (EFSA, 2025). Advances in analytical techniques have improved the detection and quantification of residues at trace levels (Stachniuk and Fornal, 2016). Effective residue monitoring and management therefore play a crucial role in ensuring food quality, protecting public health, and promoting sustainable agriculture.

What Are Pesticide Residues?

Pesticide residues are small amounts of pesticide compounds or their metabolites that remain in food after application, with their occurrence influenced by pesticide properties and post-harvest handling practices. Their presence does not necessarily indicate unsafe food, as Maximum Residue Limits (MRLs) and routine monitoring help ensure consumer safety (Bajwa and Sandhu, 2014).

Importance of Monitoring Pesticide Residues

Monitoring pesticide residues is essential for ensuring food quality, protecting public health, and maintaining consumer confidence in agricultural products. Residue surveillance programs assess whether pesticide levels remain within established Maximum Residue Limits (MRLs) and ensure compliance with national and international food safety standards. Regular monitoring helps detect unsafe pesticide residue levels, minimize dietary exposure risks, and support preventive public health measures (WHO, 2025; EFSA, 2025). It also strengthens food quality assurance by improving transparency across the food supply chain and ensuring safety during production, processing, storage, and distribution. Additionally, residue monitoring supports international agricultural trade by ensuring exported products comply with importing countries' residue standards and minimizing economic losses due to non-compliance (Handford *et al*., 2015). Monitoring programs also detect pesticide misuse, excessive application, and unauthorized use, thereby encouraging adherence to Good Agricultural Practices (GAP) and Integrated Pest Management (IPM) approaches for sustainable crop protection. Advances in monitoring technologies have further improved detection sensitivity and strengthened food safety management systems (Ayranci and Erkmen, 2026).

Modern Technologies for Residue Detection

Advances in analytical science and food monitoring technologies have greatly improved pesticide residue detection and food quality assessment. Conventional laboratory methods such as Gas Chromatography (GC), Liquid Chromatography (LC), Gas Chromatography-Tandem Mass Spectrometry (GC-MS/MS), and Liquid Chromatography-Tandem Mass Spectrometry (LC-MS/MS) remain the primary tools due to their high sensitivity, accuracy, and ability to detect trace levels of pesticide residues across diverse food matrices (Lehotay, 2011). Among these, GC-MS/MS and LC-MS/MS are widely used for multi-residue analysis because it enables rapid and simultaneous detection of multiple pesticide classes with high precision (Stachniuk and Fornal, 2016). Sample preparation methods such as QuEChERS have further enhanced extraction efficiency and simplified residue analysis in food products (Lehotay, 2011). More recently, biosensors, nanotechnology based sensors, artificial intelligence (AI) enabled systems have emerged as rapid and cost-effective approaches for real-time residue monitoring and improved food safety management (Ayranci and Erkmen, 2026).

Managing Pesticide Residues for Safe Food

Effective pesticide residue management is essential for ensuring food safety, protecting human health, and maintaining food quality. It requires an integrated approach across the entire food supply chain, with coordinated efforts from farmers, regulatory authorities, the food industry, and consumers to minimize residue contamination while supporting sustainable agricultural production (Damalas *et al*., 2024).

i) Farm-Level Practices

Effective residue management starts with responsible pesticide use, including recommended doses, adherence to pre-harvest intervals, Integrated Pest Management (IPM), proper equipment calibration, pesticide rotation, and precision application technologies to minimize residues and promote sustainable agriculture (WHO, 2025).

ii) Processing and Post-Harvest Management

Processing and post-harvest practices such as washing, peeling, cooking, drying, and proper storage help reduce pesticide residues, while advanced methods including ozone treatment, cold plasma, and ultrasonic cleaning further improve residue removal and food quality (Bajwa and Sandhu, 2014).

iii) Consumer-Level Practices

Consumers can reduce dietary exposure by washing produce, peeling, removing outer leaves, using proper cooking and storage methods, maintaining dietary diversity, and purchasing food from reliable sources. These measures help lower residue exposure and enhance food safety (Takahashi *et al*., 2025). Overall, effective pesticide residue management across the food supply chain is essential for protecting public health and promoting sustainable agriculture.

Conclusion and Future Perspectives

Ensuring food quality and safety requires effective monitoring and management of pesticide residues, as improper pesticide use may cause residue accumulation and pose health and environmental risks despite their role in improving crop productivity and food security. This article emphasizes the importance of residue monitoring and management through the implementation of regulatory frameworks, advanced analytical techniques, and good agricultural practices to ensure compliance with food safety standards and maintain food quality. Future pesticide residue management is expected to increasingly integrate advanced analytical technologies with digital and sustainable agricultural approaches. Emerging innovations, including portable sensors, biosensors, artificial intelligence, machine learning, Internet of Things (IoT), and real-time monitoring systems, are expected to improve detection efficiency, strengthen food safety systems, and support safer, more efficient, and sustainable food production.

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KNOWLEDGE INFRASTRUCTURE IN AN UNDERSERVED SCIENTIFIC FIELD

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Abstract

Between 2020 and 2026, a small team of three Indian agricultural scientists produced more than sixty books and outreach publications in agricultural meteorology and related domains. Two of the three core members were retired, and the work was carried out without institutional funding or career incentive. This article identifies three distinct contributions embedded in the effort: building foundational knowledge infrastructure in a field which has been traditionally underserved, producing contemporary works that integrate emerging technologies and methodologies into the discipline, and repositioning agricultural science itself as a driver of India's economic growth and national development. They have accomplished this by producing interdisciplinary works that bridge agricultural meteorology and allied disciplines with policy, economics, and institutional strategy. The article further proposes that existing systems of scientific productivity measurement are not designed to recognize this kind of contribution, and that the scientific community may acknowledge this body of work as a significant and, by available evidence, unprecedented contribution to agricultural science in India.

Keywords: agricultural science, knowledge infrastructure, scientific productivity, agricultural meteorology, India

Introduction

Between 2020 and 2026, a small team of Indian agricultural scientists produced more than sixty books and outreach publications in a tightly connected domain: agricultural meteorology, agroclimatology, climate risk management, weather advisory systems, dryland agriculture, and related institutional questions. The team centered on B. V. Ramana Rao, Surender Singh, and V. Uma Maheswara Rao, with a wider network of invited contributors. (Team BVR). Two members of the core trio had already retired from formal institutional life. B. V. Ramana Rao was past eighty when the effort began. He is now eighty-six.

This was not a well-funded research laboratory or a university department with postdoctoral pipelines. It was not a consortium distributing authorship across hundreds of short papers. It was three scientists who identified a gap in the knowledge architecture of their field and chose to fill it, working without institutional resources and without any expectation of career advancement. The work was, in the most literal sense, voluntary.

This article presents that Team BVR's effort should be understood as scientific infrastructure building in an underserved domain. It identifies three distinct contributions within the body of work and makes the case that the scientific community should recognize this as a significant contribution to agricultural science in India.

Building the Knowledge Foundation

Agricultural meteorology sits close to the core of Indian farming risk. Weather and climate shape sowing decisions, irrigation scheduling, disease pressure, stress events, and yield outcomes. In a country where hundreds of millions of people depend on monsoon patterns, the practical stakes of this field are high. Yet the available shelf of textbooks and comprehensive references in Indian agricultural meteorology has historically been limited relative to the field's importance. For a discipline that is taught across India's agricultural university system and that underpins the country's Agromet Advisory Services, the gap between practical importance and available literature has been significant.

A substantial portion of Team BVR's catalogue directly addresses this gap. The body of work includes textbooks, monographs, primers, MCQ collections, and practical guides designed for students, teachers, and extension workers. These are not compilations of existing material but structured, pedagogically designed works that build a foundation for learning and teaching in the discipline. In that context, sixty books is not simply a large number. It represents a deliberate and sustained attempt to build the knowledge foundation that the field's educational infrastructure requires.

Engaging the Contemporary Frontier

The second contribution is the catalogue's engagement with emerging technologies and methodologies. Books on remote sensing, GIS applications, crop modelling, data analytics, climate-smart agriculture, citizen science, and the role of artificial intelligence in agricultural systems engage with the contemporary frontier of the discipline. These are areas where the pace of development often outstrips the pace of textbook publishing, leaving students and practitioners to rely on scattered journal articles and conference papers rather than comprehensive, structured references.

By producing works that integrate these newer domains into the broader framework of agricultural meteorology, the team did more than document the field as it has traditionally been understood. It extended the discipline's intellectual reach into areas that the existing literature had not yet absorbed. This is not a routine contribution. It requires the capacity to synthesize across rapidly evolving domains while maintaining the accuracy and pedagogical coherence that scientific publishing demands.

Repositioning Agricultural Science

The third and perhaps most distinctive contribution extends beyond agricultural meteorology. The catalogue includes works that argue for the centrality of agricultural science itself in India's economic growth and national development. Titles such as India's Green Protein Revolution, From Fields to Forex: Agricultural SEZs as India's Next Growth Engine, Pathways from Poverty to Prosperity, and Soil Health, National Wealth: India's Silent Infrastructure Crisis are not peripheral additions. They represent a deliberate effort to reposition agricultural science from an isolated research domain into a central pillar of policy, economic strategy, and institutional planning.

This repositioning operates at two levels. At one level, the catalogue bridges agricultural meteorology with other agricultural sciences, connecting weather and climate knowledge with crop science, soil health, water management, and food systems. At another level, it bridges agricultural science as a whole with economics, governance, and development strategy. Works on leadership, scientific temper, research management, and ethics in agricultural research push into questions about how scientific institutions function and how research culture shapes outcomes. The result is a body of work that does not merely serve the discipline. It argues for the discipline's place in a larger national conversation.

This repositioning is what elevates the achievement from a publishing effort to a knowledge mission. It is a contribution to agricultural science's self-understanding, not just to its shelf space.

A Contribution Without Precedent

The most systematic research on scientific productivity focuses on journal articles. The widely cited work of Ioannidis and colleagues defines "hyperprolific" authors as those publishing at least 72 journal papers in a single year. That benchmark clarifies what Team BVR's work is not. Hyperprolific science is paper-heavy, consortium-driven, and spread across large collaboration networks. Team BVR is a small, stable authorship core producing books. Hyperprolific work accumulates articles within existing knowledge systems. Team BVR's work builds the knowledge system itself.

The indices that track scientific productivity, from Scopus to Web of Science to the h-index, count journal articles and citations. They do not ask whether a small team has built a coherent shelf of sixty books in one applied domain within six years. The category does not exist yet in the measurement architecture of science. By the available evidence, no comparable effort in agricultural science, in India or elsewhere, has been documented at this scale, this speed, and under these circumstances: voluntary, unfunded, and driven entirely by commitment to the field.

Conclusion

Team BVR's body of work is quantitatively rare and qualitatively unusual. It built foundational knowledge infrastructure in a field where it was underserved. It engaged the contemporary frontier of the discipline by integrating emerging technologies and methodologies via a network of experts. And it repositioned agricultural science as a central pillar of a wider interdisciplinary discourse connecting research with policy, economics, and national development. This work was carried out without institutional resources, by scientists whose motivation was the field itself rather than any career outcome. No existing system of scientific measurement is designed to capture this kind of contribution. The scientific community should recognize this body of work as a significant and, by available evidence, unprecedented contribution to agricultural science in India. The students, teachers, extension workers, and policymakers who use these books will know what was built. The question is whether the institutions that govern scientific recognition can find a way to see it too.

Disclosure: The author has contributed as coauthor to eight books within this broader effort. B. V. Ramana Rao is the author's father. The analytical claims rest on evidence rather than sentiment, but the reader should weigh both the access and the position that come with this relationship.

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NANOTECHNOLOGY IN AQUACULTURE: ADVANCED DRUG DELIVERY SYSTEMS AND TARGETED THERAPEUTICS FOR FISH DISEASE MANAGEMENT

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Abstract

Aquaculture has become one of the fastest-growing food production sectors worldwide; however, disease outbreaks remain a major constraint affecting fish health, productivity, and economic sustainability. Conventional therapeutic approaches, including antibiotics and chemical treatments, often suffer from poor bioavailability, low therapeutic efficiency, environmental contamination, and the emergence of antimicrobial resistance. In recent years, nanotechnology has emerged as a promising tool for improving aquaculture health management through advanced drug delivery systems and targeted therapeutic approaches. Nanoparticles possess unique physicochemical properties, including high surface area, enhanced stability, and controlled release capacity, which improve drug absorption, bioavailability, and site-specific delivery. Nanotechnology-based therapeutics such as nano-antibiotics, nano-vaccines, nanoemulsions, and polymeric nanoparticles are increasingly being applied for the prevention and treatment of bacterial, viral, parasitic, and fungal diseases in fish. These technologies also support immunostimulation, biosensing, water quality management, and precision aquaculture practices. Furthermore, nano-based delivery systems reduce drug dosage, minimize toxicity, and lower environmental impacts compared to conventional treatments. Despite concerns regarding nanoparticle toxicity, biosafety, and regulatory limitations, nanotechnology offers significant potential for sustainable and eco-friendly aquaculture health management. Therefore, the integration of nanotechnology into fish disease management represents an innovative approach for enhancing aquaculture productivity, fish welfare, and global food security.

Introduction

Aquaculture plays a vital role in global food security, nutritional supply, livelihood generation, and economic development. With the increasing demand for aquatic food products, aquaculture production has expanded rapidly over the past few decades and now contributes significantly to the global fish supply (FAO, 2022). However, intensification of aquaculture practices has also increased the occurrence and spread of infectious diseases caused by bacteria, viruses, fungi, and parasites. Disease outbreaks in aquaculture systems result in severe economic losses, reduced productivity, poor fish welfare, and environmental degradation (Bondad-Reantaso *et al*., 2005). Common diseases such as vibriosis, aeromoniasis, edwardsiellosis, and white spot disease continue to pose major threats to sustainable aquaculture production worldwide. Conventional disease management strategies in aquaculture primarily depend on antibiotics, chemotherapeutics, and disinfectants.

Although these treatments can temporarily control disease outbreaks, their excessive and indiscriminate use has created several challenges, including antimicrobial resistance, drug residues in aquatic products, environmental contamination, and reduced therapeutic efficiency (Cabello, 2006). Furthermore, many conventional drugs exhibit poor bioavailability, rapid degradation, limited absorption, and non-specific distribution within fish tissues, resulting in inadequate disease control and increased treatment costs. In recent years, nanotechnology has emerged as an innovative and promising approach for improving fish health management and disease therapeutics in aquaculture. Nanotechnology involves the manipulation and application of materials at the nanoscale level, generally ranging from 1 to 100 nm, where materials exhibit unique physicochemical and biological properties. Nanoparticles possess high surface area, enhanced permeability, controlled drug release capacity, and improved stability, making them highly suitable for biomedical and aquaculture applications (De Jong and Borm, 2008). Nanotechnology-based drug delivery systems provide targeted and sustained delivery of therapeutic agents, thereby improving treatment efficiency and reducing toxicity. Various nanomaterials, including polymeric nanoparticles, liposomes, nanoemulsions, chitosan nanoparticles, and metallic nanoparticles such as silver and zinc oxide nanoparticles, are increasingly being explored for antimicrobial therapy, vaccine delivery, immunostimulation, and water quality management in aquaculture systems (Rather *et al*., 2011). In addition, nano-based biosensors and smart therapeutic systems have shown considerable potential for rapid disease diagnosis and precision aquaculture management. Therefore, the application of nanotechnology in aquaculture health management represents a transformative strategy for enhancing disease control, reducing environmental impacts, and promoting sustainable aquaculture production. The present article highlights the role of nanotechnology-based drug delivery systems and targeted therapies in fish disease management, along with their applications, benefits, challenges, and future prospects in modern aquaculture.

Nanotechnology in Aquaculture Health Management

Nanotechnology refers to the manipulation and application of materials at the nanoscale level, generally ranging from 1 to 100 nanometers (nm), where materials exhibit unique physicochemical, biological, and mechanical properties. In recent years, nanotechnology has gained considerable attention in aquaculture health management due to its potential to improve disease prevention, diagnosis, and therapeutic efficiency. Nanoparticles possess high surface area-to-volume ratio, enhanced reactivity, improved stability, and superior penetration capacity, making them highly suitable for biomedical and aquaculture applications. The increasing prevalence of infectious diseases in aquaculture systems has created a growing demand for advanced and sustainable therapeutic approaches. Conventional treatments often suffer from low bioavailability, rapid degradation, non-specific distribution, and environmental toxicity. Nanotechnology-based systems overcome many of these limitations by enabling controlled drug release, targeted delivery, enhanced absorption, and prolonged therapeutic action. These properties significantly improve treatment efficiency while reducing drug dosage and adverse environmental impacts. Various types of nanoparticles are utilized in aquaculture health management. Polymeric nanoparticles are widely used for controlled drug delivery and vaccine encapsulation because of their biocompatibility and biodegradability. Liposomes are phospholipid-based vesicles capable of encapsulating both hydrophilic and hydrophobic drugs, thereby improving drug stability and absorption. Nanoemulsions are colloidal systems that enhance the solubility and bioavailability of therapeutic compounds in aquatic organisms. Metallic nanoparticles such as silver, gold, zinc oxide, and copper nanoparticles possess strong antimicrobial and antifungal activities against a wide range of aquatic pathogens. Among them, silver nanoparticles are particularly effective against bacterial infections due to their ability to disrupt microbial cell membranes and metabolic pathways (Rai *et al*., 2009). Chitosan nanoparticles, derived from natural biopolymers, have also attracted significant attention because of their immunostimulatory, antimicrobial, and biodegradable properties.

Nanotechnology has multiple applications in aquaculture disease management. Nano-based antimicrobial agents are increasingly being used to control bacterial pathogens such as *Aeromonas hydrophila*, *Vibrio* spp., and *Edwardsiella tarda*. Nanoparticles are also used as vaccine carriers for improving antigen delivery and enhancing immune responses in fish. Nano-vaccines provide sustained antigen release and improved protection against infectious diseases. In addition, nanoparticles are utilized in water quality management for the removal of toxic compounds, heavy metals, and microbial contaminants from aquaculture systems. Nanotechnology further contributes to immunostimulation and stress management in aquatic organisms. Nano-formulated feed additives and supplements improve nutrient absorption, growth performance, and immune responses in cultured fish species. Moreover, nanobiosensors and nanoscale diagnostic tools are emerging as valuable technologies for rapid disease detection and real-time monitoring of aquatic environments. Overall, nanotechnology has revolutionized aquaculture health management by providing innovative and eco-friendly solutions for disease control, therapeutic delivery, and environmental sustainability. The integration of nanotechnology into aquaculture systems offers significant opportunities for improving fish health, production efficiency, and sustainable aquaculture development.

Nanotechnology-Based Drug Delivery Systems

Nanotechnology-based drug delivery systems have emerged as advanced therapeutic approaches for improving disease treatment and health management in aquaculture. These systems are designed to deliver therapeutic agents directly to targeted tissues or pathogens with enhanced precision, controlled releaseNanotechnology-based drug delivery systems have emerged as advanced therapeutic approaches for improving disease treatment and health management in aquaculture. These systems are designed to deliver therapeutic agents directly to targeted tissues or pathogens with enhanced precision, controlled release, and improved bioavailability (De Jong and Borm, 2008). Compared to conventional drug administration methods, nano-based delivery systems offer greater therapeutic efficiency, reduced toxicity, and prolonged drug activity, making them highly suitable for modern aquaculture applications. Targeted drug delivery is one of the most important advantages of nanotechnology in fish disease management. Nanoparticles can encapsulate antibiotics, vaccines, hormones, and other therapeutic compounds, protecting them from premature degradation and ensuring their controlled release at the desired site of action. This targeted approach minimizes drug loss, improves absorption, and enhances treatment effectiveness. Additionally, nano-carriers facilitate sustained drug release, reducing the frequency of administration and lowering treatment costs. Several nanocarrier systems are currently being explored for aquaculture therapeutics. Polymeric nanoparticles, liposomes, dendrimers, solid lipid nanoparticles, and nanoemulsions are among the most commonly used nano-delivery platforms. These carriers improve the solubility, stability, and permeability of therapeutic compounds, enabling efficient transport across biological membranes. Liposomal formulations are particularly effective for delivering hydrophobic drugs and vaccines, while chitosan-based nanoparticles enhance mucosal adhesion and immune stimulation in fish (Rather *et al*., 2011). Drug delivery in aquaculture can be achieved through oral, injectable, and immersion-based routes. Oral delivery is considered the most practical and cost-effective method for mass administration in aquaculture systems. Nano-encapsulation of drugs and vaccines in feed enhances gastrointestinal absorption and protects bioactive compounds from degradation during digestion. Injectable nano-formulations provide rapid therapeutic action and are mainly used in high-value fish species. Immersion-based delivery systems allow nanoparticles to enter fish through gills and skin, making them useful for treating external infections and larval stages. Nanotechnology-based drug delivery systems offer several advantages over conventional therapeutics. These systems reduce drug dosage requirements, minimize toxic side effects, improve therapeutic efficacy, and decrease environmental contamination caused by excessive antibiotic use. Furthermore, nano-formulations enhance the stability and shelf life of therapeutic agents, thereby improving treatment reliability in aquaculture operations. Recent advancements in smart nanocarriers and stimuli-responsive nanoparticles have further expanded the potential of nano-drug delivery systems.

Targeted Therapies in Fish Diseases

Targeted therapies have emerged as an advanced and efficient approach for controlling infectious diseases in aquaculture through precise delivery of therapeutic agents to specific pathogens or infected tissues. Unlike conventional treatments, which often result in non-specific distribution and reduced therapeutic efficiency, targeted nano-therapeutics improve drug concentration at the site of infection while minimizing toxicity and environmental contamination. The integration of nanotechnology with targeted therapies has significantly enhanced disease management strategies in modern aquaculture systems. Bacterial diseases are among the major causes of economic losses in aquaculture worldwide. Pathogens such as *Aeromonas hydrophila*, *Vibrio* spp., and *Edwardsiella tarda* cause severe infections including aeromoniasis, vibriosis, and edwardsiellosis in cultured fish species. Nano-antibiotics and nanoparticle-mediated antimicrobial systems have shown considerable effectiveness against these pathogens. Metallic nanoparticles, particularly silver and zinc oxide nanoparticles, possess strong antibacterial properties due to their ability to disrupt microbial cell membranes, interfere with metabolic pathways, and induce oxidative stress in bacterial cells (Rai *et al*., 2009). Polymeric nanoparticles and liposomal carriers are also used for targeted antibiotic delivery, improving drug stability and reducing antimicrobial resistance. Nanotechnology-based therapies are increasingly being applied against viral diseases in fish. Viral pathogens such as Koi Herpesvirus (KHV), Infectious Hematopoietic Necrosis Virus (IHNV), and Viral Nervous Necrosis Virus (VNNV) are difficult to control using conventional therapeutics. Nano-vaccines and nanoparticle-assisted antiviral delivery systems enhance immune responses by improving antigen stability, controlled release, and targeted uptake by immune cells. Chitosan nanoparticles and liposome-based vaccine carriers have demonstrated significant potential for improving vaccination efficiency and long-term immune protection in fish. Parasitic infections such as white spot disease caused by *Ichthyophthirius multifiliis* and marine parasitic infestations significantly affect aquaculture productivity. Nanotechnology-based antiparasitic formulations improve therapeutic penetration and increase treatment effectiveness against external parasites. Nanoemulsions and nanoparticle-loaded herbal extracts are also being explored as eco-friendly alternatives to chemical therapeutics. Similarly, fungal diseases caused by *Saprolegnia* species can be effectively managed using nanoparticle-mediated antifungal agents that inhibit fungal growth and spore development. Recent advancements in molecular therapeutics have introduced RNA interference (RNAi)-based therapies for fish disease management. RNAi technology utilizes small interfering RNA (siRNA) molecules to silence specific pathogen-related genes and inhibit disease progression. Nanoparticles act as efficient carriers for RNA molecules, protecting them from degradation and facilitating targeted intracellular delivery. These approaches provide highly specific and environmentally safe therapeutic strategies for controlling infectious diseases in aquaculture (De Jong and Borm, 2008). Smart therapeutics and stimuli-responsive nanocarriers represent another emerging area in fish health management. These advanced systems can release therapeutic compounds in response to environmental triggers such as pH changes, temperature variation, enzymatic activity, or infection-associated signals. Such precision-based delivery systems improve treatment efficiency while minimizing unnecessary drug exposure. Overall, targeted nano-therapies offer significant advantages for fish disease management by enhancing therapeutic precision, reducing antimicrobial resistance, improving immune responses, and supporting sustainable aquaculture production. These innovative approaches are expected to play a critical role in the future development of precision aquaculture and advanced aquatic animal healthcare systems.

Applications of Nanotechnology in Aquaculture

Nanotechnology has gained significant importance in modern aquaculture due to its wide range of applications in disease management, diagnostics, nutrition, water quality improvement, and environmental sustainability. The unique physicochemical properties of nanoparticles, including high surface area, enhanced reactivity, and controlled release characteristics, make them highly effective for improving aquaculture productivity and fish health management. One of the major applications of nanotechnology in aquaculture is disease diagnosis and biosensing. Nanobiosensors are highly sensitive diagnostic devices capable of detecting pathogens, toxins, and environmental contaminants at early stages. These biosensors utilize nanoparticles such as gold nanoparticles, quantum dots, and carbon nanotubes for rapid and accurate pathogen detection. Early diagnosis of fish diseases enables timely therapeutic intervention, thereby reducing mortality and economic losses in aquaculture systems (Rather *et al*., 2011). Nano-vaccines represent another promising application of nanotechnology in fish health management. Conventional vaccines often exhibit limited stability and reduced immune responses, whereas nano-based vaccine delivery systems enhance antigen protection, controlled release, and targeted immune stimulation. Chitosan nanoparticles, liposomes, and polymeric nanoparticles are commonly used as vaccine carriers to improve vaccination efficiency in fish. Nano-vaccines also reduce stress associated with repeated vaccination procedures and improve long-term disease resistance. Nanotechnology is increasingly applied in aquafeed supplementation to improve fish growth, nutrition, and immunity. Nano-formulated feed additives enhance nutrient absorption, feed conversion efficiency, and metabolic performance in cultured fish species. Nanominerals, nano-vitamins, probiotics, and herbal nano-formulations are being explored to strengthen immune responses and improve disease resistance. These nano-supplements contribute to enhanced growth performance and better overall fish health. Water quality management is another important area where nanotechnology offers significant benefits. Nanoparticles and nanofilters are used for the removal of heavy metals, toxic chemicals, excess nutrients, and microbial contaminants from aquaculture water systems. Photocatalytic nanoparticles such as titanium dioxide and zinc oxide nanoparticles help degrade organic pollutants and improve water quality. Nanotechnology-based water purification systems contribute to maintaining a healthy aquatic environment and reducing disease outbreaks. Nanotechnology also plays an important role in biofilm control and antimicrobial surface development in aquaculture facilities. Biofilms formed by pathogenic microorganisms on tanks, pipelines, and equipment can act as reservoirs of infection. Antimicrobial nanoparticles help inhibit biofilm formation and reduce microbial contamination in aquaculture systems. Furthermore, nanotechnology is being integrated with emerging technologies such as nanorobotics, smart sensors, and automated monitoring systems for precision aquaculture management. Overall, nanotechnology has revolutionized multiple aspects of aquaculture by providing innovative solutions for disease prevention, diagnostics, nutrition, environmental management, and sustainable fish production. The continued advancement of nanotechnology-based applications is expected to enhance productivity, fish welfare, and sustainability in global aquaculture systems.

Benefits of Nanotechnology in Fish Health Management

Nanotechnology has significantly improved fish health management through enhanced disease control, targeted therapeutics, and sustainable aquaculture practices. Nanoparticles possess unique properties such as high surface area, controlled release capacity, and improved permeability, which enhance therapeutic efficiency and precision drug delivery in aquatic organisms. Nano-based drug delivery systems improve the stability, absorption, and targeted action of therapeutic agents, resulting in effective treatment of bacterial, viral, fungal, and parasitic diseases. Controlled drug release reduces treatment frequency and minimizes toxic side effects. Nano-vaccines and immunostimulants further strengthen immune responses and disease resistance in cultured fish species (Nasr *et al*., 2021). Nanotechnology also contributes to improved fish growth, survival, and production performance. Nano-formulated feed additives, minerals, vitamins, and probiotics enhance nutrient absorption, feed utilization, and metabolic efficiency, leading to better growth and higher survival rates. Additionally, nano-based therapeutics reduce excessive antibiotic usage and help minimize antimicrobial resistance and environmental contamination in aquaculture systems. Another major advantage of nanotechnology is its role in water quality management and eco-friendly aquaculture practices. Nanoparticle-based purification systems help remove pollutants, harmful microorganisms, and toxic compounds from aquaculture environments, thereby reducing disease outbreaks and improving aquatic health. Integration of nanotechnology with biosensors and smart monitoring systems also supports rapid disease detection and precision aquaculture management. Overall, nanotechnology offers an innovative and sustainable approach for improving fish health, therapeutic efficiency, environmental safety, and aquaculture productivity.

Challenges and Biosafety Concerns

Despite its promising applications, nanotechnology faces several challenges and biosafety concerns in aquaculture health management. One of the major concerns is nanoparticle toxicity, as nanoparticles may induce oxidative stress, tissue damage, and physiological abnormalities in aquatic organisms due to their high reactivity and small size. Bioaccumulation and biomagnification of nanoparticles in aquatic food chains may also create environmental and food safety risks. Metallic nanoparticles such as silver and zinc oxide can accumulate in fish tissues and affect non-target organisms. In addition, the long-term ecological impacts of nanoparticle exposure remain insufficiently understood. Another important challenge is the lack of standardized protocols for nanoparticle synthesis, characterization, dosage optimization, and safety evaluation. Variations in nanoparticle properties can influence therapeutic efficiency and toxicity. Regulatory limitations, inadequate biosafety guidelines, and limited awareness among stakeholders further restrict large-scale commercialization of nano-based products in aquaculture. High production costs, advanced technical requirements, and insufficient infrastructure also limit the adoption of nanotechnology, particularly in developing countries. Therefore, comprehensive biosafety assessments, environmental monitoring, regulatory frameworks, and interdisciplinary research are essential for ensuring the safe and sustainable application of nanotechnology in aquaculture systems.

Future Perspectives

The future of nanotechnology in aquaculture health management is highly promising due to advancements in nanoscience, biotechnology, artificial intelligence, and precision aquaculture systems. Emerging nano-based technologies are expected to improve disease diagnosis, therapeutic delivery, vaccine development, and environmental monitoring in aquaculture. Smart nano-drug delivery systems and stimuli-responsive nanoparticles can provide controlled and targeted release of therapeutic agents in response to environmental or physiological triggers, thereby improving treatment precision and reducing environmental contamination. Integration of nanotechnology with artificial intelligence, biosensors, and IoT-based monitoring systems will further support real-time disease surveillance and precision aquaculture management. Nano-vaccines, RNA interference (RNAi)-based therapies, and personalized fish therapeutics are also expected to enhance disease prevention and immune responses in cultured fish species. In addition, green nanotechnology involving biological synthesis of nanoparticles using plants, algae, bacteria, and fungi may reduce toxicity and environmental risks associated with conventional nanoparticle production methods. Future commercialization of nano-based aquaculture products will depend on technological advancements, biosafety evaluation, regulatory support, and cost-effective production systems. Overall, nanotechnology has immense potential to revolutionize sustainable fish health management and improve global aquaculture productivity.

Conclusion

Nanotechnology has emerged as a transformative approach in aquaculture health management through advanced drug delivery systems and targeted therapies for fish diseases. Nano-based therapeutics improve drug bioavailability, controlled release, treatment efficiency, and disease resistance while reducing antibiotic usage and environmental contamination. Various nanoparticles, including polymeric nanoparticles, liposomes, nanoemulsions, metallic nanoparticles, and chitosan nanoparticles, have shown significant potential in controlling bacterial, viral, fungal, and parasitic diseases in fish. Nanotechnology also contributes to improved growth, immune response, water quality management, biosensing, and precision aquaculture practices. Although challenges related to toxicity, biosafety, environmental risks, and regulatory limitations remain, continuous advancements in nano-therapeutics, nano-vaccines, smart delivery systems, and green nanotechnology offer promising opportunities for sustainable aquaculture development. Therefore, further interdisciplinary research, biosafety assessment, and policy support are essential for the safe and effective application of nanotechnology in modern aquaculture systems.

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THE CRISPR REVOLUTION: REDEFINING GENE EDITING

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Abstract

CRISPR (Clustered Regularly Interspaced Short Palindromic Repeats) has emerged as one of the most transformative technologies in modern molecular biology, enabling precise, efficient, and cost-effective genome editing. Originally discovered as an adaptive immune defense mechanism in bacteria and archaea, the CRISPR-Cas system has been engineered into a versatile tool for targeted genetic modification. This article explores the discovery, natural function, key components, and molecular mechanism of the CRISPR-Cas9 system. It discusses how CRISPR was adapted from a bacterial defense strategy into a programmable gene-editing platform and highlights its wide-ranging applications in medicine, agriculture, biotechnology, and scientific research. Particular emphasis is placed on its role in treating genetic disorders, advancing cancer research, improving crop traits, and supporting precision medicine. The article also examines recent clinical successes, including the development of CRISPR-based therapies for sickle cell disease. Furthermore, it addresses the major advantages of CRISPR technology, such as its accuracy, efficiency, and accessibility, alongside challenges including off-target effects, delivery limitations, and ethical concerns related to genome editing. Finally, the future prospects of next-generation CRISPR systems, base editing, and prime editing are discussed, underscoring the potential of gene-editing technologies to revolutionize healthcare, sustainable agriculture, and biotechnology in the coming decades.

Keywords: Genome Editing, Gene Therapy, Guide RNA (gRNA), Genetic Engineering, Precision Medicine, Biotechnology; Sickle Cell Disease, Agriculture, Base Editing, Prime, Editing and Molecular Biology**.**

Introduction

CRISPR, which stands for *Clustered Regularly Interspaced Short Palindromic Repeats*, is a revolutionary gene-editing technology derived from a natural defense mechanism found in bacteria and archaea. These microorganisms use CRISPR-associated proteins (Cas proteins) to identify and destroy invading viral DNA. Scientists discovered that this system could be engineered to target and modify specific genes in living organisms with extraordinary precision. Among the different CRISPR systems, CRISPR-Cas9 has become the most widely used tool in molecular biology and biotechnology due to its simplicity, efficiency, and versatility. The CRISPR-Cas system works by using a guide RNA (gRNA) to direct the Cas nuclease to a specific DNA sequence. Once the target DNA is recognized, the Cas protein cuts the DNA strand, enabling researchers to insert, delete, or modify genes. This technology has transformed the fields of genetics, medicine, agriculture, and biotechnology.

CRISPR

CRISPR is considered revolutionary because it has dramatically simplified the process of genome editing. Earlier gene-editing technologies such as Zinc Finger Nucleases (ZFNs) and TALENs were expensive, technically complex, and time-consuming. CRISPR, however, is highly precise, cost-effective, and easier to design for specific targets. Scientists can now edit genes within days, instead of months. Another reason for its revolutionary status is its broad range of applications. CRISPR has enabled researchers to develop potential treatments for genetic disorders such as sickle cell anaemia, cystic fibrosis, and muscular dystrophy. It has also accelerated cancer research, infectious disease diagnostics, and the development of genetically modified crops with improved resistance to pests and environmental stress. The technology has reshaped modern biological research and opened new possibilities for precision medicine.

CRISPR technology differs because it uses RNA-guided targeting rather than engineered proteins. This makes it easier to program and adapt for different genetic targets. The development of CRISPR-Cas9 has significantly accelerated advancements in genomics and personalized medicine.

Discovery of CRISPR

The first observation of unusual repetitive DNA sequences occurred in 1987 when Japanese scientist Yoshizumi Ishino and his colleagues identified repeated sequences in *Escherichia coli*. At the time, the biological function of these sequences was unknown. Over the following decades, similar sequences were discovered in several bacterial and archaeal genomes. Later, several scientists contributed significantly to CRISPR research. Francisco Mojica first proposed the immune function of CRISPR sequences. Jennifer Doudna and Emmanuelle Charpentier later demonstrated how the CRISPR-Cas9 system could be engineered for programmable genome editing. Their groundbreaking work earned them the 2020 Nobel Prize in Chemistry.

Natural role CRISPR in Bacteria

CRISPR acts as an adaptive immune system in bacteria. When viruses infect bacteria, fragments of viral DNA are incorporated into the bacterial genome within CRISPR arrays. These stored sequences serve as molecular memories of past infections. During subsequent infections, bacteria transcribe the stored viral sequences into CRISPR RNAs (crRNAs). These RNAs guide Cas proteins to matching viral DNA sequences, enabling the destruction of invading genetic material. The incorporation of viral DNA fragments allows bacteria to “remember” previous infections. This adaptive immune response enables faster recognition and elimination of recurring viruses.

Components of CRISPR

CRISPR arrays consist of short repeated DNA sequences separated by spacer sequences derived from viral DNA. These spacers act as genetic memories of past infections. Another major component, Cas proteins, they are specialized enzymes associated with CRISPR systems. Cas9 is the most widely studied protein because it can cleave double-stranded DNA at specific locations. Guide RNA directs the Cas protein to a target DNA sequence through complementary base pairing. Scientists can design synthetic gRNAs to edit virtually any gene. The Protospacer Adjacent Motif (PAM) is a short DNA sequence required for Cas protein recognition. Without a PAM sequence, Cas9 cannot bind or cleave the target DNA.

Mechanism

The CRISPR-Cas system functions through a precise mechanism that enables targeted gene editing. First, during the adaptation phase, bacteria capture fragments of invading viral DNA and store them within CRISPR arrays as genetic memories. These stored sequences are then transcribed into CRISPR RNAs (crRNAs), which combine with guide RNA to direct the Cas9 protein to a complementary target DNA sequence. The Cas9 enzyme recognizes the target near a PAM (ProtospacerAdjacent Motif) sequence and creates a double-stranded break in the DNA. After cleavage, the cell repairs the

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damaged DNA through mechanisms such as Non-Homologous End Joining (NHEJ) or Homology-Directed Repair (HDR), allowing scientists to insert, delete, or modify specific genes with high precision. The mechanism is simply explained in fig.1.

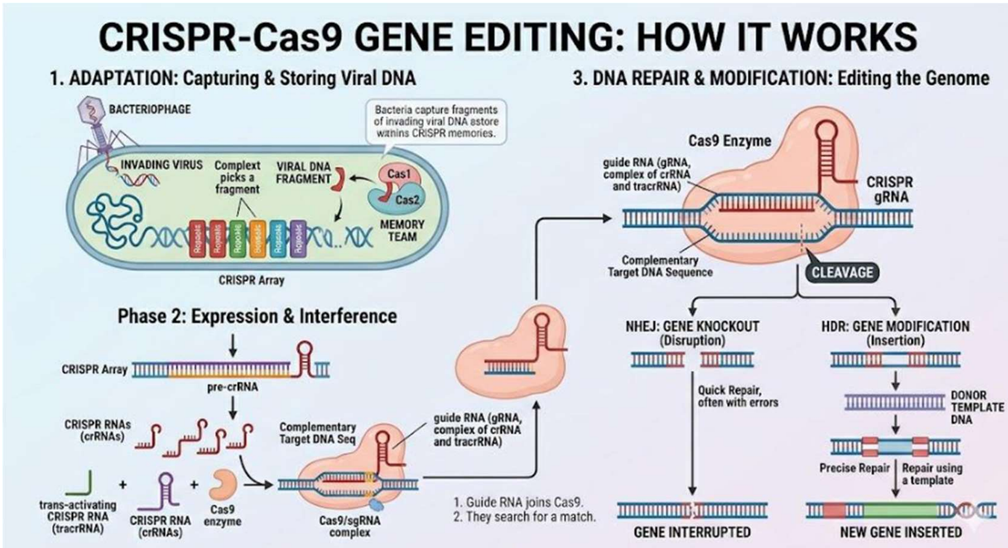

Fig.1 CRISPR-Cas9 mechanism

Transformation into a gene editing tool

Scientists transformed the natural CRISPR-Cas9 bacterial defense system into a powerful gene-editing tool by simplifying its components into a programmable system. Researchers combined crRNA and tracr RNA into a single guide RNA (sgRNA), making the technology easier to use in laboratories. By changing the sequence of the guide RNA, scientists can direct the Cas9 protein to almost any target gene, allowing precise and customizable DNA editing for research, medicine, and biotechnology.

Applications

CRISPR technology has a wide range of applications in medicine, agriculture, biotechnology, and scientific research. In medicine, CRISPR is used for the treatment of genetic disorders such as sickle cell anaemia, cystic fibrosis, and muscular dystrophy by correcting faulty genes. It also plays an important role in cancer research, immunotherapy, and rapid disease detection systems such as SHERLOCK and DETECTR for viral infections. In agriculture, CRISPR helps develop crops with improved yield, drought tolerance, pest resistance, and enhanced nutritional value. In research and industry, scientists use CRISPR for functional genomics, gene regulation studies, drug discovery, and the development of genetically modified organisms. Due to its precision, efficiency, and versatility, CRISPR has become one of the most powerful tools in modern biotechnology and precision medicine. A recent breakthrough in CRISPR research was demonstrated in the treatment of sickle cell disease using a CRISPR-based therapy called exagamglogene autotemcel (exa-cel or Casgevy). In clinical trials, patients treated with this gene-editing therapy showed a significant reduction or complete elimination of painful vaso-occlusive crises. The treatment works by editing the BCL11A gene in blood stem cells to increase fetal hemoglobin production, which prevents red blood cells from becoming sickle-shaped. This achievement marked one of the first successful clinical applications of CRISPR technology and highlighted its potential in treating inherited genetic disorders. Recent updates also confirmed the long-term safety and specificity of CRISPR-Cas9 editing in treated patients.

Advantages and Limitations

CRISPR technology offers several advantages, including high precision, efficiency, cost- effectiveness, and faster gene editing compared to older technologies such as ZFNs and TALENs. It allows scientists to accurately target and modify specific DNA sequences, making it highly useful in medicine, agriculture, and biological research. CRISPR is also simpler to design and can be applied to a wide variety of organisms. However, the technology also has important limitations and challenges. One major concern is off-target effects, where unintended parts of the genome may be edited, potentially causing harmful mutations. Ethical concerns regarding human germline editing and the possibility of "designer babies" have also raised global debates. Additionally, delivering CRISPR components safely and efficiently into human cells remains a significant challenge for clinical applications. The future of CRISPR technology is highly promising and is expected to revolutionize modern medicine, agriculture, and biotechnology. Scientists are developing next-generation CRISPR systems such as Cas12 and Cas13, which offer improved accuracy and the ability to target RNA in addition to DNA. Advanced techniques like base editing and prime editing allow precise genetic modifications without causing double-stranded DNA breaks, reducing the risk of unwanted mutations. In the future, CRISPR may play a major role in precision medicine by enabling personalized treatments for genetic diseases, cancer, and rare disorders based on an individual's genetic profile. Researchers are also exploring its applications in improving crop productivity, combating infectious diseases, and developing novel therapies. Despite ethical and regulatory challenges, continuous advancements in CRISPR technology are expected to make gene editing safer, more efficient, and more accessible worldwide.

Conclusion

In conclusion, CRISPR technology has transformed from a natural bacterial defense mechanism into one of the most groundbreaking innovations in modern science. Its ability to precisely, efficiently, and cost-effectively edit genes has revolutionized the fields of genetics, medicine, agriculture, and biotechnology. From treating genetic disorders and improving crop resistance to advancing cancer research and precision medicine, CRISPR has opened new possibilities that were once considered impossible. Despite challenges such as off-target effects, ethical concerns, and regulatory issues, continuous scientific advancements are making the technology safer and more reliable. As research continues to evolve, CRISPR is expected to play a crucial role in shaping the future of healthcare, sustainable agriculture, and biological research, making it one of the most powerful tools of the twenty-first century.

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AGROFORESTRY FOR CLIMATE CHANGE MITIGATION AND ENVIRONMENTAL SUSTAINABILITY

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Abstract

The greenhouse gases cause global warming, in which carbon dioxide (CO_2) along accounts for 60% share (Khurana., 2012). Plant acts as a sink for CO_2 by absorbing it through photosynthesis and storing it as biomass. Carbon sequestration involves long-term carbon storage in biomass, soils, geological formations, and durable products, which helps prevent global climate change. In India, temperatures have increased by 0.4 to 0.6 °C over the last 100 years. India is developing a compliance carbon market through the Carbon Credit Trading Scheme (CCTS). The institutional framework is supported by the Bureau of Energy Efficiency (BEE). Afforestation and planting activities are important methods to reduce global warming. Long rotation species have a longer carbon locking period compared to short rotation species.

Keywords: Bureau of energy efficiency (BEE), Carbon Credit Trading Scheme (CCTS), carbon sequestration, greenhouse gases, global warming.

Introduction

Approximately 68% of greenhouse gas emissions and nearly 90% of carbon dioxide emissions worldwide are attributed to fossil fuels, which include coal, oil, and gas. These fuels are by far the biggest contributors to climate change. Deforestation, which averaged more than 13 million hectares per year between 1980 and 1995 (FAO, 1997), was the primary cause of 20–25% of the world's anthropogenic greenhouse gas (GHG) emissions in the 1990s (Killmann, 2001).

Heat from the sun is trapped as greenhouse gas emissions cover the planet. As a result, the climate is shifting, and the Earth is warming. The current rate of global warming is higher than it has been at any point in history. Over time, rising temperatures are altering weather patterns and upsetting the natural equilibrium. All life on Earth, including humans, is at great risk from this. Earth's average temperature has increased by at least 1.1 °C since 1880. And most of that warming has happened since 1975. In fact, 2023 will probably be the warmest year ever recorded. Scientists have observed rising sea levels, melting ice, and increasing extreme weather events. These changes affect each region differently. For example, snow and ice are melting so quickly that the Arctic could have no summer sea ice by 2030. Coastal areas are experiencing more flooding. These are all evidence of climate change.

Climate change is one of the biggest challenges facing agriculture today. Increasing levels of carbon dioxide in the atmosphere are causing rising temperatures and unpredictable weather. Agroforestry offers a natural and sustainable way to reduce these effects.

Agroforestry

The term "agroforestry" refers to land management practices that intentionally include woody perennials (trees, shrubs, palms, bamboos, etc.) with agricultural crops and/or animals in some kind of temporal or spatial arrangement. The various elements of agroforestry systems interact both ecologically and socio-economically (FAO). Land-Use Change and Forestry report of the IPCC (2000) identified agroforestry as having the greatest potential for carbon sequestration of all the land uses examined. Compared to a monoculture field of crop plants or pasture, the addition of trees or shrubs to farms or pastures can enhance the amount of carbon stored (Sharrow and Ismail 2004; Kirby and Potvin 2007). According to the USDA, there are different types of agroforestry: alley cropping, forest farming, riparian forest buffers, silvopasture, and windbreaks.

Alley Cropping: Alley cropping is a farming method where rows of trees are planted together with crops on the same land. This practice can be followed in both tropical and temperate regions. In some systems, called strip cropping, trees or shrubs are planted in wider strips instead of single rows. These trees help improve soil fertility by adding nutrients through fallen leaves and organic matter. They also protect crops from strong winds and soil erosion while providing useful products such as fruits, nuts, timber, and fuelwood.

Forest Farming: Forest farming is a type of agroforestry in which useful and high-value crops are grown under the shade of trees. In many tropical villages, this system is commonly seen in home gardens where different plants are grown in layers. Proper management of the tree canopy and crops is important in forest farming, which makes it different from simply collecting wild plants from forests. This practice helps farmers use land efficiently while also conserving the environment.

Riparian forest buffers: Riparian buffers are strips of permanent vegetation located along or near active watercourses or in ditches where water runoff concentrates. The purpose is to keep nutrients and soil from contaminating the water.

Silvopasture: In a silvopasture system, trees are grown together with grasses and grazing animals such as cattle, goats, and sheep. The trees provide shade and a comfortable environment for animals, while the grasses serve as fodder. This system improves land use efficiency and supports both livestock production and environmental conservation. Traditional examples of silvopasture can be seen in the *dehesa* systems of Spain and *montado* systems of Portugal, where pigs and cattle are raised under scattered trees over large grazing areas.

Windbreaks: Windbreaks are rows of trees or shrubs planted around agricultural fields to reduce the speed of wind. By lowering wind intensity, they help protect crops from damage caused by strong winds and reduce excessive drying of plants and soil. As a result, windbreaks can improve crop growth and increase agricultural productivity.

Carbon Sequestration

Carbon sequestration is a natural process of storing carbon in a carbon pool. It limits the climate change by reducing the amount of carbon dioxide in the atmosphere thus managing the global carbon cycle (IPCC 2021). There are two main types of carbon sequestration: biologic (also called *biosequestration*) and geologic. Carbon sequestration acts as a carbon sink, helps to mitigate climate change and thus reduce harmful effects of climate change. It helps in reducing the atmospheric and marine accumulation of greenhouse gases, primarily carbon dioxide released from burning fossil fuels (Hodrien, 2008). Carbon sequestration is the natural carbon cycle which involves the exchange of carbon among the biosphere, pedosphere (soil), geosphere, hydrosphere, and atmosphere of Earth (McPherson *et al*., 2013). Through biological, chemical, or physical processes, carbon dioxide is naturally extracted from the atmosphere and stored in long-term reservoirs. As they develop, plants take in carbon dioxide from the atmosphere and convert it into biomass. However, because long-term sequestration cannot be ensured, biological storage (such forests and kelp beds) are regarded as volatile carbon sinks. The trapped carbon may be released back into the atmosphere as a result of events like sickness or wildfires, shifting governmental objectives, and economic pressures (Axelsson *et al*., 2024).

Mitigation of climate change through carbon sequestration can be achieved either by strengthening natural carbon sinks or by using advanced technological methods for capturing and storing carbon. In carbon capture and storage (CCS) systems, sequestration specifically refers to the long-term storage of captured carbon dioxide. Artificial storage technologies include injecting gaseous CO_2 into deep geological formations such as saline aquifers and depleted gas reservoirs, or converting CO_2 into stable solid carbonates through reactions with metal oxides. For artificial sequestration outside the natural carbon cycle, carbon must first be captured or prevented from entering the atmosphere. One effective approach is the use of carbon-rich materials in durable products and infrastructure, thereby delaying carbon release from decomposition or combustion. For example, harvested wood can be utilized in construction and long-lasting products, enabling carbon storage for several decades or even centuries. In industrial sectors, carbon dioxide is commonly captured from emissions generated by factories and power plants.

The executive Order 13990, "Protecting Public Health and the Environment and Restoring Science to Tackle the Climate Crisis," was issued in the United States in 2021. It emphasized the importance of sequestering carbon through the preservation and restoration of natural ecosystems like wetlands and forests. The order promoted market-based conservation tactics and acknowledged the role that farmers, landowners, and coastal communities play in preserving carbon sinks. But according to a 2025 estimate, even using all of Earth's geological carbon storage capacity will only slow global warming by only 0.7°C.

Agroforestry with Carbon Sequestration

Carbon sequestration is among the major ecosystem services provided by agroforestry systems which help to increase carbon storage both in the soil and in the woody parts of trees. Trees absorb carbon dioxide from the atmosphere and store it in their trunks, branches, roots, and surrounding soil. Similar to newly established forests, agroforestry can help to recover some of the carbon lost due to deforestation and land degradation.

In addition to storing carbon, agroforestry also provides valuable products such as food, fodder, fuelwood, fruits, and timber. The amount of carbon stored largely depends on factors such as the age of the trees and how the harvested products are used. By supplying forest-based products directly from farms, agroforestry reduces dependence on natural forests and helps decrease pressure on primary forest resources (Montagnini and Nair, 2004). In agroforestry systems, the roots of trees hold the soil together, preserving its fertility and structure and preventing soil erosion. Better water infiltration and retention follow, lowering the chance of drought and raising overall agricultural output.

Benefits Beyond Carbon Storage

The advantages include increased agricultural production and profitability, decreased soil erosion, wildlife habitat creation, animal waste management, enhanced biodiversity, better soil structure, and carbon sequestration. Compared to traditional agricultural and forest production techniques, agroforestry systems may offer benefits. Increased productivity, social, economic, and environmental advantages, as well as a wider range of ecological goods and services, are all possible outcomes. These advantages are contingent upon effective agricultural management. This entails selecting the appropriate trees and routinely trimming them, among other things.

Conclusion

Agroforestry is a sustainable land-use method that blends environmental preservation with agricultural output by integrating trees with crops and livestock, agroforestry enhances carbon sequestration, improves soil fertility, conserves biodiversity, and boosts farmers' livelihoods. As climate change continues to threaten global agriculture and ecosystems, agroforestry offers a practical and nature-based solution for reducing atmospheric carbon dioxide levels. Encouraging agroforestry adoption can contribute significantly to sustainable agriculture, climate resilience, and long-term environmental protection.

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WHY DO WE END UP BUYING MORE THAN WE PLANNED?

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Abstract

Shopping has become much more than a way to fulfil basic needs. In today's fast-paced and digitally connected world, consumers are constantly exposed to advertisements, discounts, social influences and personalized online recommendations that shape their purchasing decisions. Many buying choices are influenced not only by practical requirements but also by emotions, convenience, social approval and the appeal of attractive offers. The growth of e-commerce has further increased opportunities for spontaneous and impulse purchases. This article explores the psychological, social and economic factors that influence consumer behaviour and highlights the importance of mindful purchasing. By understanding these influences, consumers can make more informed, responsible and financially sound buying decisions.

Key Words - Consumer Behaviour, Impulse Buying, Consumer Psychology, E-commerce, Informed Decision-Making

Introduction

Have you ever experienced going to market to purchase curd and coming back with ice-cream, chips or maybe with a discounted item? Or sometimes you opened a shopping app on your phone casually, and placed an order swiftly. If this scenario sounds familiar, there's no need to become anxious as it's a common behaviour for most consumers.

Daily we face numerous purchasing schemes, some could be deliberate and some could be spontaneous. We think we are buying necessary items but in reality our buying choices are influenced by many subtle factors like personal needs, psychological triggers and economic aspects. By identifying these factors we can become educated buyers.

More than just need

Traditional the shopping was centred only for meeting daily basic needs of food, clothing and household goods. But nowadays shopping has become more extensive. Items are not merely purchased for their practicality but it is done to fulfil the emotional and psychological needs.

Considering an example of branded phone, while its basic function is communication, consumers might chose to spend significantly more in specific brand. This purchasing decision is basically more influenced by emotions like sense of accomplishment, social standing and self-assurance.

This incidence can occur in our other purchases such as watch, shoes, organic food etc. By such purchases most of the consumers are seeking an emotional connection. On this basis, marketers find consumer behaviour fascinating because they understand that emotions have a greater impact than logical reasoning.

The world around us influence our choices

Sometimes certain items capture our interest instantly. This could be because of vibrant packaging, attractive displays and attention garbing advertisements. Companies invest heavily in branding, packaging and presentation of the product as the initial impression is vital.

The digital realm is working on the same concept. To seize attention of consumers E-commerce platforms also utilise appealing visuals, time-limited promotions and personalised suggestions. With a single click, a potential buyer can move from necessary purchasing to unnecessary purchasing.

In the past few years, India's E-commerce sector has grown very vast. Online purchasing and digital payments have become a common part of the daily lives of millions of consumers. Although online shopping is convenient and effortless, it has contributed to an increase in spontaneous and impulsive purchasing behaviour. An object that was not initially planned for purchasing suddenly appears on the screen with the reduced price and fast delivery option steers one towards irrelevant purchasing. In reality many psychological triggers get influenced by a sudden choice of needless buying.

Why discounts feels so good

A good deal is one of the greatest motivators in helping change your purchasing behaviour. Imagine seeing a product that costs Rs.2000. Now, imagine the same thing and this time is it has a sign that says "15% OFF - today only". That makes the product attractive all of a sudden. Humans are thrilled by discounts, which convinces the consumers that they are saving money when in fact they had no intention of purchasing the item anyway. Terms like limited offer, flash sales, last chance, only a few items left these terms create a sense of importance, evoking a concern about losing a chance, often known as the "fear of missing out" or FOMO in the field of psychology. When people believe that an opportunity could disappear shortly, they are more likely to act quickly rather than thinking over it for a long time.

People Influence People

Essentially, we humans love to be social and look for advice before making decisions like where to stay during vacations, dining out with friends or buying new things. In most cases, before you make any decision, you check reviews and just get your friends recommendations because it gives you peace of mind that someone has tried the product already.

Online ratings and feedbacks from customers have gained importance over the years. Secondly, a product that receives many reviews will be viewed as more trustworthy than a product without any review. You have utilized a platform on social networking that will further enhance this trend, where influencers play a crucial role in shaping consumer opinions. Their recommendations are viewed as authentic, transforming their viewers into supporters by portraying the influencer as someone who shares understandable real-life situations. However, it's important for consumers to be aware that not all suggestions are unbiased. A lot of recommendations are paid promotions. Understanding this reality allows people to make thoughtful choices instead of hasty ones.

The hidden role of emotions

Feelings play a significant role in shaping how consumers make buying decisions. People don't always buy things because they need them, sometimes they do so because they are happy, stressed, want to make a success, or simply want to feel better. Businesses understand this well and use various methods such as playing calming music, using welcoming lighting, setting up comfortable environments, and providing excellent customer service to trigger positive feelings. In the same way, E-commerce stores use personalized suggestions and targeted advertisements to generate a similar reaction. Consequently, impulse shopping is prevalent. Although these purchases offer instant satisfactions, numerous items go neglected or unused after being bought. This is why financial experts often recommend postponing substantial expenditures. Pausing can assist in differentiating real needs from temporary feelings.

Shopping in the modern age

In today's world, the modern customer is surrounded by a continuous flow of information. Advertisements are present on various platforms such as TV, smartphones, social networks, website and even during video streaming. Simultaneously individuals are becoming more conscious and discriminating. Many buyers are now prioritizing factors like quality, sustainability and worth over simply opting for the least expensive choice. There is also a rising inclination towards supporting local enterprises and domestic labels. Consumers are increasingly seeking products that resonate with their principles and convictions. This transition indicates that contemporary purchasing decisions involve a blend of sentiment and accountability. The task is not to cease shopping but to make informed shopping decisions.

Becoming a Smarter Consumer

Knowing consumer psychology empowers us, helping us avoid regretful purchases by being aware of decision-influencing factors. To make wiser buying choices, it is beneficial to pause and reflect before making a purchase by considering the following questions:

- Is this item or necessity?
- Am I purchasing it due to its usability or just because it's discounted?
- Is my decision driven by emotions?
- Have I explored alternative choices?
- Will this accusation retain its significance in the days to come?

Asking these basic inquiries can curb unnecessary expenses and promote improved financial behaviours.

Conclusion

Each purchase narrates a tale. Sometimes, it's about necessity, other times it's about solace, joy, self - assurance or fitting in. These emotions are natural and acceptable. The issue arises when we allow our emotions and marketing tactics to dictate choices entirely. Companies will always craft appealing products and compelling promotions as part of their duty. As consumers, our responsibility is to stay informed, considerate and mindful. The next instance you are about to make a purchase, whether reaching for your wallet or tapping the "buy now" icon, take a brief pause.

Ask yourself a simple query
"Am I making this choice myself, or am I being influenced by advertising and trends?"
This brief pause might be the wisest buying decision you ever make.

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SHIELD AND YIELD: SMART TIPS FOR GREENHOUSE FARMING

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Abstract

In Telangana Protected cultivation has emerged as a viable technology to overcome seasonal and climatic limitations in horticultural crop production. Greenhouses and other protected structures enable precise control of temperature, humidity, light, and ventilation, allowing year-round cultivation of high-value crops even under adverse weather conditions. This article outlines key practices for maximizing yield in protected systems, with reference to current practices in Telangana where approximately 1,150 hectares are under protected cultivation. It covers structural design, soil and bed preparation, sterilization, pH and EC management, fertigation, mulching, crop-specific spacing, and integrated pest and disease management strategies for crops including tomato, capsicum, cucumber, carnation, rose, and gerbera. Adoption of these scientific practices can significantly improve productivity, resource-use efficiency, and quality of produce in protected environments.

Keywords: Protected cultivation, greenhouse, horticultural crops, fertigation, soil sterilization, yield maximization, Telangana.

Introduction

Structures designed to partially or fully regulate climate and provide optimal growing conditions for plants are known as greenhouses. By managing temperature, humidity, light, and ventilation, crops can be grown successfully throughout the year, even under unfavorable weather conditions. In Telangana alone, approximately 1,150 hectares of horticultural crops are currently cultivated under greenhouse structures.

Crops Suitable for Protected Structures : High-value crops such as tomato, colored capsicum, gherkin, cherry tomato, carnation, gerbera, daisy, rose, orchid, strawberry, lettuce, and leafy greens perform well in greenhouses and shade nets. Low-cost protected systems including low tunnels, walk-in tunnels, and rockeries are ideal for leafy greens, carrot, cabbage, cucumber, watermelon, cantaloupe, and summer vegetables.

Structure Design and Layout: Greenhouses should be oriented east-west to ensure uniform sunlight distribution. When multiple units are constructed, they must be interconnected with gutters and aligned north-south for efficient drainage and ventilation.

Soil Selection, Bed Preparation, and Sterilization: Soil quality and sterilization are critical for high yields. Prepare the growing medium using red soil, well-decomposed cattle manure, sand, or rice husk. Add single superphosphate and neem cake based on crop requirements. Since soil may contain harmful fungi, pathogens, insects, eggs, and larvae, sterilization is essential. A common method is chemical fumigation: prepare a solution of 5 liters formaldehyde in 200 liters of water, moisten the soil, and spray it uniformly. Alternatively, apply Tesamid granules at 30-40 g/m², cover beds with black polythene, and keep the polyhouse sealed for 4-7 days. After fumigation, irrigate with 100 liters of water per m² and transplant seedlings after 7-15 days. Form sterilized soil into raised beds 30-45 cm high and 80-100 cm wide. Bed length depends on polyhouse size, with 50 cm spacing between beds for easy access.

Soil pH and Environmental Conditions : Soil pH and electrical conductivity must be crop-specific. EC should not exceed 1 mS/cm. Maintain relative humidity inside the polyhouse at 60-65%.

Table 1: Optimal pH Range for Crops

Crop	Optimal pH Range
Carnation	5.5-6.5
Gerbera	5.5-7.5
Rose	6.0-6.5
Tomato, Cucumber, Capsicum	6.0-7.0

Irrigation, Fertigation and Mulching: Install 16 mm inline drip laterals on prepared beds with 40 cm spacing between drippers. Applying fertilizers through drip, called fertigation, saves water and improves nutrient use efficiency. Use 25-micron mulch sheets for short-duration vegetables, 50-micron for flowers and 10-12 month crops, and 100-micron for crops >12 months. White mulch reflects heat in summer, while black mulch conserves warmth in winter.

Plant Spacing and Crop Management:

Table 2: Recommended Plant Spacing

Crop	Recommended Spacing
Carnation	15 x 15 cm
Gerbera	37.5-40 x 30 cm
Rose	40 x 20 cm
Capsicum	45 x 30 cm, triangular
Tomato	60 x 45 cm, triangular
Cucumber	60 x 60 cm, triangular

- **Capsicum:** Retain 2 main stems, prune side shoots weekly for 3 months then every 10 days. Provide twine support.

- **Tomato:** Train to single stem, remove side shoots, limit to 2-4 fruiting nodes. Use twine to prevent fruit drop.
- **Cucumber:** Keep 2 lateral branches, pinch tip at 25 cm, use umbrella system for training.
- **Carnation:** Use 4-5 layers of GI wire/nylon net. Pinch terminal bud at 15 cm height after 4-5 weeks to induce branching.
- **Rose:** Install GI pipes with 3 rows of 14-gauge wire. Prune in June-July. For cut flowers, retain terminal bud.
- **Chrysanthemum:** Pinch main stem at 3-5 leaf stage to induce uniform branching.

Pest and Disease Management: Use yellow sticky traps + soil sterilization as preventive measures. For mites: Dicofol 5 ml/L, Abamectin 0.4 ml/L. For aphids: Fipronil 2 ml/L or Imidacloprid 0.3 ml/L.

For soil-borne diseases: mix 20 t/ha FYM, apply Carbofuran 3G @ 50 g/m² + neem cake 200 g/m², incorporate Pseudomonas + Trichoderma @ 2 kg each/ton FYM, and use summer solarization at 45°C.

Conclusion

Protected cultivation offers a sustainable solution to meet the growing demand for quality horticultural produce while minimizing risks from climate variability. Scientific management of greenhouse structures, soil health, irrigation, and crop-specific agronomic practices plays a decisive role in achieving high yields and premium quality. Adoption of these expert practices by farmers in states like Telangana can improve profitability and ensure year-round supply of vegetables, flowers, and fruits. Future efforts should focus on low-cost structures, automation, and bio-intensive pest management to make protected cultivation more accessible and sustainable.

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SWEET CORN: A HIGH VALUE CROP FOR ENHANCING FARMERS' INCOME IN NORTH EAST REGION (NER), INDIA

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Abstract

Sweet corn (*Zea mays* var. *saccharata*) is a high-value specialty maize crop gaining popularity due to its superior taste, nutritional benefits and increasing market demand. Unlike normal maize, sweet corn is harvested at the milky (immature) stage and contains higher sugar content, making it suitable for fresh consumption and processing. The favourable agro-climatic conditions of NER, India provide excellent opportunities for its commercial cultivation. Sweet corn offers several advantages to farmers, including premium market prices, short crop duration and additional income from green fodder after cob harvest. Rich in carbohydrates, dietary fibre, vitamins, minerals and antioxidants, it is increasingly preferred by health-conscious consumers. However, timely harvesting, proper post-harvest handling and efficient marketing are essential due to its short shelf life. With suitable varieties, improved production practices and better market linkages, sweet corn cultivation can significantly enhance farm income, promote crop diversification and strengthen livelihood security in NER, India.

Keyword: Sweet corn, Income generation, NE region, Cross pollination, Nutritious value

Introduction

Agriculture in NER is gradually shifting from subsistence farming towards market-oriented production systems. Farmers are increasingly exploring crops that can provide higher returns within a shorter period of time. Among such crops, sweet corn has emerged as a promising alternative due to its growing consumer demand, attractive market price, nutritional value and multiple uses.

Sweet corn is a special type of maize harvested at the immature stage when the kernels are tender, juicy and rich in natural sugars. Unlike conventional maize, which is primarily grown for grain, sweet corn is cultivated mainly as a vegetable crop. The increasing popularity of sweet corn in urban and semi-urban areas, hotels, restaurants, shopping malls and roadside food outlets has created new market opportunities for farmers. For NER, where climatic conditions are favourable for maize cultivation, sweet corn offers excellent prospects for income generation and crop diversification.

Why sweet corn is different from normal maize

Sweet corn belongs to the same species as maize (*Zea mays* L.) but differs in its genetic makeup. The kernels accumulate more sugar and less starch, making them sweeter and softer than ordinary maize. While normal maize is harvested after complete maturity, sweet corn is harvested much earlier, usually when the kernels are at the milk stage.

The crop is highly appreciated by consumers because of its pleasant taste, tenderness and versatility in cooking. Fresh cobs can be consumed after boiling, roasting, or steaming, while kernels are widely used in soups, salads, pizzas, sandwiches, noodles and various processed food products.

Nutritional importance

Sweet corn is not only tasty but also highly nutritious. It serves as a valuable source of carbohydrates and provides quick energy. In addition, it contains dietary fibre, vitamins, minerals and several health-promoting compounds.

The crop is particularly rich in:

i. Vitamin A, which supports vision and immunity.
ii. Vitamin C, which acts as an antioxidant.
iii. B-complex vitamins that help in energy metabolism.
iv. Potassium and magnesium, important for maintaining heart and muscle functions.
v. Dietary fibre, which improves digestion.
vi. Natural antioxidants such as carotenoids that contribute to overall health.

As consumer awareness regarding healthy food habits increases, the demand for sweet corn is expected to rise further in the coming years.

Scope of sweet corn cultivation in NER, India

NER, Inida possesses several advantages for successful sweet corn cultivation. The region's moderate temperature, adequate rainfall, fertile soils and availability of suitable growing seasons create favourable conditions for crop growth.

Sweet corn can be cultivated in different agro-climatic zones of the region, particularly in peri-urban areas where farmers can easily access markets. The proximity of production areas to towns and cities offers opportunities for marketing fresh produce with minimal transportation costs.

The crop fits well into existing farming systems and can be grown as:

i. A sole crop.
ii. An intercrop with vegetables.
iii. A component of crop rotation systems.
iv. A fodder-cum-food crop.

Because sweet corn matures within a relatively short period, farmers can grow multiple crops annually and increase overall farm productivity.

Economic advantages for farmers

One of the major attractions of sweet corn cultivation is its profitability. Compared with grain maize, sweet corn generally fetches a higher market price because it is sold as a vegetable rather than a cereal.

The economic benefits include:

1. Premium market price

Consumers are willing to pay higher prices for fresh sweet corn due to its taste and nutritional value. Fresh cobs sold in local markets, tourist centres and roadside stalls often generate substantial income.

2. Short crop duration

Sweet corn reaches harvestable stage much earlier than grain maize. This enables farmers to obtain quicker returns on their investment and plan subsequent crops efficiently.

3. Additional income from fodder

After harvesting the green cobs, the remaining plant biomass can be used as nutritious green fodder for livestock. This reduces feed costs and provides an additional economic advantage.

4. Opportunities for value addition

Sweet corn can be processed into frozen kernels, canned products, soups, snacks and ready-to-eat foods. Such value-added products can further enhance profitability.

Recommended varieties for the North Eastern Region

Several sweet corn varieties and hybrids have been identified for cultivation in the North Eastern region. Farmers should select varieties based on local adaptability, market demand and seed availability.

Popular cultivars include:

i. Sugar 75
ii. Misthi (NSCH-12)
iii. Candy (KSCH-333)
iv. Central Maize VL Sweet Corn-1
v. Hy-Brix 53
vi. Hi-Brix 39
vii. VL Sweet Corn Hybrid-2

These varieties have demonstrated good performance under diverse agro-climatic conditions and are suitable for commercial cultivation.

Important cultivation practices

1. Land preparation

The field should be well prepared with fine tilth. Proper drainage is essential, especially in high rainfall areas. Application of farmyard manure or compost improves soil fertility and moisture retention.

2. Sowing

Healthy and quality seed should be used for sowing. Timely sowing ensures better germination and crop establishment. Proper plant spacing should be maintained to achieve optimum plant population.

3. Nutrient management

Sweet corn responds well to balanced fertilization. Application of organic manures along with recommended doses of fertilizers helps achieve higher productivity and better cob quality.

4. Weed management

Weeds compete with the crop for nutrients, moisture and sunlight. Timely weeding during the early growth stages is crucial for maximizing yields.

5. Irrigation

Although rainfall is generally adequate in Meghalaya, irrigation during dry spells can significantly improve crop performance, especially during flowering and cob development stages.

6. Harvesting and post-harvest management

Harvesting at the correct stage is critical in sweet corn production. Cobs should be harvested when kernels are fully developed and contain milky fluid upon pressing.

Unlike grain maize, sweet corn has a very short shelf life. After harvest, sugars rapidly convert into starch, resulting in reduced sweetness and quality. Therefore, harvested cobs should be marketed as quickly as possible.

The following practices help maintain quality:

i. Harvest during cooler hours of the day.
ii. Avoid direct exposure to sunlight.
iii. Transport produce immediately to the market.
iv. Store at low temperatures whenever possible.
v. Use insulated containers during transportation.

Prompt handling and marketing are essential for obtaining premium prices.

Marketing opportunities

Marketing remains one of the most important factors determining profitability. Sweet corn growers should identify potential buyers before planting the crop.

Potential marketing channels include:

i. Local vegetable markets.
ii. Roadside retail outlets.
iii. Restaurants and hotels.
iv. Educational institutions.
v. Tourist destinations.
vi. Supermarkets and retail chains.
vii. Food processing units.

Direct marketing often allows farmers to capture a larger share of the consumer price and improve net returns.

Challenges and their management

Despite its potential, sweet corn cultivation faces several challenges:

1. **Short shelf life**

Fresh cobs deteriorate rapidly after harvest. Development of cold storage facilities and efficient supply chains can help address this issue.

2. **Transportation costs**

Remote production areas may face higher transportation expenses. Farmer groups and cooperatives can reduce costs through collective marketing.

3. **Market fluctuations**

Prices may vary depending on seasonal supply and demand. Staggered planting can ensure a continuous supply and help farmers avoid market gluts.

4. **Cross-pollination**

Sweet corn quality can be affected by pollen from nearby normal maize fields. Isolation distance, border rows and staggered planting can minimize this problem.

Future prospects

The demand for sweet corn is expanding rapidly due to urbanization, changing food habits and growing awareness of healthy diets. The increasing popularity of fast foods, ready-to-eat products and convenience foods has created new opportunities for sweet corn producers.

For NE Region, promotion of sweet corn cultivation can contribute significantly to:

i. Higher farm income.
ii. Employment generation.
iii. Crop diversification.

iv. Nutritional security.
v. Development of agri-business enterprises.

Support in the form of quality seed supply, farmer training, post-harvest infrastructure and market linkages can further accelerate adoption of the crop.

Conclusion

Sweet corn represents an attractive high-value agricultural enterprise for NER farmers. Its short duration, premium market price, nutritional importance and multiple uses make it an ideal crop for commercial cultivation. With appropriate production practices, efficient post-harvest handling and better market access, sweet corn can become an important component of profitable and sustainable farming systems in the state. The crop offers not only higher economic returns but also opportunities for entrepreneurship, value addition and livelihood improvement, making it a promising option for the future of agriculture in Meghalaya.

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MAJOR DISEASES THREATENING CITRICULTURE IN INDIA

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Abstract
Citrus is one of the most important fruit crops in India, contributing significantly to nutritional security, rural livelihoods, and horticultural economy. However, several diseases continue to threaten citrus production in the country by reducing the yield, fruit quality and orchard longevity. Among these, huanglongbing, citrus canker, citrus tristeza, foot-rot and anthracnose are of major concern across the citrus growing belt of the country. These diseases cause substantial economic losses through tree decline, premature fruit drop, reduced marketability and in severe cases, death of the tree. This article highlights the causal organisms, key symptoms, modes of spread, economic importance and management strategies of the major citrus diseases prevalent in India. Additionally, emphasis is placed on integrated disease management for maintaining overall orchard health. Adoption of these preventive and integrated approaches can help growers minimize disease losses and sustain profitable citrus cultivation.

Keywords: Citrus, orchard health, huanglongbing, integrated disease management

Citrus
Citrus is believed to have originated in Northeast India, northern Myanmar, and adjoining regions of Southeast Asia (Albrigo *et al.*, 2019). In India, citrus remained deeply connected with food, traditions, household remedies and Ayurveda since ancient times. Today, India is the third-largest producer of citrus in the world (FAOSTAT, 2025) and citrus ranks as the third most important fruit crop in India after mango and banana. Beyond fresh consumption, citrus fruits are widely used in juice processing, pharmaceuticals, flavouring agents, and essential oil production. However, despite its immense significance, citriculture in India is increasingly threatened by devastating diseases that affect the orchard health, fruit quality, and overall productivity.

Major Diseases of Citrus in India

1. **Huanglongbing (Citrus Greening Disease)**
   Causal organism: *Candidatus* Liberibacter asiaticus
   Vector: Asian citrus psyllid (*Diaphorina citri*)

Huanglongbing (HLB), commonly known as citrus greening, is one of the most destructive diseases of citrus in India. It is widely distributed across major citrus growing regions, including Northeastern states, Maharashtra, Andhra Pradesh, Karnataka, Tamil Nadu, Punjab and Rajasthan. Infected trees show blotchy leaf mottling, yellow shoots, canopy thinning, small lopsided fruits with aborted seeds and a bitter taste. The pathogen spreads mainly through grafting infected plants and the Asian citrus psyllid vector. Rapid vector multiplication and disease spread is favoured by warm temperatures. Since there is no effective curative treatment, management depends on disease free planting materials, regular psyllid monitoring and control, prompt removal of infected trees, and balanced nutrient management to maintain tree vigour and orchard productivity.

2. Citrus Canker

Causal organism: *Xanthomonas citri* p.v. *citri*

Citrus canker is among the most important bacterial diseases of citrus and is widely reported from all the major citrus growing regions in India. It causes severe losses up to 50 % yield loss by blemishing fruits, reducing market value, and in severe cases, causing defoliation, twig die back, and premature fruit drop (Ali *et al*., 2023). Infected leaves, twigs and fruits develop small water-soaked lesions that later becomes raised, corky and brown with a characteristic yellow halo. The disease spreads through wind driven rain, infected nursery plants, and mechanical movement of contaminated plant materials. Warm and humid weather further favours the spread of the disease. Management includes the use of disease-free planting material, pruning and destruction of infected twigs, windbreaks, and timely protective sprays at recommended dosage by plant protection personnel.

3. Citrus Tristeza

Causal organism: *Citrus tristeza virus* (CTV)

Vector: Brown citrus aphid (*Toxoptera citricida*)

Citrus tristeza is a major viral disease of citrus in India causing serious losses in several citrus belts. The disease reduces tree vigour, causes yellowing and stem pitting, decline and quick tree death. Fruits from infected trees may become misshapen, thick rinded and less marketable, making the disease economically significant even before the tree death occurs. It spreads through infected budwood and aphid vectors especially where susceptible planting materials are used. Effective management relies on the use of certified virus-free budwood, selection of tolerant rootstocks, regular monitoring and control of aphid populations, and removal of severely infected trees to minimize further spread.

4. Foot rot (Gummosis)

Causal organism: *Phytophthora parasitica*, *Phytophthora citrophthora* and *Phytophthora palmivora*

Foot rot is a serious soil-borne disease of citrus that becomes especially damaging under poor drainage and humid conditions. Typical symptoms include gum exudation from the trunk during dry season, bark discoloration, root decay and eventual decline of trees, making the orchards less productive over time. Infected trees often show yellowing, wilting and dieback as the root system weakens. The pathogen thrives in waterlogged soils and can spread through infected planting materials, soil movement and wounds near the trunk base. Management depends on good drainage, avoiding trunk injuries, keeping the graft-union above the soil line, and applying recommended protective fungicidal measures when needed.

5. Citrus Anthracnose

Causal organism: *Colletotrichum* species complex

The disease affects leaves, flowers, twigs and fruits, especially during the humid weather. It causes flower blight, twig dieback, fruit lesions, and premature fruit drop, which together reduce both yield and fruit quality. The disease is most noticeable when necrotic spots surrounded by a dark margin expand on young tissues. Moist and humid condition accompanied by poor canopy aeration favours rapid infection and spread. The disease spreads through infected plant debris and fungal spores carried by rain splash. Management involves pruning diseased twigs, removing fallen infected material, canopy pruning to improve aeration and preventive chemical sprays only when recommended.

Integrated Disease Management Strategies

- Use certified disease-free planting materials from reputable sources or a government-recognized nurseries.
- Ensure proper drainage by preparing raised beds or mounds to prevent water logging.
- Remove weeds and debris from previous crops to reduce inoculum sources.
- Establish nursery in disease-free area with proper isolation from existing citrus orchards.
- Maintain appropriate planting space depending on the variety to prevent overcrowding and ensure good air circulation.
- Keep graft-union above the soil line (15-20 cm) to prevent gummosis and root collar rot.
- Balanced application of NPK along with micronutrients (Zn, Mn, Fe, Cu) to maintain tree vigour and disease resistance.
- Cut off water sprouts, suckers, poorly placed branches, dead and diseased branches to establish good tree framework.
- Monitor pests using yellow sticky traps, pheromone traps, light traps and visual inspections.
- Spray Neem oil (2%) during peak flush emergence stage to control insect pests.
- Apply Bordeaux mixture during new flush emergence as a disease preventive measure.
- Use registered biological products (e.g., *Trichoderma* or *Pseudomonas* based formulations) according to label recommendations and advisory services.
- Rotational insecticide program alternating neem oil, horticultural oils, contact insecticides and systemic insecticides to prevent resistance development.
- Conserve natural enemies such as ladybirds, lacewings, parasitic wasps, spiders etc and avoid use of broad-spectrum insecticides.
- Follow label recommendations for dosage and frequency.
- Regular interaction with extension officials at KVK, ICAR and agricultural universities.

Conclusion

India's citrus industry has immense potential, but this potential can only be realized when orchard health is protected from destructive diseases. Huanglongbing, citrus tristeza, citrus canker, foot rot and anthracnose continue to weaken trees, reduce fruit quality and erode farmer profits across major citrus growing areas. Due to the limited curative options for some of these diseases, the most effective strategy is to prevention through the use of clean planting material, careful orchard hygiene, vector management, and balanced fertilization. Protecting citrus orchards through early disease detection and integrated management will be essential for ensuring the long-term sustainability and profitability of citriculture in in India.

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OKRA MUCILAGE: A NATURAL POLYSACCHARIDE WITH DIVERSE FUNCTIONAL APPLICATIONS

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Abstract

Okra (*Abelmoschus esclentus* Moench) is an important vegetable crop that is widely consumed around the world. One of its valuable components is its mucilage that is obtained from the okra pods. This mucilage is rich in complex polysaccharides and contains small amounts of proteins, minerals and bioactive compounds. Due to its excellent water holding capacity, thickening, emulsifying and film forming properties makes it ideal for use in various industries. Also, its ecofriendly nature has made it a promising natural biopolymer with significant potential for future industrial and biomedical applications.

Introduction

Okra (*Abelmoschus esclentus* Moench) is an integral part of human diet as it is a rich source of minerals, vitamins and vegetable protein. In various parts of the world, it known by various names like bhindi in India and Pakistan, guano-guano in Spain and ladies' finger or gumbo in England and America. It first originated in Ethiopia and now is propagated in many countries such as India, Pakistan, Japan, Iraq, Ghana, Greece, Brazil, Italy, Burma, Afghanistan, and Iran. Globally, India ranks first in okra production, having an area of 509 ha with an annual production of 6094.9 million tons and productivity of 12 million tonnes/ha.

Okra mucilage is a naturally occurring hydrocolloid obtained from the pods of *Abelmoschus esculentus* (L.) Moench. Owing to its excellent water-holding capacity, high viscosity, emulsifying ability and biocompatibility, okra mucilage has attracted considerable attention as a sustainable natural biopolymer. In recent years, its applications have expanded from traditional food uses to pharmaceutical, biomedical and environmental sectors. Furthermore, its biodegradability, non-toxicity and functional properties make it a promising alternative to synthetic additives and commercial hydrocolloids.

a)  b) 

Fig 1: (a) Okra pods (b) Okra mucilage (Kale et al., 2020)

Composition of Okra Mucilage

Okra mucilage is a complex acidic heteropolysaccharide composed mainly of carbohydrates along with small amounts of proteins, minerals and phenolic compounds. Its composition varies depending on the cultivar, maturity stage and extraction method. The okra mucilage contains around 55-75 carbohydrates, therefore is considered a carbohydrate rich biopolymer. Several studies have shown that the principal monosaccharides present in okra mucilage are D-galactose, L-rhamnose and galacturonic acid. These sugars form highly branched polysaccharides, primarily rhamnogalacturonan-I (RG-I) and arabinogalactan structures. The high proportion of galactose, rhamnose and galacturonic acid imparts high viscosity and excellent water-holding capacity, making okra mucilage suitable for food, pharmaceutical and biomedical applications. The mucilage also contains several minerals like Calcium, magnesium, Potassium, Sodium, Iron and Zinc. The presence of calcium and magnesium contributes to its gel-forming and rheological properties. Several bioactive compounds like phenolics, flavonoids and antioxidants are also present. Table 1 summarizes the various components, their composition and role in okra mucilage.

Table 1: Composition and Major Components of Okra Mucilage

Component	Composition/Range (%)	Remarks
Total carbohydrates	55–75	Major constituent of mucilage
Protein	4–15	Contributes to emulsifying properties
Crude fiber	5–15	Includes soluble and insoluble fractions
Ash	5–12	Represents mineral content
Lipids	<2	Present in very small amounts
Galactose	25–45 of total monosaccharides	Major neutral sugar
Rhamnose	20–35 of total monosaccharides	Characteristic of rhamnogalacturonan-I
Galacturonic acid	15–30 of total monosaccharides	Responsible for acidic nature and gelling properties
Arabinose	2–10 of total monosaccharides	Minor sugar constituent
Glucose	1–8 of total monosaccharides	Present in small quantities
Xylose	1–5 of total monosaccharides	Minor constituent
Minerals	Ca, K, Mg, Na, Fe, Zn	Contribute to functional properties
Phenolic compounds	Trace amounts	Responsible for antioxidant activity

Extraction of Okra Mucilage

The most common method used for extracting okra mucilage from fresh pods is the hot water extraction followed by precipitation with ethanol and acetone. The pods are washed with distilled water and cut into thin slices. For extraction, the slices are heated with distilled water (1:5 to 1:10 w/v) at 50-80 °C for 1-2 hours with continuous stirring. The extract is then cooled and is filtered through a muslin/cheese cloth. The extract is then centrifuged at 4000-5000 rpm for 10-15 min to attain higher purity. Then mucilage is precipitated by adding three volumes of 95% ethanol or acetone slowly to filtrate and stirring continuously. The mixture is allowed to stand for 12-14 hours at 4°C and the precipitated mucilage is separated by filtration. The impurities left are removed by washing it with ethanol. Finally, the mucilage is dried at 40-50 °C or is freeze dried and grinded into a fine powder.

Applications of Okra Mucilage

Okra mucilage due to its biodegradability, biocompatibility, non-toxicity, high water-holding capacity, and excellent rheological properties have attracted considerable scientific and industrial interest. These characteristics have enabled its application in diverse sectors, including food, pharmaceuticals, agriculture, environmental management, cosmetics, and packaging industries.

1. Food industry

Okra mucilage has thickening, emulsifying, stabilizing and gelling properties which makes it suitable for use in food industry. It aids in improving the texture and viscosity of food products like soups, sauces, dairy products and beverages. Due to its ability to stabilize emulsions and retain moisture it has been investigated as a fat replacer in low fat food formulations and as an edible coating material to extend the shelf life of fruits and vegetables. It has also shown potential to be used as an encapsulating agent for probiotics and bioactive compounds.

2. Pharmaceutical industry

In pharmaceutical industry, okra mucilage is used as tablet binder, disintegrant, suspending agent, and controlled-release polymer due to its mucoadhesive property. It helpd in enhancing retention time and improving bioavailability. Also, its non-toxic and biodegradable nature make it ideal alternative to synthetic pharmaceutical polymers.

3. Environmental application

The presence of hydroxyl and carboxyl functional groups in Okra mucilage enables it to adsorb heavy metals, dyes, and other pollutants from wastewater demonstrating its potential as a natural biosorbent and flocculating agent. Consequently, it has gained attention as an eco-friendly and cost-effective material for water purification and environmental remediation.

4. Agriculture sector

In agriculture sector, the water-retention capacity of Okra mucilage has been investigated as a seed-coating material and as a carrier for controlled-release fertilizers. Its helps maintain soil moisture and promotes seed germination and seedling establishment. Additionally, its biodegradable nature makes it suitable for developing sustainable agricultural inputs.

5. Cosmetic industry

In cosmetic industry okra mucilage is used as a natural thickener, stabilizer, and moisturizing agent in creams, lotions, gels, and personal care products. Its excellent water-binding properties improve the texture and hydration characteristics of cosmetic formulations.

Okra mucilage has also gained attention in the fields of biodegradable packaging and nanotechnology. It has been incorporated into biodegradable films and polymer composites as an environmentally friendly alternative to synthetic plastics. Moreover, its polysaccharide matrix has been explored for the green synthesis and stabilization of nanoparticles, opening new avenues for its application in advanced materials and nanomedicine. Table 2 summarizes the various application of okra mucilage in different industries.

Table 2: Application of Okra mucilage in different industries.

Sector	Application	Function of Okra Mucilage
Food industry	Thickener and stabilizer	Improves viscosity and texture of soups, sauces, and dairy products
	Emulsifier	Stabilizes oil-in-water emulsions

Sector	Application	Function of Okra Mucilage
	Fat replacer	Used in low-fat food formulations
	Edible coatings and films	Extends shelf life and reduces moisture loss
	Encapsulation material	Protects bioactive compounds and probiotics
Pharmaceutical industry	Tablet binder	Improves tablet cohesion and mechanical strength
	Disintegrant	Facilitates tablet disintegration
	Sustained-release polymer	Controls drug release
	Suspending agent	Maintains uniform drug dispersion
	Mucoadhesive agent	Enhances drug retention and bioavailability
Environmental sector	Wastewater treatment	Adsorbs dyes and heavy metals
	Flocculating agent	Assists in particle aggregation and sedimentation
Packaging industry	Biodegradable films	Alternative to synthetic plastic packaging
Agriculture	Seed coating	Improves moisture retention and seed germination
	Controlled-release fertilizer carrier	Enhances nutrient use efficiency
Cosmetics industry	Thickener and stabilizer	Used in creams, lotions, and gels
	Moisturizing agent	Improves skin hydration and texture
Biotechnology	Immobilization matrix	Supports enzymes and microorganisms
Nanotechnology	Nanoparticle synthesis and stabilization	Used as a green reducing and capping agent

Conclusion

Okra mucilage is a valuable natural biopolymer that offers a combination of desirable functional and biological properties. Future research should focus on improving extraction techniques, understanding its structure function relationships, and exploring its use in advanced applications such as drug delivery systems, biodegradable materials, and nanotechnology. Overall, okra mucilage holds great promise as a multifunctional and sustainable material for the development of innovative products and green technologies.

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CLIMATE-RESILIENT AGRICULTURE IN INDIA: A REMOTE SENSING PERSPECTIVE

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Abstract

Climate change is significantly affecting Indian agriculture through rising temperatures, erratic rainfall, and increasing extreme weather events. India's large rainfed farming system (≈52% of cultivated land) is particularly vulnerable to monsoon variability (IPCC, 2023). Recent studies indicate that climate variability accounts for nearly 30–40% of crop yield fluctuations (Lobell *et al*., 2011). Heat stress, droughts, and floods are reducing crop productivity and increasing production instability. Remote Sensing (RS) and Geographic Information Systems (GIS), integrated with Artificial Intelligence (AI), provide powerful tools for real-time crop monitoring, drought assessment, and yield prediction. Technologies such as NDVI enable early detection of crop stress and support climate-resilient decision-making. This article highlights recent (2020–2026) climate trends, their impacts on Indian agriculture, and the role of geospatial technologies in improving resilience and sustainability (ISRO 2022).

Keywords: Climate change, Remote sensing, GIS, NDVI, Agriculture

Introduction

Agriculture in India is highly sensitive to climatic parameters such as temperature, rainfall, and solar radiation. Climate change, driven by anthropogenic greenhouse gas emissions, is altering these parameters and increasing climatic variability. India's agriculture supports nearly half of the population and remains largely dependent on monsoon rainfall, with about 52% of cultivated land being rainfed. Recent scientific studies indicate that climate variability is already impacting crop productivity and stability (Ray e*t al*., 2013). Rising temperatures, irregular rainfall, and frequent extreme weather events are emerging as major threats to food security. In this context, Remote Sensing (RS) and Geographic Information Systems (GIS) are playing a crucial role in monitoring climate impacts and supporting adaptive agricultural practices (WMO 2025).

Climate change Trends

India has experienced a significant rise in temperature, with an increase of about 0.8–0.9°C since the early 20th century, as highlighted by the Intergovernmental Panel on Climate Change (IPCC AR6, 2023)**.** Recent decades show accelerated warming, especially in northwest India, leading to more frequent and intense heatwaves. These extreme heat events are becoming longer and more widespread, posing serious risks to agriculture, water resources, and human health (IPCC, 2023; WMO, 2025).

Monsoon Trends

The Indian monsoon is becoming increasingly erratic due to climate change. While some regions show a decline in average rainfall, there is a clear rise in extreme rainfall events**,** resulting in floods and dry spells occurring in the same season. This reflects the intensification of the hydrological cycle under warming conditions, disrupting cropping patterns and increasing vulnerability of rainfed agriculture (IPCC, 2023; WMO, 2025).

Extreme Weather Events

India is witnessing a sharp increase in extreme weather events such as heatwaves, floods, cyclones, and droughts**,** now occurring almost throughout the year. Ocean warming in the Indian Ocean is intensifying cyclones, while changing atmospheric conditions are increasing disaster frequency. These events are already impacting agriculture and livelihoods, confirming that India has become a climate-risk hotspot requiring urgent adaptation strategies (IPCC, 2023; Government of India, 2023).

Temperature & Heat Stress Impacts

Rising temperatures are significantly reducing crop productivity in India, particularly during sensitive growth stages. Studies aligned with the Intergovernmental Panel on Climate Change (IPCC AR6, 2023) indicate that even small increases in temperature can sharply reduce yields. For example, wheat yields in the Indo-Gangetic Plains are projected to decline by 1–8% due to temperature rise alone and up to 36% when combined with water stress (Lobell *et al*., 2011). Long-term projections also show that rice yields could decline by up to 22% under high-emission scenarios. Heat stress further increases evapotranspiration, leading to higher irrigation demand and reduced water-use efficiency.

Impact of climate change on agriculture

Monsoon Variability & Water Stress Impacts

Climate change is intensifying rainfall variability, directly affecting agricultural stability. Research indicates that by 2050, paddy yields may decline by ~24%**,** while wheat yields could fall by 6–7% in the Indo-Gangetic Plains under moderate climate scenarios. Erratic monsoon patterns such as delayed onset and uneven distribution lead to both droughts and floods within the same season. Since over 50% of India's population depends on agriculture**,** and a large share of farming is rainfed, this variability significantly threatens food security and farmer livelihoods.

Extreme Events, Pests & Soil Impacts

The increasing frequency of extreme events such as heatwaves, floods, and cyclones is causing substantial crop losses and economic damage. Studies suggest that climate change could lead to yield losses exceeding 25–30% for major crops by the end of the century under high-emission scenarios. Additionally, about 60% of farmers report increased pest and disease incidence due to changing climatic conditions, further reducing productivity (Government of India, 2023). Soil degradation is also accelerating, with rising temperatures and erratic rainfall contributing to loss of soil organic carbon, salinity, and reduced fertility (Lal 2015). Together, these impacts are increasing yield variability and making Indian agriculture more vulnerable to climate risks.

Role of Remote Sensing and GIS

Crop Monitoring (NDVI)

Remote sensing indices like NDVI enable large-scale monitoring of crop health and stress (ISRO 2022). Studies show >80% of India's agricultural areas have positive NDVI trends**,** while sudden declines help detect early stress and support yield forecasting (Indian Space Research Organisation;IPCC,2023**)**.

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Fig. 1. Crop Monitoring

Drought & Flood Monitoring

GIS and satellite data provide near real-time assessment of soil moisture, rainfall, and crop conditions. Flood mapping using SAR imagery has shown that ~9.5 million ha of cropland were affected in 2025, enabling early warning and contingency planning (FAO, 2022).

Precision & AI-based Agriculture

Remote sensing integrated with GIS and AI supports precision farming through site-specific input use. These technologies can improve input efficiency by 15–25% and enable early yield and pest forecasting, making agriculture more climate-resilient (IPCC, 2023; ICAR, 2023).

Strategy Area	Key Practices	Adaptation Benefits	Mitigation Benefits	Source
Climate-Resilient Crops	Heat- & drought-tolerant varieties, millets, short-duration crops	Reduce yield loss by 10–30% under stress	Efficient resource use	IPCC (2023); ICAR (2023)
Water Management	Drip irrigation, rainwater harvesting, AWD in rice	Saves 30–50% water, stabilizes yields	AWD reduces ~30% CH_4 emissions	FAO (2022); IPCC (2023)
Soil & Cropping Practices	Zero tillage, residue retention, crop diversification	Improves soil moisture & resilience	Increases soil carbon, reduces burning (~40–50%)	Lal (2015); ICAR
Risk Management	Agro-advisories, early warning systems, crop insurance (PMFBY)	Reduces climate risk & economic losses	Promotes sustainable practices	Government of India (2023)
Agroforestry & Precision Farming	Tree-based systems, site-specific nutrient management	Enhances farm stability & microclimate	Sequesters 2–4 t CO_2/ha/year	FAO (2022); IPCC (2023)

Fig. 2. Agroforestry & Precision Farming.

Conclusion

India's agriculture is increasingly vulnerable to climate change, with rising temperatures and erratic rainfall reducing yields and increasing production variability. Evidence from IPCC and national assessments indicates an accelerating trend of climate risks. Geospatial technologies (RS/GIS), integrated with AI, enable real-time crop monitoring (e.g., NDVI), early warning of droughts and floods, and precision-based decision-making. Transitioning from reactive to predictive agriculture will require climate-smart practices, improved crop varieties, efficient water management, and risk mitigation tools such as insurance and advisories. Sustainable approaches, including conservation agriculture and agroforestry, further enhance resilience through soil carbon improvement. A combined strategy of technological innovation and sustainable agronomy is essential to ensure long-term food security under changing climatic conditions.

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PLANT GROWTH PROMOTING RHIZOBACTERIA (PGPR) AND CROP PRODUCTIVITY

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Abstract

Beneath every field of grain and every garden bed lies an invisible world that most of us never think about a universe of microorganisms working ceaselessly around plant roots, shaping the health and productivity of the crops we depend on. Among these microscopic inhabitants, a particularly helpful group known as Plant Growth Promoting Rhizobacteria, or PGPR, have been attracting serious scientific attention for decades. These beneficial bacteria colonise the rhizosphere the narrow zone of soil immediately surrounding plant roots and through a sophisticated array of biological mechanisms, they help plants grow better, fight disease, and tolerate environmental stress.

This article explores what PGPR are, how they work, what they can do for major food crops like maize and cowpea, and why they represent one of the most promising pathways toward an agriculture that is both productive and kind to the planet. Drawing on recent peer-reviewed research, it also addresses the real challenges that stand between current scientific excitement and widespread farmer adoption and what the future might look like if we get this right.

Keywords: Plant Growth Promoting Rhizobacteria (PGPR), rhizosphere, biofertilizers, nitrogen fixation, phosphate solubilization, biocontrol, sustainable agriculture, maize, cowpea, soil health and crop productivity.

Introduction

There is a farming crisis unfolding in slow motion across the world, and it does not make headlines the way floods or droughts do. It is quieter than that, buried in the soil itself. Decades of intensive chemical agriculture the heavy application of synthetic nitrogen fertilizers, phosphate supplements, herbicides, fungicides, and insecticides have dramatically increased crop yields and fed billions of people. That is a genuine achievement and should not be dismissed. But the bill is coming due.

Soils that were once biologically rich and self-sustaining are losing their fertility. Waterways are being polluted by fertilizer runoff. Beneficial insects are declining. Soil microbes the organisms that drive nutrient cycling, decompose organic matter, and maintain the living architecture of healthy soil are being killed off by the very chemicals meant to improve agricultural output. And the crops themselves, paradoxically, are becoming more dependent on ever-greater chemical inputs just to maintain yields.

At the same time, the world is adding more mouths to feed every year. The United Nations projects a global population of 9.7 billion by 2050. Climate change is already shaving yields from critical cereal crops about 3.8% losses in maize and 5% in wheat have been attributed to rising temperatures. Drought, salinity, and heavy metal contamination are turning productive farmland into wastelands. The old playbook is not going to be enough.

This is why Plant Growth Promoting Rhizobacteria deserve attention not just from scientists, but from farmers, policymakers, students, and anyone who eats food. PGPR represent nature's own solution to many of the problems that chemical agriculture has either failed to solve or actively created. They are not magic, and they are not without limitations. But the evidence for their effectiveness is substantial, growing, and genuinely exciting.

The Rhizosphere: Where Plants and Bacteria Strike a Deal

To understand PGPR, you first need to appreciate the rhizosphere one of the most ecologically complex and productive environments on Earth, despite fitting within a few millimetres of soil.

Every plant root is constantly leaking substances into the surrounding soil. Water-soluble organic compounds, amino acids, sugars, enzymes, and even gases like CO_2 and ethylene seep out of roots in a process called rhizodeposition. This might seem like a waste, but it is far from it it is an invitation. These root exudates attract and feed a dense, diverse community of microorganisms. The rhizosphere soil around a plant root can contain bacterial populations ten to a hundred times denser than the surrounding bulk soil. It is, quite literally, a microbial hotspot.

Within this community, relationships between microbes and plant roots range from mutually beneficial to parasitic. But among the most important players are the PGPR bacteria that have evolved to colonise root surfaces, draw energy and carbon from root exudates, and in return provide the plant with services that genuinely improve its health and growth.

The term "rhizosphere" was coined by the German scientist Lorenz Hiltner all the way back in 1904, when he noticed the unusual microbial richness around plant roots. The formal concept of PGPR came later, introduced by J.W. Kloepper in 1978, who defined them as root-colonising bacteria capable of enhancing plant growth and yield. In the nearly five decades since, thousands of research studies have documented what these bacteria can do and the picture that emerges is remarkable.

PGPR fall into two broad categories. Extracellular PGPR (ePGPR) live in the rhizosphere soil, on root surfaces, or in spaces between root cortex cells. This group includes well-studied genera like *Bacillus*, *Pseudomonas*, *Azotobacter*, and *Serratia*. Intracellular PGPR (iPGPR), by contrast, actually enter root cells and often form specialised nodule structures the most famous being the rhizobia, such as *Rhizobium* and *Bradyrhizobium*, which form the iconic nitrogen-fixing nodules on legume roots.

How PGPR Help Plants Grow: The Mechanisms

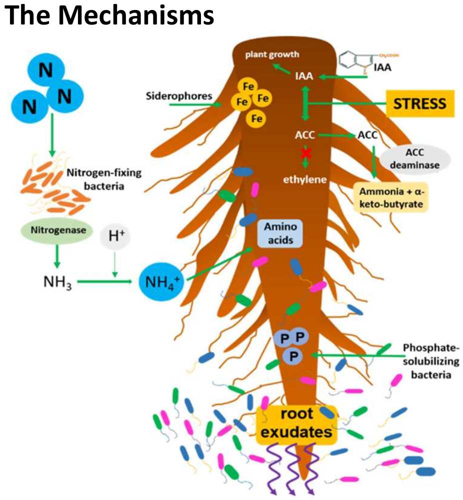

Figure 2: Mechanisms of PGPR

PGPR do not work through a single trick. They operate through a remarkable toolkit of both direct and indirect mechanisms some that nourish plants by making nutrients available, and others that protect plants by suppressing pathogens and boosting immunity.

Direct Mechanisms: Nourishing the Plant

Nitrogen Fixation

Nitrogen is the nutrient that plants need above all others. It is a building block of proteins, chlorophyll, and DNA without it, growth simply stops. The good news is that nitrogen is extraordinarily abundant: it makes up 78% of the air we breathe. The bad news is that plants cannot use it in this gaseous form (N_2). They need it converted into ammonia (NH_3) or nitrate and that conversion, called biological nitrogen fixation, is something that only certain microorganisms can do.

PGPR achieve this through the enzyme nitrogenase, which breaks the extraordinarily strong triple bond in N_2 and combines nitrogen with hydrogen to form ammonia. Some PGPR the rhizobia do this in intimate symbiotic partnerships with legume plants like cowpea, soybean, and clover, forming the characteristic root nodules that are visible to the naked eye. Others, like *Azotobacter*, *Azospirillum*, and *Gluconacetobacter*, fix nitrogen freely in the rhizosphere, providing it to non-legume crops including maize, rice, and wheat.

The implications for farmers are significant. Nitrogen fertilizer is expensive, its production consumes fossil fuels, and its overuse pollutes the environment. Nitrogen-fixing PGPR offer the possibility of meeting some or all of a crop's nitrogen needs through biological processes alone.

Phosphate Solubilization

Phosphorus is the second most important macronutrient for plants, involved in virtually every major metabolic process photosynthesis, energy transfer, root development, and seed formation. It is abundant in most agricultural soils, but here is the problem: between 95 and 99% of soil phosphorus is locked in insoluble chemical forms that plant roots simply cannot absorb. Plants can only take up phosphorus as dissolved ions, but most of it is tightly bound to soil minerals or complexed in organic matter.

Phosphate-solubilizing PGPR break this deadlock by releasing organic acids gluconic acid, citric acid, oxalic acid that acidify the soil immediately around the root, dissolving insoluble phosphate compounds and releasing phosphorus into the soil solution where plants can access it. They also produce enzymes (phosphatases) that release phosphorus from organic compounds. Genera that do this particularly well include *Bacillus*, *Pseudomonas*, *Burkholderia*, *Enterobacter*, and *Serratia*. Research has shown that phosphate-solubilizing bacteria can reduce the amount of phosphate fertilizer needed by around 25%, which is both economically and environmentally significant.

Potassium Solubilization

Potassium rounds out the trio of essential macronutrients, playing a critical role in water regulation, enzyme activation, and stress responses in plants. Like phosphorus, it has an availability problem: more than 90% of potassium in most soils exists in insoluble rock and silicate mineral forms. Without enough available potassium, plants develop weakly, produce small seeds, and yield poorly.

PGPR such as *Paenibacillus* sp., *Bacillus edaphicus*, *Acidothiobacillus*, and *Pseudomonas* produce organic and inorganic acids that weather potassium-bearing minerals, releasing potassium into the soil solution. This mechanism is less studied than nitrogen fixation and phosphate solubilization, but it represents another avenue through which PGPR can reduce dependence on synthetic mineral supplements.

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Siderophore Production and Iron Availability

Iron is essential for photosynthesis, amino acid synthesis, nitrogen fixation, and respiration and yet it is remarkably scarce in most aerobic soils. Despite being the fourth most abundant element in the Earth's crust, iron in oxygenated soils exists mainly as insoluble ferric oxide (Fe^{3+}), barely available to plants or microbes.

PGPR respond to iron scarcity by producing siderophores small, specialised molecules with an exceptionally high affinity for iron. These molecules capture iron atoms from the soil and transport them back to the bacterial cell, where iron is released for metabolic use. More than 500 different siderophores are known, belonging to three main chemical families: hydroxamates, catecholates, and carboxylates. Importantly, many plants can also use bacterial siderophores as iron sources, benefiting directly from this PGPR activity.

Siderophore production by PGPR also serves as a biocontrol mechanism: by capturing iron in the rhizosphere, PGPR deprive pathogenic fungi and bacteria of an essential growth factor, limiting their ability to cause disease.

Phytohormone Production

Plants govern their own growth and development through hormones chemical signals produced in tiny quantities that regulate everything from seed germination to flowering to stress responses. What is perhaps less appreciated is that many soil bacteria produce the same hormones, or their precursors, and can influence plant physiology from the outside.

Indole-3-acetic acid (IAA) the most common natural auxin is produced by an estimated 80% of rhizobacteria. It stimulates root elongation, branching, and hair formation, dramatically expanding the root system's surface area and thereby increasing the plant's capacity to absorb water and nutrients. Research has shown that IAA-producing PGPR like *Azospirillum*, *Pseudomonas*, and *Agrobacterium* can significantly increase root length, the number of root hairs, and root branching compared to uninoculated plants.

Cytokinins produced by PGPR promote cell division in shoots and delay leaf senescence the aging and yellowing of leaves keeping the photosynthetic machinery working longer. Gibberellins stimulate stem elongation and contribute to overall plant development. Abscisic acid (ABA), though often associated with stress responses, helps plants activate their defenses against pathogens and environmental challenges.

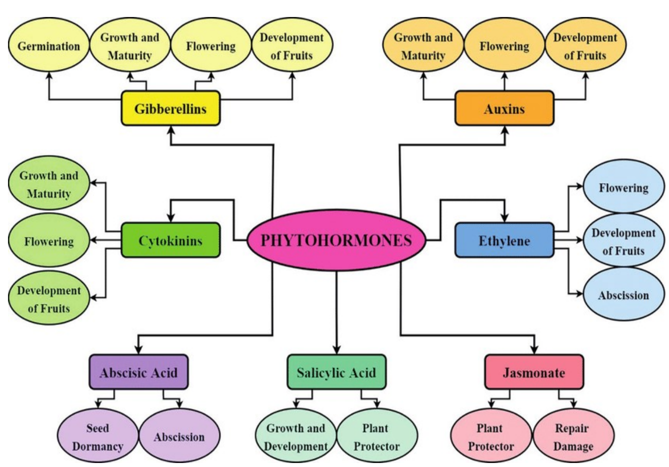

Figure 2: Role of Phytohormones in Plant Growth

Indirect Mechanisms: Defending the Plant

Beyond feeding plants, PGPR serve as active defenders against the microbial threats that can devastate crops.

Antibiotic and Antimicrobial Compound Production

The word "antibiotic" usually conjures images of medicine, but in the soil, antibiotics are ancient chemical warfare tools bacteria use against each other and against fungi that compete for space and resources. Many PGPR produce these compounds, and in doing so, they protect plant roots from pathogens before infections can take hold.

Pseudomonas species produce a particularly well-studied suite of antifungal compounds, including 2,4-diacetylphloroglucinol (DAPG), phenazines, pyoluteorin, and pyrrolnitrin, which suppress a range of plant-pathogenic fungi. *Bacillus* species produce lipopeptides including surfactin, iturin, and fengycin with broad-spectrum antibacterial and antifungal activity. *Bacillus thuringiensis* (Bt) is famous for producing proteins lethal to certain insect pests, making it one of the most widely used biological pesticides in the world.

Lytic Enzyme Production

Some PGPR go a step further and directly attack fungal pathogens by producing enzymes chitinases, glucanases, proteases, cellulases, lipases that degrade the structural components of fungal cell walls. Chitin and glucan make up the bulk of most fungal cell walls; bacteria that produce chitinases and β-glucanases can essentially dissolve these walls, killing the fungus directly. This has been demonstrated against crop pathogens including *Fusarium oxysporum*, *Rhizoctonia solani*, *Botrytis cinerea*, and *Pythium ultimum* responsible for devastating diseases in vegetables, cereals, and legumes worldwide.

Induced Systemic Resistance (ISR)

Perhaps the most impressive trick in the PGPR arsenal is their ability to prime the plant's own immune system triggering a state of heightened defensive readiness throughout the entire plant, not just at the site where bacteria have colonised the root.

This phenomenon, called Induced Systemic Resistance (ISR), is the plant equivalent of a vaccination. When certain PGPR colonise roots, they produce signalling molecules lipopolysaccharides, flagellin, siderophores, volatile organic compounds that are detected by the plant and trigger a cascade of defensive preparations. The plant activates enzymes like chitinases and peroxidases, accumulates antimicrobial compounds called phytoalexins, and reinforces its cell walls with lignin and callose. When a real pathogen eventually attacks, the plant is ready.

ISR has been shown to protect plants against a remarkably broad spectrum of threats, including bacterial diseases, fungal infections, viral diseases, and even attacks by insects and nematodes. It is systemic, long-lasting, and unlike chemical fungicides does not damage the soil.

PGPR and Stress Tolerance: Growing in a Changing Climate

Climate change is not a distant threat for farmers it is already reshaping the conditions under which crops grow. Longer droughts, higher temperatures, increasing soil salinity, and more frequent flooding are transforming the calculus of agricultural production. The ability of PGPR to help crops tolerate these stresses is one of the most exciting dimensions of current research.

Drought stress, which already threatens crop hydration, photosynthesis, and nutrient uptake across vast areas, is perhaps the most urgent concern. PGPR address drought in multiple ways: by producing ACC deaminase to reduce ethylene-driven growth inhibition, by producing exopolysaccharides that maintain soil moisture around roots, and by triggering plants' own protective stress responses. Studies have shown that *Pseudomonas* sp. inoculation of maize under drought conditions improved both solute accumulation and antioxidant status essentially helping the plant cope biochemically with water deficit. Inoculation of wheat seeds with the drought-tolerant strain *Pseudomonas libanensis* EU-LWNA-33 improved both plant growth and phosphorus uptake under drought conditions.

Salinity is another severe abiotic stressor. Soil salinisation is advancing at an estimated 1–2% per year in arid regions, and around 20–30% of the world's irrigated land is already affected. EPS-producing PGPR have been shown to reduce sodium bioavailability to plants in saline soils, while ACC deaminase-producing strains help plants maintain growth that saline conditions would otherwise suppress.

Heavy metal contamination from industrial effluents, mining operations, and long-term use of metal-containing agricultural inputs is yet another challenge. Certain PGPR can bind heavy metals through negatively charged functional groups on their cell walls, removing or immobilising them in the soil. PGPR producing ACC deaminase reduce the ethylene surge that heavy metal stress triggers in plants, allowing roots to continue growing in contaminated soil.

Conclusion

There is something quietly profound about the idea that some of the most important agricultural innovations of the coming century are not being invented in chemical plants or engineering labs they are being discovered in the soil beneath our feet, where bacteria have been doing extraordinary things for billions of years.

PGPR are not a silver bullet, and they are not going to replace all synthetic inputs overnight. The challenges of variability, formulation, and farmer access are real and deserve honest acknowledgment. But the weight of evidence is clear: these bacteria can fix nitrogen, unlock phosphorus, regulate plant hormones, fight pathogens, induce systemic immunity, improve soil structure, and help crops survive drought, salinity, and contamination. Applied to vital crops like maize and cowpea, they can increase yields meaningfully while reducing the chemical burden on soils and waterways.

We are at a point in agricultural history where we genuinely need better options. The chemical model has served us, but it has also cost us in soil health, in biodiversity, in water quality, and in the long-term productivity of the land itself. PGPR point toward something better: an agriculture that works with nature rather than against it, that builds soil health rather than depleting it, and that can be as productive in the long run as it is in any given season.

The soil has always been alive. The opportunity and perhaps the responsibility before us is to understand that life well enough to work alongside it.

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SHRIMP HEAD WASTE: A VALUABLE FOOD INGREDIENT AND SUSTAINABLE APPROACH TO SEAFOOD INNOVATION

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Abstract

The industrial seafood processing sector generates massive quantities of shrimp by-products, primarily consisting of heads and shells. Although traditionally discarded as environmental pollutants, recent scientific investigations reveal that these processing residues are actually rich reservoirs of essential proteins, amino acids, bioactive carotenoids, and chitin. Driven by advanced bio-processing technologies, researchers and food scientists are now converting these marine by-products into high-value functional ingredients, including natural flavour powders and protein concentrates. Integrating these nutrient-dense extracts into commercial food formulations—such as fortified noodles, snacks, and crackers—significantly enhances their nutritional profiles and sensory characteristics. Ultimately, this circular "waste-to-wealth" strategy mitigates the ecological footprint of seafood disposal, optimises resource efficiency, and unlocks new economic avenues for sustainable food production systems.

Keywords: Shrimp-heads, Shrimp waste, Flavour, Noodles.

Introduction

Seafood is a global dietary cornerstone, supplying essential proteins, lipids, and micronutrients. However, shifting consumer demands toward convenience foods coincide with a critical industrial challenge: the generation of massive volumes of processing waste. In shrimp processing, unutilized heads, shells, and tails constitute up to 50% of the raw biomass. Historically discarded, this mismanagement poses severe ecological liabilities.

Recent bio-resource research redefines these processing residues not as waste, but as dense matrices of structural polymers, carotenoids, minerals, and bioactive proteins. Shrimp cephalothoraxes (heads) and exoskeletons are particularly rich in chitin, chitosan, and astaxanthin, alongside high-value amino acids. Recovering these components offers a dual pathway to mitigate environmental degradation and advance circular economy models within global fisheries.

A prominent innovation in this field is the synthesis of natural seafood flavour powders. Shrimp heads contain high concentrations of endogenous glutamic acid, the primary driver of the savory umami palate. Utilizing advanced processing methodologies—such as targeted enzymatic hydrolysis, thermal dehydration, and spray drying—scientists can convert this volatile biomass into shelf-stable, nutrient-dense flavour concentrates. These powders present a viable, clean-label alternative to synthetic flavour enhancers.

Converting marine processing by-products into functional food ingredients represents a highly efficient closed-loop system. This methodology simultaneously curtails industrial pollution, optimizes resource efficiency, and meets the rising consumer demand for nutrient-fortified, clean-label products. Ultimately, such biotechnological innovations demonstrate how food science can bridge the gap between industrial sustainability and global nutritional security.

Shrimp Waste: An Untapped Resource

The rapid growth of the seafood processing industry has resulted in the generation of substantial quantities of by-products, particularly from shrimp processing. Shrimp heads, shells, and tails can account for nearly 50–60% of the total raw material, posing significant disposal and environmental challenges if not managed properly (Bassig *et al*., 2021; Nirmal *et al*., 2021). However, recent research has revealed that these by-products are rich sources of proteins, lipids, minerals, carotenoids, chitin, and chitosan, making them valuable raw materials for the development of innovative food and industrial products (Cahu *et al*., 2012; Kandra *et al*., 2012).

Instead of being treated as waste, shrimp by-products are increasingly being recognized as a sustainable resource that can contribute to a circular economy. Their utilization not only minimizes environmental pollution but also creates opportunities for generating high-value products from materials that would otherwise be discarded.

Recovery of Valuable Bioactive Compounds

Scientists have made significant progress in extracting valuable compounds from shrimp waste. According to Cahu *et al*., (2012), shrimp heads can be processed to recover protein hydrolysates, carotenoids, chitin, and chitosan. These compounds possess functional, nutritional, and biological properties that make them useful in food, pharmaceutical, cosmetic, and biotechnology industries.

Similarly, Kandra *et al*., (2012) emphasized that shrimp waste contains numerous bioactive substances, including amino acids, fatty acids, pigments, and chitin derivatives, which can be utilized in diverse commercial applications. More recently, Nirmal *et al*., (2021) highlighted emerging uses of shrimp-derived compounds in bioplastics, bioremediation, and eco-friendly energy conversion technologies. These developments demonstrate how seafood processing waste can be transformed into valuable resources while promoting sustainability.

Natural Seafood Flavour Powders

Among the most promising food applications is the production of natural flavour powders from shrimp heads and shells. Shrimp heads possess a characteristic seafood aroma and contain glutamic acid and other flavour-enhancing compounds associated with umami taste. Researchers have developed flavour powders by concentrating shrimp extracts and drying them into stable powdered products. Similar approaches have been applied to tuna processing liquids and other seafood by-products, demonstrating that waste streams can be transformed into ingredients that improve flavour while adding nutritional value.

Studies on shrimp head flavour powders have reported high protein content, good solubility, and favourable sensory acceptance. Different carrier materials such as dextrin, wheat flour, and maltodextrin have been used to optimize powder characteristics, including moisture content, bulk density, and flavour retention. Importantly, these natural flavour powders offer an alternative to excessive reliance on synthetic flavour enhancers and align with consumer demand for cleaner-label food products.

Enhancing Food Products with Shrimp-Derived Ingredients

Seafood-derived flavour powders have been incorporated into a variety of snack foods, including crackers, extruded products, and stick snacks. Research indicates that moderate inclusion levels can enhance aroma, taste, and overall consumer acceptability without negatively affecting product quality. In some formulations, shrimp head extracts have improved crispiness, flavour intensity, and protein content of ready-to-eat snacks. These findings demonstrate that shrimp by-products can serve not only as waste-reduction tools but also as functional ingredients that improve food quality.

Fortification of Noodles: A Nutritious Innovation

Noodles are among the most widely consumed convenience foods worldwide. However, conventional noodles are primarily carbohydrate-based and often deficient in essential amino acids. Researchers have therefore explored the incorporation of seafood-derived ingredients to improve their nutritional profile.

Parvathy *et al*., (2016) successfully developed fish-fortified noodles with enhanced protein content, while Mahanand *et al*., (2019) demonstrated that fish protein enrichment improved both nutritional and textural characteristics of extruded noodles. Chowdhury *et al*., (2020) emphasized that fish-based ingredients provide essential amino acids, omega-3 fatty acids, vitamins, and minerals that are often lacking in cereal-based foods.

Nutritional and Functional Benefits

Beyond flavour enhancement, shrimp-derived ingredients offer significant nutritional benefits. Suparmi *et al*., (2020) identified seventeen amino acids in shrimp waste flavour powder, including nine essential amino acids and high levels of glutamic acid. Dayakar *et al*., (2022) reported that carotenoprotein powder extracted from shrimp head waste contained more than 86% protein and exhibited strong antioxidant properties, indicating its potential as a functional food ingredient and nutraceutical.

Such products not only improve the nutritional quality of foods but also contribute valuable bioactive compounds that may promote health and well-being.

Towards a Circular and Sustainable Seafood Industry

The conversion of shrimp processing waste into flavour powders, protein concentrates, and fortified food products represents a major advancement in sustainable seafood processing. Studies by Bassig *et al*., (2021) and Deepika *et al*., (2022) have demonstrated that many of these products remain stable during storage and possess commercial potential.

As global demand for sustainable and nutritious foods continues to rise, the utilization of shrimp by-products offers a practical solution for reducing waste, conserving resources, and generating economic value. By embracing innovative technologies and value-added product development, the seafood industry can transform an environmental challenge into an opportunity for sustainable growth and food innovation.

Conclusion

Shrimp processing waste, once regarded as a disposal problem, is now emerging as a valuable resource for sustainable food innovation. Research has demonstrated that shrimp heads and shells can be transformed into flavour powders, protein-rich ingredients, and functional food additives with significant nutritional and economic value. The incorporation of these ingredients into products such as snacks and fortified noodles not only enhances flavour and nutrition but also promotes efficient utilization of marine resources. By converting waste into value-added products, the seafood industry can reduce environmental pollution, improve profitability, and support a circular economy. Such innovations highlight the potential of science and technology to create sustainable, nutritious, and environmentally responsible food systems for the future.

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