Open Access Multidisciplinary Online Magazine

Agri-India TODAY

Monthly Magazine-cum-eNewsletter
ISSN : 2583-0910

Volume 05 | Issue 11 | November 2025

www.agriindiatoday.in

Editorial Board

INDEX

INDEX

INDEX

ISSN : 2583-0910
Agri-India TODAY
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Peer reviewed
monthly newsletter

Article ID : 05/XI/01/1125

AGROFORESTRY & BAMBOO FARMING: SUSTAINABLE INCOME & ENVIRONMENTAL RESILIENCE

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Introduction

A silent green revolution is emerging on India's farmlands as farmers incorporate bamboo and trees into their agricultural plans. It's about climate resilience, soil regeneration, and sustainable income, not simply shade or beauty. Rice, wheat, and maize were the only annual crops grown in traditional agriculture, making them susceptible to unpredictable rainfall and market fluctuations. However, that equation is being altered by including fruit species, trees, and quickly growing perennials like bamboo. Growing trees alongside crops and cattle is known as agroforestry, and it is currently being praised as the "climate-smart face of Indian agriculture." Year after year, it provides a varied revenue stream, conserves soil, sequesters carbon, and increases agricultural output. Trees are at last reclaiming their proper position on farms thanks to new rules like the National Agroforestry Policy (2014) and the Maharashtra Bamboo Industry Policy 2025.

Agroforestry

Agroforestry combines forestry and agriculture by using land to grow crops and trees in a way that is advantageous to both. Between rows of trees or bushes that produce fruits, fuel, fodder, wood, or non-timber forest products, farmers grow food crops. It's a tried-and-true concept supported by contemporary science. Agroforestry is regarded by the FAO as one of the most effective methods for soil restoration and climate adaptation worldwide.

The main models include

- **Agri-silviculture:** Combining trees with field crops.
- **Agri-horticulture:** Integrating fruit trees with seasonal crops.
- **Silvi-pasture:** Trees with pasture and livestock.
- **Boundary plantations:** Trees like neem, teak, or bamboo on field margins for windbreaks and soil protection.

This approach ensures year-round productivity, even when crops fail due to droughts or floods.

Importance of Agroforestry

The urgency for agroforestry comes from three fronts climate change, land degradation, and income insecurity.

1. **Climate Resilience:** Trees act as buffers against extreme weather they reduce heat stress, prevent soil erosion, and increase groundwater recharge.

2. **Carbon Sequestration:** Agroforestry can sequester up to 25 tonnes of CO_2 per hectare per year, helping India meet its climate commitments under the Paris Agreement.
3. **Biodiversity Restoration:** Mixed systems attract birds, bees, and beneficial insects, enhancing ecosystem balance.
4. **Income Diversification:** Timber, fruits, fodder, and bamboo create multiple revenue streams beyond annual crops.
5. **Soil Fertility:** Leaf litter and root systems enhance organic carbon and microbial life, rejuvenating degraded lands.

Bamboo : "Green Gold" of Indian Farms

Policy changes have made bamboo, which was once regarded as "forest produce," a recognized agricultural crop. Bamboo is one of the renewable resources with the quickest rate of growth in India, with over 136 species flourishing there. It is also a new source of income for farmers.

How Bamboo Makes Sense

- **Fast Growth:** Some species mature in 3–4 years.
- **Multiple Uses:** Furniture, handicrafts, paper, construction, and bioenergy.
- **Environmental Role:** Excellent carbon sink and erosion control.
- **Low Maintenance:** Grows on marginal soils with minimal irrigation.
- **Continuous Returns:** Once planted, culms can be harvested annually for decades.

Economic Snapshot

The Indian bamboo industry is projected to reach ₹50,000 crore by 2030, driven by domestic manufacturing and export demand. The Maharashtra Bamboo Industry Policy 2025, for instance, aims to create 5 lakh jobs and develop bamboo-based clusters for furniture, handicrafts, and construction. "Bamboo farming is like having a fixed deposit on my land," says **Keshav Waghmare**, a farmer from Chandrapur, Maharashtra. "Once established, it gives annual returns without replanting."

Integrating Bamboo and Trees with Crops

The key to successful agroforestry lies in design — choosing complementary species that share resources rather than compete.

Common Agroforestry Models in India

- **Poplar + Wheat/Maize:** Popular in northern India; trees provide shade and timber, crops ensure seasonal income.
- **Bamboo + Pulses/Vegetables:** Widely adopted in central and eastern India for soil moisture conservation and dual income.
- **Coconut + Cocoa/Pineapple:** Coastal agroforestry system improving vertical space use.
- **Neem + Fodder/Grasses:** Enhances soil fertility and provides fodder for livestock.

The **ICAR-Central Agroforestry Research Institute (CAFRI), Jhansi**, has developed region-specific models demonstrating up to **30–40% higher overall returns** compared to monocropping.

Economic & Ecological Benefits:

Aspect	Agroforestry & Bamboo Impact
Income Diversification	Reduces dependence on a single crop; year-round returns.

Aspect	Agroforestry & Bamboo Impact
Soil Health	Adds organic carbon, fixes nitrogen (legume trees) and Prevents erosion.
Water Conservation	Root systems improve infiltration and reduce runoff.
Carbon Sequestration	Acts as long-term carbon storage, improving carbon credits potential.
Climate Resilience	Reduces crop failure risk under extreme weather.
Livelihood Generation	Supports small-scale industries and artisans.

Farmers with agroforestry plots have reported **20–60% more stable incomes** during climate-induced crop failures compared to conventional farms.

Policy Push and Institutional Support

1. National Agroforestry Policy (2014):

India became the **first country in the world** to adopt such a policy. It streamlines permissions for tree felling, promotes private nurseries, and integrates agroforestry with schemes like MGNREGS and NMSA.

2. Bamboo Mission (NBM) & Industry Policy 2025:

- The **National Bamboo Mission (NBM)** supports planting material, cluster formation, and value-chain development.
- The **Maharashtra Bamboo Industry Policy 2025** targets large-scale bamboo processing hubs, aiming for ₹50,000 crore in investment and significant rural job creation.

3. ICAR & CAFRI:

Conducting long-term trials on carbon sequestration, species combinations, and bioeconomic returns.

4. Corporate & ESG Initiatives:

Companies are investing in **carbon-neutral farming projects** and **agroforestry plantations** as part of their **Environmental, Social, and Governance (ESG)** commitments — creating new funding streams for farmers.

Challenges:

Despite progress, large-scale adoption faces several bottlenecks:

- **Initial gestation period:** Trees and bamboo take years to mature.
- **Market linkages:** Need organized supply chains for timber and bamboo.
- **Awareness:** Many farmers still view trees as “non-crops.”
- **Policy harmonization:** Different states have varying felling and transit regulations.

These challenges can be overcome through **farmer cooperatives**, **public-private partnerships**, and **buy-back contracts** with industries.

The Future of Green Development in Rural India

Agroforestry is essential to farming's future; it is not a luxury. Integrating perennials is a sensible insurance policy for farmers and the environment alike, given soil degradation, declining groundwater, and climatic unpredictability. Bamboo is the "engine" of this green revolution because of its quick growth and adaptability to many uses, which concurrently provide employment, revenue, and carbon credits. Agroforestry has the potential to alleviate rural poverty, help India reach its net-zero targets by 2070, and turn millions of hectares of wasteland into productive carbon sinks if it is mainstreamed.

Conclusion

Agroforestry serves as a reminder that the distinction between "farm" and "forest" is arbitrary, since both are a part of the same living environment. Together with crops, farmers may foster resilience and regeneration by planting bamboo and trees. They gather stability, shade, and ecological balance in addition to fruits and lumber. With bamboo supporting livelihoods, soil enhanced by trees, and farms built not only for productivity but also for long-term peace with environment, Indian agriculture may have a bright future.

ISSN : 2583-0910
Agri-India TODAY
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Peer reviewed monthly newsletter

Article ID : 05/XI/02/1125

AI IN ANIMAL HUSBANDRY: EARLY DETECTION OF LIVESTOCK DISEASES USING COMPUTER VISION & IOT

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Introduction

Imagine your cow stops eating for a day. You notice it the next morning but by then the animal is weak, the vet bill is higher, and the risk of spread to other animals has grown. Now imagine a tiny sensor or a camera that notices subtle changes in behaviour, body temperature, or gait the moment they begin and pings you on your phone: "Check cow no. 17 decreased feed intake; possible early fever." That early nudge can be the difference between a quick recovery and a costly outbreak.

This is not sci-fi. It's the promise of AI combined with Internet of Things (IoT) in animal husbandry: computer vision that reads facial expressions and gait, thermal cameras that spot fever, microphones that recognize coughing patterns, and edge devices that aggregate these signals into actionable alerts. Early detection doesn't just protect animal health it protects livelihoods, reduces antibiotic overuse, and strengthens food security.

Early detection matters now

Livestock are the backbone of millions of rural households. Diseases from respiratory infections and mastitis to foot-and-mouth disease and parasitic outbreaks reduce productivity, raise mortality, and can ripple through markets. In low-margin dairy or poultry systems, even a small drop in productivity can push a household into loss. Traditional disease detection depends on farmer observation and periodic veterinary checks. That model works when herd sizes are small and farmers are present, but it fails when subtle or pre-symptomatic signals appear, when labor is limited, or when peri-urban and commercial farms have hundreds or thousands of animals.

Early detection addresses three urgent needs:

1. **Animal welfare:** catching disease before suffering worsens.
2. **Economic resilience:** fewer lost days of production, lower treatment costs.
3. **Public health & AMR (antimicrobial resistance):** targeted treatment reduces unnecessary broad-spectrum antibiotic use.

Technology stack looks like sensors, cameras, and the brain (AI)

AI in animal health is not a single gadget it is a system assembled from complementary parts. Here's the typical stack:

1. Edge sensors and IoT devices

- **Wearables & collars:** measure heart rate, rumination, activity.
- **Smart ear tags:** combine GPS, accelerometers and temperature sensing for free-ranging cattle.
- **Environmental sensors:** barn temperature, humidity, ammonia levels (which influence respiratory disease risk).

These devices stream lightweight signals to local gateways (phones or field hubs) or the cloud.

2. Computer vision (cameras and analytics)

- **RGB cameras** observe posture, gait, feeding behaviour, and general alertness.
- **Thermal cameras** detect localized heat signatures: a hotspot on a udder can indicate mastitis; higher body temperature points to fever.
- **Video analytics** powered by convolutional neural networks (CNNs) translate visual patterns into health indicators: slow movement, head droop, abnormal lying/standing patterns, swelling.

3. Acoustic monitoring

Microphones with AI models can recognize cough frequency and type useful for detecting respiratory outbreaks in pigs and poultry before clinical signs overwhelm the barn.

4. Data fusion + predictive analytics

AI models combine signals temperature rises + reduced rumination + less activity = high probability of early disease. Machine learning models can be trained to predict the likelihood of specific conditions and prioritize alerts.

5. Decision support & interface

Alerts are delivered to farmers via mobile apps, SMS, or integrated farm dashboards. Recommendations might include simple on-farm checks, isolation advice, or an automatic call to the vet. Over time, aggregated data helps farms and extension services spot emerging trends at herd, village, or regional scale.

Concrete examples of what AI can detect early

(Descriptions are generic to avoid inventing specific study claims; they reflect common, validated use-cases in the technology community.)

- **Fever detection:** thermal imaging spots elevated body temperature before visible lethargy. Early isolation prevents spread.
- **Mastitis indicators:** subtle changes in udder temperature and cow behaviour (more frequent standing/resting switches) hint at udder inflammation.
- **Reduced rumination:** rumination sensors detect decreased cud chewing, a red flag for metabolic or digestive issues.
- **Cough clusters in poultry houses:** acoustic algorithms pick up increased cough rates, prompting air-quality checks and prophylactic measures.
- **Lameness / gait change:** computer vision identifies uneven gait or longer lying times, enabling early hoof or joint care.

Economic benefits: the numbers that matter to farmers

- **Lower treatment costs:** Catching disease early often means less medication, fewer injections, and quicker recovery.
- **Less production loss:** For dairy, even a day of lower yield reduces income; early treatment shortens those days.
- **Reduced culling and mortality:** Healthy replacement rates preserve herd value.
- **Improved market confidence:** Healthy, traceable animals are easier to sell to quality-conscious buyers and processors.

While exact ROI depends on farm size and technology cost, pilots show that modest investments in detection systems can pay back within a season on commercial units and within a year for larger operations.

Institutional roles and how extension should evolve

To make AI and IoT meaningful across India's diverse livestock systems, institutions must play a role:

- **Krishi Vigyan Kendras (KVKs)** and veterinary extension services should run demo farms and training sessions showing device use and data interpretation.
- **Veterinary colleges** can help validate AI models for the local disease ecology (pathogens, seasonal patterns).
- **Farmer Producer Organizations (FPOs)** can aggregate demand and operate shared devices a single thermal camera could serve multiple smallholders on a rotational basis.
- **Public-private partnerships** accelerate product development and local adaptation, while subsidies or low-interest finance reduces the barrier to entry.

Challenges and practical limits

Adopting AI in animal husbandry is not a magic wand. Challenges include:

1. Data quality & labeling

AI models need good labeled data reflecting local breeds, environments, and lighting conditions. Models trained on European dairy breeds may not generalize directly to local zebu or crossbred cattle.

2. Connectivity & power

Rural farms often lack reliable internet or electricity. Solutions must work offline, with periodic sync, and rely on solar power or low-energy sensors.

3. Cost and scale

While sensor costs are falling, a fully instrumented herd can still be expensive. Shared service models (rental, cooperative ownership) are often more realistic for smallholders.

4. False positives and trust

If a system generates too many false alerts, farmers will ignore it. AI performance must be tuned to be conservative and provide clear, actionable guidance, not noise.

5. Data privacy and ownership

Who owns animal health data? Farmers should retain control; transparent policies are essential.

How to design farmer-centric solutions

To be useful, AI solutions should follow a few simple design rules:

- **Start small, deliver simple value:** Begin with one high-value use case (e.g., mastitis detection) rather than an overwhelming suite of features.
- **Offline first:** Devices must log data locally and synchronize when connectivity is available.
- **Clear alerts & next steps:** Every alert should come with a one-line practical recommendation "Check udder, clean and call vet if red."
- **Local language & low literacy:** Use icons, voice prompts, and local language SMS to communicate.
- **Maintenance & repair:** Devices should be rugged and repairable locally; include a local technician network.
- **Affordable business models:** Subscription, pay-per-use, or FPO-managed rental models work better for smallholders than one-time high capital expense.

Policy opportunities and ethical considerations

AI in animal husbandry touches policy areas from animal welfare to trade and data governance:

- **Subsidies & incentives:** Governments can support pilot programs, offer matching grants for sensor purchases, or fund communal devices at village level.
- **Standards & certification:** Validation standards for device performance and AI accuracy help build trust.
- **Antimicrobial stewardship:** Early detection should be linked to protocols that favor targeted therapy over blanket antibiotic use, helping to curb AMR.
- **Data governance:** Clear rules on who stores, accesses, and monetizes farm data protect farmers and encourage adoption.

Ethically, developers must avoid creating surveillance systems that penalize farmers (e.g., insurers denying claims based on unexplained data). Instead, data must empower farmers and vets.

Emerging innovations and future outlook

The coming five years will see several trends:

- **Edge AI:** More analytics on the device (not in the cloud), reducing connectivity needs and protecting privacy.
- **Multimodal sensing:** Combining video, sound, temperature, and feed data yields more reliable detection.
- **Federated learning:** Models trained across many farms without centralizing raw data improving accuracy while protecting privacy.
- **Integration with precision nutrition:** Alerts could trigger automatic changes in feed rations or targeted supplements to prevent disease.
- **Traceability:** Health logs feed into quality certification systems that bring premium prices for disease-free or properly treated animals.

If scaled responsibly, AI will shift animal husbandry from reactive cure to **predictive care**, with big gains for welfare and livelihoods.

Practical takeaways for a farmer, extension worker, or buyer

- **For smallholders:** Start with one low-cost sensor (temperature ear tag or activity collar) and test it for a season. Join an FPO that shares devices.
- **For veterinarians & KVKs:** Run demo days showing how AI alerts translate into simple on-farm checks. Collect local labeled data to improve models.

- **For policymakers:** Fund community devices and training programs rather than only subsidizing individual purchases. Encourage open standards and public vet involvement.
- **For entrepreneurs:** Build rugged, repairable devices that work offline, and sell them with bundled advisory services.

Conclusion

AI and IoT are not about replacing farmers or vets they are about amplifying human care. A camera that notices the first signs of fever, a microphone that hears the first coughs, a collar that flags rumination drop these small, early signs, when caught in time, prevent suffering, save money, and keep food systems resilient. Animal husbandry has always been a blend of observation, instinct, and care. AI adds a new layer: continuous, objective sensing that nudges human attention where it's needed most. The result is healthier animals, more stable incomes for farm families, and a more robust supply of animal protein for millions. In the next decade, farms that adopt intelligent early-warning systems will be not just more productive, but also kinder places for animals and that's a future worth farming for.

ISSN : 2583-0910
Agri-India TODAY
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Peer reviewed
monthly newsletter

Article ID : 05/XI/03/1125

FROZEN BUT THRIVING: HOW ANTARCTIC FISHES BEAT THE COLD

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Abstract

In spite of the well-regulated mechanisms in the human body, we can't even bear temperatures below 4 degrees Celsius. Interestingly, there are some fish that survive in the subzero temperatures too. How does this happen? A variety of factors and modifications play an immense role in this. Yes, the fish that live in Antarctica have physical features that allow them to survive in their conditions, as well as cellular special features. Because they have evolved special characteristics that enable them to survive in one of the coldest and harshest environments on Earth, Antarctic fishes are outstanding examples of evolutionary adaptation. They have developed physiological and physical adaptations to help them survive and reproduce because they live in waters that are consistently below freezing. Their blood produces antifreeze glycoproteins to prevent ice crystals from growing. In an environment where resources are scarce for a large portion of the year, their bodies are also adapted to grow slowly and mature later, which helps them conserve energy. This article will delve into how Antarctic fish undergo physiological adaptations.

Keywords: Antarctic fish, antifreeze glycoproteins, oxidative stress

Introduction

Antarctic fishes exhibit distinct characteristics at the cellular level, including decreased metabolic rates, altered enzymes that work well at low temperatures, and specialized reproductive strategies such as the production of large eggs rich in yolk, prolonged embryonic development, and extended parental care. The combination of these characteristics makes Antarctic fishes a valuable model system for studying adaptation to extreme environments. Collectively, these specializations reflect how Antarctic fishes have fine-tuned their ecology to the polar environment, and the physiological and genetic adaptations of icefishes make them a compelling system for studying vertebrate adaptation to extreme cold.

Genomic Evolution and Adaptive Radiation

The story of the notothenioid, which split off from a single ancestor into 120–140 species when the Southern Ocean cooled, is one of adaptive radiation. Their genomes reveal a story of gene family expansions, chromosomal fusions, and excessive transposable element activity, all of which were fueled in part by stress from the cold. Diversification was driven by a prehistoric spike in mutation rates, especially in genes linked to skeletal changes. Their genetic variety has been further enhanced by gene flow and hybridization across species, even across evolutionary divisions.

Structural and Physiological Adaptation

Antarctic fish have structural changes that help them survive in their environment, along with various cellular modifications. Their specialized circulatory systems ensure that oxygen reaches their tissues effectively. Increased mitochondrial density meets their energy and oxygen demands (Urschel & O'Brien, 2008; Johnson *et al.,* 1988). To manage the cold, they have developed thinner skeletons, a feature related to genetic changes similar to those seen in human skeletal disorders. Hemoglobin, the protein that carries oxygen in the blood, is completely absent in members of the Channichthyidae family called icefishes (Cocca *et al.,* 1995; Sidell & O'Brien, 2006). Ice fishes have lost hemoglobin because some of their globin genes were deleted, and other changes in gene regulation reduce globin production even more. To survive without red blood cells, they rely on special heart and blood vessel adaptations that help deliver oxygen efficiently. This may also be related to the low iron levels in Antarctic waters, since iron is needed to make hemoglobin. Some of these fish also lack myoglobin in their hearts, which is an interesting twist in evolution. The need for red blood cells is reduced because the oxygen easily dissolves in the cold waters of the oxygen-rich Southern Ocean. To generate energy effectively in the cold, Antarctic fish have supercharged their mitochondria, giving them more surface area and density. Because they don't have red blood cells, icefish go one step further and have larger hearts (cardiomegaly), more blood, and complex blood channels that branch out to ensure oxygen reaches their tissues. Additionally, high plasma osmolarity maintains their physiology in balance and keeps their systems functioning well under harsh circumstances.

Enzymatic Adaptations

Since most metabolic reactions would stall in near-freezing waters, Antarctic fish have adapted their enzymes to work under these conditions. Their enzymes are made more active in cold waters by having more polar residues, such as serine and arginine, which lead to increased flexibility. These fish have higher amounts of antioxidant enzymes such as superoxide dismutase (SOD), catalase etc. Increased superoxide dismutase (SOD), particularly in red-blooded species, helps neutralize damaging radicals and fight the high levels of reactive oxygen species (ROS) in the oxygen-rich Southern Ocean. Another supporting enzyme, catalase, which breaks down hydrogen peroxide, is also found in Antarctic fishes; however, it is not as active as it is in freshwater fish. It's interesting to note that while Antarctic fish are unable to ramp up these proteins on demand, they continuously create heat shock proteins to fix proteins that are stressed by the cold.

Antarctic fish have adapted by adopting a relaxed lifestyle. In an environment where enzymatic reactions are slow, their slow growth and metabolic rates save energy. They have extended gene families, such as superoxide dismutase 3 and NAD(P)H: quinone acceptor oxidoreductase, which detoxify ROS (Reactive Oxygen Species), to cope with the oxidative stress caused by the oxygen-rich waters. Additionally, selenium proteins (such as glutathione peroxidase) support cellular defenses against oxidative damage. Antarctic fish have a strong antioxidant defense system to manage high levels of reactive oxygen species in the environment. While catalase absorbs hydrogen peroxide, albeit at a lesser rate than in other fish, superoxide dismutase works tirelessly to neutralize superoxide radicals. In addition to using enzymes, these fish strengthen non-enzymatic defenses, such as having high plasma levels of vitamin E, to prevent ROS-induced lipid peroxidation and protect their PUFA-rich membranes.

Proteins That Prevent Freezing and Membrane Lipid Content

The most important adaptation of Antarctic fish is their antifreeze glycoproteins (AFGPs); it attaches to small ice crystals and prevents them from growing which leads to the adaptation and survival in subzero temperatures (De Vries, 1971; Cheng & DeVries, 1991). Animals like the icefish *Chaenocephalus aceratus* carry many copies of the pancreatic gene that gave rise to these proteins. The size polymorphism of the AFGP provides different modalities of freezing protection. Bizarrely, the proteins seem to have been completely lost in Patagonotothen guntheri and other notothenioid lineages from warmer sub-Antarctic seas. An extended family of zona pellucida genes offers protection against freezing—some even promote the melting of ice—for embryos that lack AFGPs. Antarctic fish have membranes that are full of polyunsaturated fatty acids (PUFAs) to keep their cells functioning in the cold Southern Ocean (Hazel, 1995). These PUFAs keep the membranes fluid in spite of the cold. Although necessary, this adaptation increases the membranes' susceptibility to ROS-induced oxidative damage. Lipid droplets function as energy stores inside cells and may also aid in maintaining the suppleness of membranes, enabling cells to function well in extremely cold temperatures.

Adapatations to Visual System

Even in Antarctica, where light is weak and flickers, one must develop specialized vision to see. This has given notothenioids unique retinal architecture and photoreceptor properties that help enhance vision in these chilly, dimly lit conditions. The performance of rhodopsin, a key light-sensing protein, is enhanced in cold environments by changes at the amino acid position (Pointer *et al.,* 2005; Castiglione *et al.,* 2023). Vision-related genes show evidence of positive selection, indicating that these fishes have adapted to the unique lighting conditions of the Southern Ocean, which is advantageous for hunting and navigation.

With their diverse feeding strategies and strange reproductive rites, Antarctic fishes exhibit a staggering array of behaviors revealed by their highly developed adaptive radiation. For example, differences in habitat use and communication have allowed for further differentiation in the use of other ecological niches. Their embryos, which prefer water for reproduction, will thus rely on increased sets of zonapellucida genes as antifreeze agents in subsequent generations to ensure that they can withstand the ice-cold waters.

Reproduction in Polar Conditions

To successfully reproduce in the harsh polar environment, where temperatures are consistently close to freezing and food is only available during certain seasons, Antarctic fishes have developed a number of unique adaptations. Unlike tropical fishes, which produce large, yolk-rich eggs that provide enough nutrition for embryos during their prolonged development in cold water, most species grow slowly and mature late (Kock & Kellermann, 1991). To ensure that larvae hatch at the same time as phytoplankton blooms and have an abundance of food for survival, spawning is typically timed to coincide with the brief summer season. In order to shield their eggs from predators and adverse environments, many Antarctic fishes—particularly notothenioids—also exhibit prolonged parental care, such as nest construction, egg guarding, or brooding. Moreover, development can proceed without risk because antifreeze glycoproteins present in blood, eggs, and larvae stop ice crystals from forming in freezing waters. Additionally, during their lengthy incubation periods, embryos and larvae maintain extremely low metabolic rates, which lowers their energy needs. The proteins that prevent ice formation in eggs and larvae, called antifreeze proteins, have evolved multiple times across different fish lineages, as found by a recent study.

The adaptations of genes also support their slow development and survival. Seasonal spawning, large yolky eggs, antifreeze proteins, slow metabolism, and parental care are some of the adaptations that allow Antarctic fishes to thrive in one of the world's harshest and most difficult environments.

Environmental Consequences and Risks

Because they make up almost nine-tenths of all fish biomass, notothenioid fishes dominate Antarctic shelf communities, which is evidence of their evolutionary success. Considered a fish group with extraordinary adaptations, including limited tolerance to heat, they are the first to be affected by climate change factors such as warming and acidification of the oceans. These fish have unique characteristics that have made them ideal candidates for modeling human diseases and providing insight into genetic and developmental systems. These characteristics include anemia and enlargement of the heart. Due to their unique adaptations, notothenioid fishes are extremely vulnerable to changes in their environment, which presents serious ecological risks. Population declines may result from disturbances in their metabolism, reproduction, and distribution caused by warming waters and ocean acidification. Their vulnerability could have a ripple effect on the ecosystem, impacting both predators and prey, as they are essential parts of the Antarctic food web. Changes in their population may also affect the cycling of nutrients and the stability of the ecosystem as a whole, underscoring the wider effects of climate change in polar marine environments.

Conclusion

Antarctic fishes have evolved to survive in the frigid depths of the Southern Ocean by producing antifreeze proteins, having altered metabolisms, and possessing unique vision. Over hundreds of thousands of years, these species have become remarkable examples of nature-inspired solutions to extreme environmental challenges. Studying them provides valuable insights into ecological resilience and potential implications for human health, as they may be particularly vulnerable to the effects of a warming world. These fishes highlight that even Antarctica’s ecosystems are susceptible to global change by illustrating how evolutionary specialization brings both resilience and fragility.

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ISSN : 2583-0910
Agri-India TODAY
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Peer reviewed
monthly newsletter

Article ID : 05/XI/04/1125

ANTIMICROBIAL PEPTIDES: INSECT-DERIVED SOLUTIONS FOR POST-HARVEST FRUIT PRESERVATION

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Introduction

Antimicrobial peptides (AMPs) are short chains of fewer than fifty amino acids with low molecular weight (Keymanesh *et al.,* 2009), naturally produced by microbes, plants, and animals. They play a crucial role in innate immunity due to their broad-spectrum activity against viruses, fungi, and bacteria. Modern studies on innate immunity began with Fleming's discovery of lysozyme in 1922, with over 3300 AMPs now identified from diverse sources (Toress *et al.,* 2022). AMPs serve as natural food preservatives, with compounds like nisin from *Lactococcus lactis* and lactoferrin from milk effectively inhibiting pathogens such as *Listeria monocytogenes* and *Staphylococcus aureus* (Gálvez *et al.,* 2020). Their natural origin aligns with consumer demand for safer and environmentally friendly food additives. Beyond direct preservation, AMPs are increasingly incorporated into edible or biodegradable films for active packaging, enabling controlled antimicrobial release. Nano-encapsulation further enhances their stability and bioavailability, improving shelf life of perishable foods like fruits, vegetables, and meat while supporting sustainability goals by reducing food waste. Post-harvest losses of fruits.

Fruits are highly perishable due to their soft skin, high moisture content (70–95%), and rapid respiration, which favor pathogen attacks. Significant losses occur between harvest, storage, and consumption. A 2022 survey by ICAR-CIPHET and NABARD estimated post-harvest fruit losses at 6.02–15.05%, the highest compared to cereals, pulses, and vegetables. Major bacterial (Pseudomonas, Erwinia) and fungal pathogens (Alternaria, Botrytis, Aspergillus, Penicillium, Sclerotinia, Diplodia, Colletotrichum, Rhizopus, Phomopsis, Mucor) cause spoilage (Sharma *et al.,* 2009), leading to decay and poor fruit quality.

Antimicrobial peptides (AMPs) offer promising strategies to reduce these losses. They can be incorporated into packaging or applied directly to fruit, showing activity against both Gram-positive and Gram-negative bacteria. Examples include Jelleine from honeybee royal jelly, effective against bacteria and fungi, especially Candida (Fontana *et al.,* 2004); Diptericin from the blowfly, active against Gram-negative bacteria and important in Drosophila immunity (Bulet *et al.,* 1999); and Cathelicidins in mammals, broad-spectrum peptides with immunomodulatory roles (Zanetti, 2004). Oyster-derived AMPs from Saccostrea glomerata also show efficacy against pathogens like Streptococcus pneumoniae and S. pyogenes. Their broad, rapid action and low resistance potential drive their growing importance in biopharma and peptide antibiotic markets.

Packaging

Packaging plays a key role in protecting fruits from contamination and preventing physical, chemical, and biological changes. Conventional materials, however, are ineffective in controlling deterioration. Novel approaches such as active packaging (AP) have been developed to enhance fruit quality and shelf life. AP is classified into two types: (a) nonmigratory AP, which acts without migration, and (b) active release packaging, where volatile compounds are gradually released into the product atmosphere, also called controlled release packaging (Yildirim *et al.,* 2018). These compounds help maintain food safety and quality, though achieving precise control of release remains a challenge. A newer concept, responsive packaging, enables antimicrobial release triggered by changes in the food environment. Antimicrobial packaging systems are commonly developed by incorporating peptides through three approaches: direct mixing into the polymer matrix, surface coating, or immobilization.

AMPs as the best alternative to conventional antibiotics

AMPs are considered highly effective because microorganisms rarely develop resistance against them. Most AMPs disrupt microbial membranes by pore formation or cell lysis, causing nutrient and ion leakage (Last and Miranker, 2013). This prevents microbes from adapting through membrane alterations or mutations. Based on activity, AMPs can be antibacterial, antiviral, antifungal, antiparasitic, or anticancer peptides (Huan et al., 2020), with potential in both prophylactic and therapeutic applications. Current research focuses on improving their specificity to target pathogens without harming beneficial microbes or hosts, which requires a clear understanding of their structure and mechanisms. Although AMPs may share sequences, their conformational motifs differ. With antimicrobial resistance rising, AMPs provide a promising alternative for disease control.

Insect-derived AMPs

Insect-derived AMPs are highly potent, often showing IC50 values in the low micromolar or submicromolar range. Key examples include ponericins, cecropins, drosocin, defensins, and attacins, with glycine- and proline-rich peptides particularly effective against Gram-negative bacteria (Rozgonyi *et al.,* 2009). Among venomous animals, Hymenoptera insects are the most diverse, with ~1,20,000 identified species far exceeding spiders (44,906), cone snails (3253), snakes (3248), sea anemones (3248), and scorpions (1454).

Ants as a major source of AMPs

Insects are a major source of antimicrobial peptides, and ants are unique for possessing metapleural glands that secrete antimicrobial compounds. Living in soil with dense colonies exposes ants to pathogens, against which these secretions serve as the first line of defense (Yek and Mueller, 2011). Ants, belonging to Class Insecta, Order Hymenoptera, and Family Formicidae, comprise ~13,000 species across 21 families (Agosti and Johnson, 2005). Their venoms contain proteins, peptides, enzymes, alkaloids, formic acid, and hydrocarbons with antimicrobial, insecticidal, and defensive properties. Venom, secreted from tubular glands, also aids in communication. Among Hymenoptera, ants are sister groups to bees and wasps, having evolved from wasps. With 16 stinging subfamilies and ~9100 extant species, ants are more diverse than snakes and scorpions.

AMPs used in the management of post-harvest diseases

Several studies highlight the effectiveness of AMPs in managing fruit diseases. Inui Kishi *et al.,* (2018) tested six peptides from citrus, amphibians, and porcine sources against bacterial pathogens of citrus, with three showing strong bactericidal and bacteriostatic effects and low hemolytic activity. Munoz et al. (2007) evaluated eight short AMPs for controlling postharvest green mold of oranges caused by *Penicillium digitatum*, while Lima *et al.,* (2021) reported antifungal activity of eight synthetic peptides against the same pathogen, which disrupted fungal membranes and caused cell death. AMPs can be derived from diverse sources such as plants, mammals, amphibians, microbes, insects, and marine organisms, with plant-derived AMPs particularly rich in amino acids like arginine, lysine, glutamic acid, and aspartic acid.

AMPs in coating fruit/packaging material

AMPs can be incorporated into films and coatings to develop antimicrobial packaging that suppresses spoilage and foodborne pathogens. Bacteriocins, which disrupt microbial cell walls, are effective in such systems, and their addition to polymer matrices can inhibit a wide range of bacteria. For example, halloysite nanotubes loaded with nisin showed strong activity against *L. monocytogenes*, *S. aureus*, and *C. perfringens*, while nisin-based nanocomposite films reduced *L. monocytogenes* growth (Meira *et al.,* 2016). Growing concerns over synthetic plastics have increased interest in edible films and coatings for preserving perishable foods. Biopolymer-based coatings from plants, insects, animals, and microbes offer sustainable alternatives (Basumatary *et al.,* 2022), and can be enhanced with natural extracts such as AMPs. For instance, bioactive peptides from palm kernel cake fermented with *Lactobacillus plantarum* and *L. fermentum* incorporated into polymers showed antifungal activity against mango-infesting fungi.

Fruit coating with natural coating materials

Coating technology protects fruits from oxygen, light, and microbes, while edible packaging satisfies both consumer and environmental needs. AMPs provide a promising alternative to conventional antibiotics, reducing resistance risks. They can be incorporated into natural or synthetic polymers for edible coatings. For example, gums, natural polysaccharides (Salehi and Kashaninejad, 2015), can be combined with insect-derived AMPs such as those from ants, which are positively charged. Some AMPs act through receptor-mediated mechanisms for greater selectivity, though removal of specific domains leads to non-receptor-mediated but still active peptides (Teixeira *et al.,* 2012).

Conclusion

Antimicrobial peptides (AMPs) are a promising alternative to fungicides and antibiotics. Insects, a diverse group of venomous animals, provide a rich source of these peptides. AMPs kill harmful microorganisms without affecting the host, are more stable than proteins, and exhibit broad-spectrum activity against fruit pathogens, including resistant strains. Being safe for humans, AMPs can replace conventional antimicrobials in packaging, helping reduce post-harvest losses.

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ISSN : 2583-0910
Agri-India TODAY
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Article ID : 05/XI/05/1125

ARAKU COFFEE: A SUSTAINABLE AGRIBUSINESS MODEL EMPOWERING TRIBAL FARMERS IN INDIA

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How a tribal-led initiative turned a remote valley into a global coffee destination

What began as a livelihood project in the tribal hills of Andhra Pradesh has grown into one of India's proudest agribusiness success stories. Araku Coffee blends sustainability, farmer empowerment, and premium branding - proving that rural India can compete on the world stage, one cup at a time.

Introduction

Nestled in the Eastern Ghats of Andhra Pradesh, the Araku Valley is home to thousands of tribal families whose lives once revolved around subsistence farming. Over the years, this serene valley has transformed into a symbol of inclusive agribusiness success, known worldwide for its organic, high-quality coffee.

The journey of *Araku Coffee* is not just about beans and brews — it's about people, empowerment, and perseverance. It represents a powerful model of how sustainable agriculture and smart marketing can turn a community project into a global brand.

A New Beginning in the Valley

Two decades ago, life in the Araku Valley was far from easy. Most tribal families depended on traditional *podu* (shifting) cultivation - a practice that exhausted the soil and yielded meagre harvests. Income was uncertain, and opportunities were scarce.

In 2001, a new chapter began when the Naandi Foundation, a Hyderabad-based social enterprise, stepped in with a simple yet powerful idea-to transform livelihoods through sustainable coffee cultivation. The vision went beyond improving income; it sought to revive the land, restore dignity, and preserve the tribal way of life.

Through continuous training and technical support, farmers began adopting organic and regenerative farming methods. Coffee was grown under the natural shade of trees, enriching biodiversity and improving soil fertility. By replacing chemicals with compost and natural inputs, farmers not only nurtured healthier crops but also a more resilient ecosystem.

Key Highlights of the Araku Coffee Transformation

- **Community Empowerment:** Over 10,000 tribal farmers united under a cooperative to produce and market coffee collectively.

- **Sustainable Farming:** Focus on organic cultivation and agroforestry, improving soil health and biodiversity.
- **Premium Product:** Coffee produced is single-origin, shade-grown, and carbon-positive, meeting international quality standards.
- **Income Generation:** Farmers receive premium prices and bonuses, improving livelihoods and reducing migration.
- **Environmental Restoration:** Agroforestry practices have brought back greenery and resilience to the hilly landscape.

Farmers as Partners, Not Labourers

A cornerstone of Araku's success lies in its unique cooperative model, which places farmers at the centre of the business. Instead of relying on middlemen or external buyers, the tribal farmers of Araku came together to form the Small and Marginal Tribal Farmers Mutually Aided Cooperative Society (SAMTFMACS). Today, this cooperative represents over 10,000 tribal farmers, each of whom is not just a grower but a shareholder in the enterprise. By ensuring ownership and collective decision-making, the model guarantees that profits flow directly back to the community.

Every bag of *Araku Coffee* bears the name of the farmer who cultivated it - a small yet powerful gesture that symbolises identity, pride, and transparency. This direct link between the producer and consumer redefines how agribusiness can work - with dignity, fairness, and shared value at its heart.

From Local Beans to a Global Brand

The world first noticed Araku Coffee when it was launched in Paris in 2017. The store, designed by a French architect, showcased India's potential to create premium, sustainable brands. For the first time, coffee from Indian tribal farmers stood alongside global names from Africa and South America.

Today, *Araku Coffee* is sold in France, Japan, South Korea, and India. The beans are 100% organic, single-origin, and shade-grown. International coffee experts have praised its smooth flavour and unique aroma, while consumers love its ethical sourcing story.

Sustainability That Pays

Araku's coffee plantations are grown through agroforestry - a system that mixes coffee plants with fruit trees like jackfruit, silver oak, and pepper vines. This method improves soil fertility, prevents erosion, and captures carbon from the atmosphere. In fact, Araku Coffee is one of the world's few carbon-positive coffee brands.

Farmers receive bonus payments for following organic practices, ensuring that sustainability brings real financial rewards. Along with better income, the initiative has helped restore biodiversity and improve the region's microclimate.

A Model for Agribusiness Success

What makes Araku Coffee special is how it beautifully combines social impact with business innovation. It's not just a farming project — it's a complete agribusiness ecosystem that benefits both people and the planet. The Araku model is built around four key pillars:

- **Farmer Ownership and Empowerment:** Tribal farmers are not just producers — they are co-owners in the value chain through their cooperative society (SAMTFMACS). This ensures transparency, fair pricing, and shared profits.

- **Premium Product Positioning:** By focusing on single-origin, organic, and high-quality coffee, Araku has successfully entered premium global markets, transforming a local crop into a luxury product.
- **Ethical Branding and Global Marketing:** The brand connects consumers directly to farmers, emphasizing sustainability and traceability. Each coffee pack proudly carries the farmer's name - a symbol of trust and authenticity.
- **Environmental Restoration:** Coffee is cultivated through agroforestry, restoring degraded land, improving biodiversity, and creating a carbon-positive ecosystem that benefits future generations.

By adding value at every step - from cultivation to roasting, packaging, and export - the Araku model ensures that profits stay with the farmers. It is living proof that even in remote rural areas, agribusiness can be both profitable and sustainable when guided by the right vision and partnership.

Inspiring Rural India

The success of *Araku Coffee* has become a beacon of hope for rural and tribal India. What began as a small experiment in the hills of Andhra Pradesh is now inspiring similar projects in states like Odisha, Jharkhand, and Chhattisgarh, where farmers are turning towards coffee and other high-value crops. The Araku experience shows that empowerment begins when farmers become entrepreneurs. With proper training, collective organization, and access to markets, even remote communities can build globally recognized brands.

This story is a reminder that rural India is not defined by poverty but by potential - potential that can be unlocked through the right mix of technology, sustainability, and inclusion.

As one proud farmer from Araku Valley says:
"*Earlier, we sold coffee beans. Now, we sell our brand. The world knows who we are*."

Their journey proves that when the smallest farmer becomes part of a larger vision, agriculture transforms into agribusiness, and rural transformation becomes a reality.

A Brew of Hope

Araku Coffee is more than just a beverage - it is a symbol of empowerment, sustainability, and transformation. Every cup tells a story of how collective action, ecological farming, and fair trade can change lives. From the red soils of Araku Valley to the elegant cafés of Paris, the aroma of this coffee carries with it the spirit of India's tribal farmers - their resilience, innovation, and pride.

This remarkable journey has redefined what rural India can achieve when empowered with the right vision and support. It shows that good farming, when combined with good business practices, can create lasting prosperity for communities that were once left behind.

As the aroma of Araku Coffee spreads across the world, it reminds us that the true strength of India's agribusiness lies in its people - the farmers who cultivate hope, one bean at a time.

Conclusion

The story of *Araku Coffee* is a testament to how vision, collaboration, and innovation can transform even the most remote rural landscapes into hubs of prosperity. What began as a social initiative has evolved into a globally admired agribusiness model, blending the principles of sustainability, equity, and excellence. By empowering farmers as entrepreneurs, promoting eco-friendly practices, and building a strong global brand, Araku has shown that India's tribal communities can compete and excel in international markets. As Araku Coffee continues to make its mark across the world, it stands as a shining example of how inclusive agribusiness can create both economic growth and social transformation. It reminds us that the true flavour of success comes not just from what we produce, but from *how* and *for whom* we produce it.

ISSN : 2583-0910
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Peer reviewed
monthly newsletter

Article ID : 05/XI/06/1125

ARTIFICIAL INTELLIGENCE ON THE FARM: MACHINE LEARNING FOR DAIRY SUCCESS

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Abstract

The dairy industry is embracing Machine Learning (ML) to improve productivity, animal health, and sustainability. ML models use farm data to predict milk yield, milk composition, feed efficiency, and reproductive performance, while also detecting diseases such as mastitis and ketosis at an early stage. Regression models help forecast continuous traits like yield and quality, whereas classification models support decision-making in health and breeding. Algorithms such as Artificial Neural Networks, Random Forest, and Gradient Boosting Machines have shown strong performance, with hybrid models gaining importance for complex predictions. Although challenges such as data quality and overfitting remain, the integration of ML with sensors and automated systems promises smarter herd management, precision nutrition, and sustainable dairy farming in the future.

Key words: Machine learning, Dairy farming, Artificial intelligence.

Introduction

The dairy farming industry is undergoing a significant transformation to enhance efficiency, sustainability, and meet the growing demands of a global population. As traditional farming methods can no longer keep up with the increasing scale and complexity of operations, innovative technologies like Machine Learning (ML) are stepping in to provide data-driven solutions. Machine learning, a powerful subfield of Artificial Intelligence (AI), uses algorithms that learn from vast amounts of data, improving decision-making processes and automating tasks that were previously done manually. This article explores the application of Machine Learning (ML) in dairy farm management, highlighting its role in optimizing milk production, early disease detection, addressing key challenges, and exploring future opportunities in the dairy farming industry.

Application of Machine Learning (ML) in dairy farm management

Machine learning models are primarily developed for two analytical objectives: regression and classification. Regression models are employed to predict continuous quantitative traits, such as milk yield parameters (peak yield, total milk yield), milk composition parameters (e.g., fat, protein, lactose content), and feed efficiency. On the other hand, classification models are used for tasks like disease detection (e.g., mastitis), pregnancy prediction, and milk quality classification, where cows are categorized into distinct groups (e.g., healthy vs. diseased). Machine Learning models are trained using datasets that consist of predictor (independent variables) and corresponding outcomes (dependent variables). These models learn to predict the outcomes based on input data, helping farmers make better decisions about herd management. In the dairy industry, ML is applied in several areas:

1. **Disease Detection:** ML algorithms can predict health issues such as mastitis (Hyde *et al.,* 2020), ketosis (Ehret *et al.,* 2015) or repeater animals at an early stage. Early detection allows for timely intervention, preventing the spread of disease and reducing treatment costs. Several studies have used ML models to predict diseases like mastitis, milk yield, electrical conductivity, average milking duration and season etc. (Mammadova and Keskin, 2015; Miekley *et al.,* 2013).
2. **Milk Production and Milk Quality Prediction:** ML models can also predict milk yield and quality by analysing data such as milk composition, cow characteristics, and environmental factors. For example, ML can predict the first test day milk yield of dairy heifers or forecast the amount of milk a cow will produce based on factors like breed, age, and feed intake. (Dongre *et al.,* 2012; Dallago *et al.,* 2019).
3. **Insemination outcome and Pregnancy Predictions:** Another crucial application is predicting the timing of calving, real time estrus detection, insemination outcome (Shahinfar *et al.,* 2014) and pregnancy-related events (Marques *et al.,* 2024). ML algorithms use variables like date of insemination, lactation stage, days open, service period and cow health to predict when a cow will calve, helping farmers manage breeding schedules more efficiently. (Hempstalk *et al.,* 2015; Fenlon *et al.,* 2016)

Challenges and Opportunities in Applying ML

While the potential of ML in dairy farming is immense, the technology is not without its challenges. Key issues include:

- **Data Quality and Availability**: Incomplete or inconsistent data, along with unbalanced datasets, can hinder the accuracy of predictions.
- **Feature Selection and Algorithm Tuning**: Selecting the right features and fine-tuning algorithms is time-consuming and computationally demanding.
- **Overfitting and Model Generalization**: Overfitting occurs when models perform well on training data but poorly on new data, making generalization a key challenge.

Best Performing Machine Learning Models

Through various studies, certain ML algorithms have shown superior performance in dairy farming applications. Artificial Neural Networks (ANNs), have proven effective in predicting milk yield, disease detection, and calving times (Gandhi *et al.,* 2009; Panchal *et al.,* 2016; Bangar *et al.,* 2021). Similarly, Decision Tree-based algorithms like Random Forest and Gradient Boosting Machines have excelled in both classification and regression tasks, such as diagnosing diseases, prediction of 305 day milk yield (Shahinfar and Khan 2018; Bovo *et al.,* 2021; Raschia *et al.,* 2022).

The Future of Machine Learning in Dairy Farming

The future of dairy farming is undoubtedly data-driven, with Machine Learning at the forefront of this transformation. The integration of ML algorithms into Farm Management Information Systems will enable farms to become more autonomous, allowing for better decision-making, reduced costs, and increased productivity. However, challenges related to data quality, algorithm optimization, and feature selection will continue to require attention. Ongoing research into improving these areas will be essential for the broader application of ML in dairy farming. The ongoing development of more advanced algorithms and tools will further empower farmers to make timely, informed decisions, ensuring the long-term sustainability and profitability of dairy operations.

Conclusion

Machine Learning has emerged as a powerful tool for transforming dairy farm management by enabling data-driven decision-making, improving productivity, and enhancing herd health. This article highlighted the key applications of ML in predicting milk yield, monitoring milk quality, detecting diseases at an early stage, and optimizing reproductive performance. Looking ahead, the integration of advanced ML algorithms with real-time farm data, wearable sensors, and automated management systems will further revolutionize dairy farming. Future applications are likely to include precision nutrition, early warning systems for multiple health disorders, and fully automated herd management platforms, paving the way for smarter and more profitable dairy operations.

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ISSN : 2583-0910
Agri-India TODAY
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Peer reviewed
monthly newsletter

Article ID : 05/XI/07/1125

FROM STRUGGLE TO SUSTAINABILITY: A FIELD HERO'S JOURNEY

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Abstract

This is the story of a progressive farmer Shailendra Singh Patel, son of late Shri Ramkishun Verma of Village Aung, Block Malawa of Fatehpur district of Uttar Pradesh, who worked hard to develop a modern "Integrated Farming System" to transform his livelihood. By Integrated farming approach (cultivating onion, paddy in Kharif and garlic, wheat and mustard in Rabi using modern techniques, dairy and agribusiness) earning lakhs, he has attracted everyone's attention. Today, Mr. Shailendra is known among the progressive farmers of the state. Here is his success story, in his own words.

Introduction

Early life

According to Shailendra, after his father's death in 1994, he inherited half an acre of land and a thatched house. His family faced extreme hardship during the rainy and winter seasons. He also had debts from his father's illness, and when he asked for money on loan, people were reluctant to lend it. At that time, Shailendra was only 17 years old. After his father's death, he went to Ludhiana, Punjab, in search of a job. He earned only 2,500 rupees per month in a private job, working 12-13 hours a day . Despite his hard work, the wages seemed insufficient, and the hardship of being away from his family forced him to return to his village. Eventually, he returned to his village. Unable to sit idle, Shailendra took up a job as a driver. He then decided to take up farming. Shailendra Singh along with his family members traditionally cultivated cereal crops like pigeon pea, paddy, wheat, mustard, besides parwal, tomato, pomegranate and kewanch in small areas, but repeated losses and uncertainty of weather forced him to think.

Expansion of Area for Cultivation

The limited area of cultivation posed a major challenge for Shailendra. He found a solution, leasing four acres of land for Rs 12,500 per acre per year. He cultivated pointed gourd (parwal) on approximately two acres, garlic on one and a half acres, and tomatoes on half an acre. He primarily cultivated pointed gourd , garlic, and tomatoes, and also cultivated potatoes, Kharif onions, and Rabi onions as other horticultural support crops. He used to cultivate pomegranate and *Kewanch* (Velvet bean) as an intercrop. Faced with the problem of selling *Kewanch*, he now used his experience to radically alter the crop cycle and move towards commercialization. The urge and passion to achieve something through hard work and innovative thinking Shailendra has propelled the family from Zero to the destination. Innovative agricultural techniques have enabled them to grow on just 4.5 acres of land, that too only half an acre of his own land and four acres on lease at a rate of Rs 12,500 per year, he cultivated onion and paddy in Kharif season and garlic, wheat and mustard in Rabi season using cutting-edge techniques and earned lakhs of rupees. Today, Mr. Shailendra is well known among the progressive farmers of the state.

A Unique Journey from Zero to Becoming a Hero of the Fields

Shailendra recounts that in 2007, he met the District Horticulture Officer, Patel Saheb, during a training program for the Horticulture Department's Horticulture Development Program. Upon seeing Shailendra's nearly half-acre crop, he offered him the wise advice: cultivate garlic. A passionate Shailendra began cultivating garlic, as well as pointed gourd and tomatoes, and selling them in the market. He explains that farming became a joy when the Horticulture Department received garlic seeds from the National Horticultural Research and Development Foundation in 2008-09. He subsequently connected with Foundation officials, and when he began cultivating the G- 282 variety of garlic using the techniques, he learned during a seven-day trip organized by the Horticulture Department, he began seeing significant improvements in his income. After this, Shailendra never looked back. That same year, with the support of the Horticulture Department and the Foundation, Shailendra began cultivating garlic on one and a half acres, which increased his income and boosted his morale. When the department provided financial assistance from Jain Irrigation Limited, Shailendra installed a sprinkler that same year. Following Shailendra's success, his fellow farmers in the village also began cultivating garlic and tomatoes, significantly increasing their incomes. Shailendra became a role model for all these farmers. With the help of *Krishi Vigyan Kendra* and with his elder son Anand, he started understanding advanced techniques through internet.

He left traditional farming and chose the path of innovative commercial farming by adopting sprinkler irrigation, crop diversification, integrated farming and intensive farming methods. He expressed that he is highly impressed with Dr. K.N. Tiwari who educated and demonstrated about importance of balanced and integrated plant nutrient supply system involving smart fertilizers like IFFCO Nanofertilizers (Nano Urea Plus, Nano DAP, Nano Zinc, Nano Cu), water soluble fertilizers, NPK Consortia and Sagarika granules as soil health booster and Sagarika liquid as plant growth promoter (bioenhancer) so as to refine and make the nutrient use cost effective and eco-friendly. Shalendra moved towards balanced crop nutrition by using these new age fertilizers, improved seeds, advanced farming methods, integrated nutrient and pest management. He believes that innovative farming proved to be the turning point of his life.

Shailendra is a Renowned Expert in Onion and Garlic Cultivation

Shailendra started Kharif onion cultivation from 2014, first starting with planting of seedlings and later from 2022 by making beds and preparing small sized bulbs, he started cultivating onions which get ready in two-and-a-half months. Initially, for crop nutrition, he uses 19:19:19 for foliar spray twice in the season. Thereafter, when the bulb formation starts, he sprays a solution of 0:52:34 and 0:0:50 on the leaves along with using IFFCO's nano fertilizers and Sagarika liquid. Similar meticulous management is done in garlic and other crops .

Balanced and Effective Use of Smart Fertilizers Resulted Increased Yield and Income

Shailendra believes that using smart fertilizers like IFFCO Nano Urea, Nano DAP, Nano Zinc, Nano Copper, water soluble fertilizers, plant growth promoters like Sagarika significantly improves crop yield and product quality while reducing production costs by 25%. He also believes that after using Nano DAP, Nano Zinc and Nano Copper, the plants become especially strong, which increases the resistance of crops against insects and diseases, thereby reducing the use of chemicals for crop protection and lodging too.

Cultivation of commercial crops and diversification and intensification with best seeds, integrated approaches of plant nutrition along with IFFCO's Nano fertilizers, water soluble fertilizers, bioenhancer and NPK consortia, and timely crop protection has made significant change in growth and development of crops, yield, product quality and profits. He always emphasizes for use of stickers in solutions used for foliar sprays. Through integrated nutrient management, smart fertilizers, sprinkler irrigation, mulching, integrated crop protection, and experience, he believes that his farming costs have decreased and profits have increased. Today, with modern technology, hard work, and innovative thinking, progressive farmer Shailendra is earning lakhs from this 4.5 acres of land, he cultivates. Now he has increased it to about 7 acres earning about 7-8 lakhs annually through his robust integrated farming system. A field view of his crops is displayed in **Picture 1**.

Picture 1. A comparison of farming then and now

Developed A Robust Integrated Farming System

Shailendra's family consists of his wife, Urmila, three daughters, and two sons . His children's education and other needs are met through farming income. His three daughters and eldest son Anand are graduates and married, while his youngest son is pursuing his intermediate education in an English-medium school. Shailendra's farming is primarily done by family members, which is an exemplary and inspiring model of family farming (**Picture 2**).

Picture 2**.** An inspiring model of Shailendra's family farming

Along with farming, Shailendra has developed a robust integrated farming model by prioritizing animal husbandry and agribusiness. He believes this helped boosting his income significantly and has proven to be the turning point in his life. In addition to agricultural crops, he has established a 0.75 acre farm of Thai guava trees, three buffaloes, and a flour mill, oil mill, and spice grinding plant, all of which he runs on solar energy. This has alleviated electricity problems and reduced electricity costs. Shailendra has now begun teaching other farmers in the village the tricks of modern farming and demonstrates his farm every month. He believes, **"If farmers adopt new technologies and choose crops wisely, a prosperous life is possible even with less land**". A glimpse of animal husbandry and agriculture-related businesses is depicted here in **Picture 3.**

Picture 3. A glimpse of animal husbandry and agriculture-related businesses

The Man Who Revolutionized His Farming and Economy

Shailendra's fields are now recognized as Ideal demonstration area (**demo plot)** available to the farmers of the district and dignitaries for seeing and believing. He spends time every day for teaching modern farming to young people whoever visits his fields. He organizes the events of field visits to create greater awareness about innovative agriculture and importance of Integrated Farming to boost farmers income for better livelihood. He believes, ***" Farming is a loss-making business as long as farmers are afraid to adopt new technology."***

According to Shailendra, even if he gets ₹2,000 per quintal for Nashik red onions, he earns a minimum of ₹150,000 per acre, Garlic earns ₹100,000 at ₹5,000 per quintal, ₹30,000 from paddy, ₹ 20,000 from Shri Ram 303 and Karna Vandana wheat, ₹45,000 from mustard, and annually ₹150,000 from dairy**.** He has recently sold half an acre of guava orchard for ₹ 60,000. The dairy yields Shailendra a ₹200,000 net profit annually. After deducting expenses and loan installments from the factory, he earns a net income of ₹16,000 per month. Depending on the production under climate uncertainty era and market rate of the produce, Shailendra earns a total net profit of 7-8 lakh annually from total 7 acres of land.

A Successful and Happy Farmer

Times have changed, and Shailendra's hard work has paid off, and now he has a beautiful permanent home, along with a solar-powered flour, oil, and spice grinding plant or say factory. He also has a small farmhouse and a solid storage system on his own tubewell. With his earnings, Shailendra in addition to these arrangements, he also secured a motorcycle, a tractor, and necessary agricultural equipments. Shailendra's success earned him numerous awards and coverage in print media. See **Pictures 4** and **5**.

Picture 4. A glimpse of the prestigious awards received by Shailendra

Picture 5. A glimpse of media coverage of Shailendra's innovative agriculture

Summary

Farmer Shailendra’s integrated farming success has had a significant positive impact on the local community. By adopting an innovative model combining crops, dairy, and agri-business, he not only improved his own livelihood but also created employment opportunities and boosted local agricultural productivity. His approach encouraged neighbouring farmers to diversify and adopt sustainable practices, leading to increased income stability and resilience against crop failures or market fluctuations. Additionally, Shailendra’s success helped foster knowledge sharing and skill development at the village level, promoting better resource use efficiency and environmental sustainability. This has contributed to strengthening the rural economy and enhancing food security within the community.

Inspiring Conclusions

The story of Shailendra Singh shows that if innovative commercial farming is done and the model of integrated farming (agriculture, animal husbandry and agriculture related businesses) is adopted in a planned manner with full understanding as per the weather forecast, market price and demand of the product, then the goal of earning lakhs of money can be achieved even with limited land.

ISSN : 2583-0910
Agri-India TODAY
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Peer reviewed
monthly newsletter

Article ID : 05/XI/08/1125

AMARANTHUS: A FORGOTTEN GRAIN FOR THE FUTURE OF HEALTH AND WELLNESS

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Abstract

Ancient pseudocereal amaranth (Amaranthus spp.), once valued by ancient cultures, is regaining international recognition as a nutrient-dense, climate-resilient functional food. Amaranth is renowned for its incredible nutritional composition, which includes high-quality protein (particularly lysine), dietary fibre, unsaturated fatty acids, and vital minerals including calcium, magnesium, and iron, even though it has been underutilised for decades. More significantly, it has an abundance of biologically active components that support its anti-inflammatory, cholesterol-lowering, and antioxidant qualities, comprising phenolic acids, carotenoids, flavonoids, and squalene. It also discusses new uses of amaranth in microencapsulation technology, biodegradable packaging, and functional food. Amaranth shows promise as a crop for tackling contemporary health issues and promoting sustainable nutrition because of its capacity to flourish in unfavourable agro-climatic conditions and its applicability in plant-based and gluten-free diets. The purpose of the article is to harness the potential of amaranth in modern food systems by bridging traditional knowledge with new scientific discoveries.

Keyword: Amaranth, Protein, Bioactive compound, Functional food, Nutrition

Introduction

Imagine a tiny seed that once fueled ancient warriors, worshipped in rituals, and cultivated in mountain terraces centuries ago—now quietly making a powerful comeback on modern plates. Amaranth, a resilient "super grain" that's not really a grain, yet richer in nutrition than many cereals we consume daily. In today's world, where lifestyle diseases are on the rise and people are becoming increasingly aware of what they eat, there's a growing demand for foods that do more than just fill the stomach. We want food that heals, strengthens, and sustains—and amaranth checks all the boxes.

In the evolving landscape of global nutrition, the focus has shifted from merely addressing hunger to achieving optimal health through food. This shift has spurred a growing interest in functional foods—those that go beyond basic nutrition to provide physiological benefits or reduce the risk of chronic disease. In recent decades, there has been a revival of interest in underutilized and climate-resilient crops, and amaranth has once again found its place in the spotlight—this time, as a potential functional food for modern health challenges**.**

Although amaranth is categorised as a pseudocereal by botanists, it is utilised similarly to wheat and barley despite not being a member of the grass family. The remarkable nutritional profile of amaranth is what makes it unique: it is naturally gluten-free, high in dietary fibre, high-quality protein (particularly the amino acid lysine, which is scarce in other grains), and vital minerals like calcium, magnesium, iron, and zinc. Additionally, amaranth leaves and seeds are rich in bioactive substances such peptides, polyphenols, flavonoids, and squalene, a rare lipid with cholesterol-lowering and antioxidant properties. In addition to its high nutrient content, research has shown that amaranth may help treat or prevent a number of illnesses, such as diabetes, heart disease, anaemia, and inflammatory diseases. It is especially beneficial for people with metabolic syndrome or those seeking to prevent health issues through diet because of its low glycaemic index, antioxidants, and anti-inflammatory qualities. In addition to being a nutrient-dense food, amaranth is a sustainable crop for food security in the face of climate change because it grows well in marginal soils, resists heat stress and drought, and has a short growing season. Nutritionists, public health specialists, and agricultural policymakers have all taken notice of these attributes. The moment is right to bring amaranth back into the human diet as a functional food ingredient supported by science, given the rising demand for plant-based, gluten-free, and clean-label products.

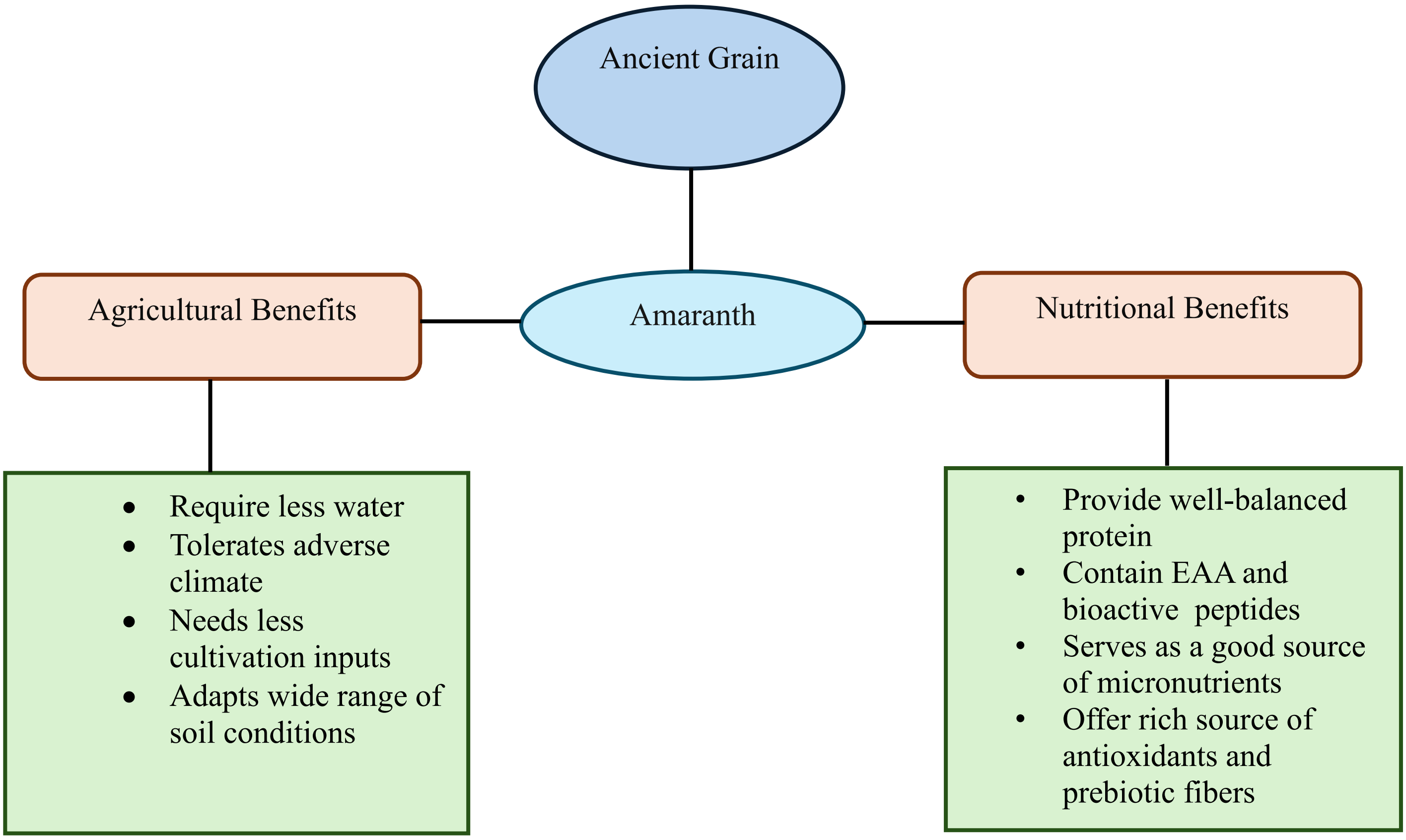

Figure 1. Agricultural and nutritional benefits of amaranth

Novel and exploratory technological applications for amaranth

a. **Functional food:** Amaranth is utilized in functional foods to enhance various products. For example, fish dishes are fortified with bioactive compounds from amaranth seeds and sprouts. In addition, a functional beverage has been developed by fermenting germinated amaranth with *Lactobacillus plantarum*, which may offer antioxidant and hypoglycemic benefits.
b. **Microencapsulation:** Protein-rich fractions and amaranth starch work well as wall materials to shield delicate bioactive substances such vitamins, betanin, vanillin, and β-

carotene. Different encapsulation strategies have been studied to enhance stability and delivery efficiency.

c. **Functional films:** Amaranth shows promise in producing edible films, where its protein isolates form the base material. These films are reinforced with starch granules or nanocrystals, improving their mechanical properties. The incorporation of phenolic compounds and betalains further enhances their functionality, making them suitable for food packaging applications.

d. **Emulsifiers/additives:** Amaranth proteins exhibit excellent emulsifying and additive properties. For instance, 11S globulins demonstrate high surface hydrophobicity, solubility, and emulsifying capacity, making them ideal for use as gelling agents, foam stabilizers, and thickeners in food formulations.

Nutritional Composition

1. Basic Nutritional Composition

Nutrient	Value(per 100g)
Moisture	11.27 g
Energy	372 kcal / 1554 kJ
Protein	13.55 g
Fat	7.03 g
Ash	2.86 g
Carbohydrate	65.25 g
Sugar	1.69 g
Starch	57.17 g
Dietary Fiber	6.70 g

2. Essential Amino Acids (per 100 g protein)

Amino Acid	Range (g)
Isoleucine	3.6–4.2
Leucine	5.7–6.4
Lysine	4.8–5.2
Sulfur Amino Acids*	4.5–4.7
Aromatic Amino Acids**	7.2–7.0
Threonine	3.3–3.4
Tryptophan	1.1–1.8
Valine	4.5–4.6
Histidine	-

*Methionine + Cysteine | **Phenylalanine + Tyrosine

3. Mineral Content (per 100 g)

Mineral	Value (mg)
Copper	0.51
Manganese	1.51
Iron	9.62
Zinc	5.55
Magnesium	231
Calcium	165
Phosphorus	527
Potassium	530

4. Major Bioactive Compounds

Bioactive Compound	Approximate Amount
Squalene	4.7–8.0 g/100 g oil
Phenolic compounds	40–120 mg GAE/100 g
Flavonoids	12–50 mg QE/100 g
Phytosterols	12–20 mg/g oil
Tocopherols (Vitamin E)	2.0–4.0 mg/100 g oil
Carotenoids	22–45 mg/100 g FW
Betalains	40–60 mg/100 g FW
Saponins	1.0–3.5% dry weight
Tannins	0.3–1.0% dry weight

Biological and Pharmacological Activity

Amaranth offers numerous beneficial health effects. The pharmacological activity of amaranth is attributed to its betacyans, protoalkaloids, and saponins. The scientific literature contains information on amaranth's positive effects on the nervous and cardiovascular systems, as well as its hypoglycemic effect, antibacterial activity, antioxidant activity, and other properties. Amaranth is utilised extensively in the pharmaceutical sector to make antibacterial, antifungal, and anti-inflammatory medicines as well as medications to treat tuberculosis, atherosclerosis, and stomach ulcers. Amaranth seed oil has antioxidant, hypotensive, anti-atherosclerotic, and hypolipidemic properties. As a result, eating it could prevent or postpone the emergence of civilization's diet-related illnesses.

Health benefits

Health Benefit	Key Nutrient/Compound	Reason
Muscle growth, tissue repair	Protein (Lysine)	Complements cereal proteins
Heart health	Fiber, squalene, unsaturated fats	Lowers LDL cholesterol, reduces inflammation
Blood sugar control	Fiber, complex carbs	Low GI, slows glucose absorption
Celiac-safe	Gluten-free	Safe for gluten-intolerant individuals
Immunity boost	Iron, zinc, magnesium	Supports immune cell function
Anti-inflammatory	Flavonoids, polyphenols	Reduces chronic inflammation
Gut health	Fiber	Supports digestion and microbiota
Bone & blood health	Calcium, iron	Prevents osteoporosis and anemia
Weight management	Protein, fiber	Enhances satiety
Cancer protection (possible)	Squalene, polyphenols	Antioxidant, anti-tumor activity (under research)

Conclusion and future sights

Amaranth is an outstanding example of how a traditional, frequently disregarded crop can satisfy the needs of contemporary sustainability, nutrition, and culinary innovation. It is an extremely valuable ingredient in the development of functional foods because of its high protein quality, gluten-free status, rich mineral profile, and profusion of health-promoting bioactive compounds. Its functions in boosting immunity, controlling blood sugar, reducing nutritional deficiencies, and increasing cardiovascular health are all supported by scientific research. The uses of amaranth in technology extend beyond its traditional culinary use. These days, its proteins and starch are employed in innovative industries like edible films, microencapsulation, and natural emulsifiers, expanding its use to eco-friendly food packaging and nutraceutical delivery. These developments support more sustainable food systems in addition to raising the crop's worth as individuals. Malnutrition might be prevented, dietary diversity could be increased, and climate-resilient agriculture could be supported by incorporating amaranth into global food supply chains through governmental support, consumer education, and farmer incentives. Amaranth is in a strong position to turn from a conventional grain into a popular superfood of the future due to rising consumer demand for plant-based, clean-label, and functional food.

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ISSN : 2583-0910
Agri-India TODAY
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Article ID : 05/XI/09/1125

BIOCHAR: A BLACK GOLD FOR SOIL HEALTH AND WATER SUSTAINABILITY

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Abstract
Biochar is a form of charcoal produced by the pyrolysis of biomass in an oxygen limited environment.Biochar enhances soil fertility by increasing water retention, nutrient retention, and soil aeration, thereby improving plant growth and crop yields. It also supports beneficial microbial communities in the soil and reduces nutrient leaching, which can lower fertilizer needs. Additionally, biochar plays a critical role in climate change mitigation by sequestering carbon in the soil for hundreds to thousands of years, reducing greenhouse gas emissions.This article explores the potential of biochar in improving soil health and water retention, thereby ensure crop growth and productivity.

Keywords : Biochar, Water retention, Soil fertility, Climate resilience, Sustainable agriculture

Introduction
Biochar is a carbon-rich material produced from the pyrolysis of organic biomass. It is a stable compound, which creates a highly porous structure that will enhances both soil health and soil water holding capacity. It addresses critical agricultural challenges like soil degradation, low fertility, and water scarcity by improving soil structure, increasing water holding capacity to improve crop drought resistance, and regulating microbial habitats in the soil. By boosting nutrient efficiency, biochar minimizes the need for chemical fertilizers, reducing environmental pollution from nutrient leaching and harmful greenhouse gas emissions such as nitrous oxide. Furthermore, it acts as a long-term carbon sink, sequestering carbon in the soil to mitigate climate change. This dual ability to enhance agricultural productivity while promoting environmental sustainability makes biochar an invaluable tool for developing resilient farming systems capable of withstanding climate stress and resource scarcity.

Raw materials for biochar production
Physiochemical properties such as yield and performance of biochar greatly depend on the raw materials used for its production. A wide range of feedstocks can be given for the process of pyrolysis for its production. They are;

- **Agricultural Residues-**Agricultural residues such as corn stalks, rice husk, sugarcane bagasse, wheat straw, groundnut shells and coconut shells are the most common and easily available raw materials for biochar production. They possess high lignocellulosic content and produce biochar with high porosity and moderate nutrient content.
- **Forestry Residues-**They are the by-products of the timber and wood industry, like bark, wood shavings and twigs. They produce stable and carbon-rich biochar due to it's high lignin content. However, they have lower nutrient content than the agricultural residues.

- **Animal Manure-** Cowdung, poultry litter, and pig manure are the livestock wastes. They produce biochar rich in nutrients such as nitrogen and phosphorous. In addition to this, its high ash content makes it a good soil conditioner. Since they emit volatile gases during pyrolysis a proper pretreatment is required.
- **Municipal and Industrial Organic Wastes-** The biodegradable portions of urban and industrial wastes such as paper wastes, green waste from gardens, food waste, sewage sludge etc., constitute feedstock of this group. They have a potential threat of heavy metal contamination.
- **Dedicated Energy Crops-** The plants grown specifically for biochar production due to their high biomass productivity and easy renewability comes under dedicated energy crops. Switchgrass, miscanthus, bamboo and water hyacinth can be used for large-scale biochar production. Furthermore, they produce uniform biochar with high quality.

Production of Biochar

Biochar is produced as a by-product or a co-product of thermochemical conversion of biomass . The processes are fast pyrolysis, slow Pyrolysis and gasification.

1.Fast Pyrolysis: In fast pyrolysis , the heating rate is set to a maximum for higher bio-oil production.The heating rate differs with feedstock and reactor type. Low ash lignocellulosic biomass feedstock undergoing fast pyrolysis produces approximately 60-70 % of bio-oil by weight while the yield of biochar is only 12-15% by weight.

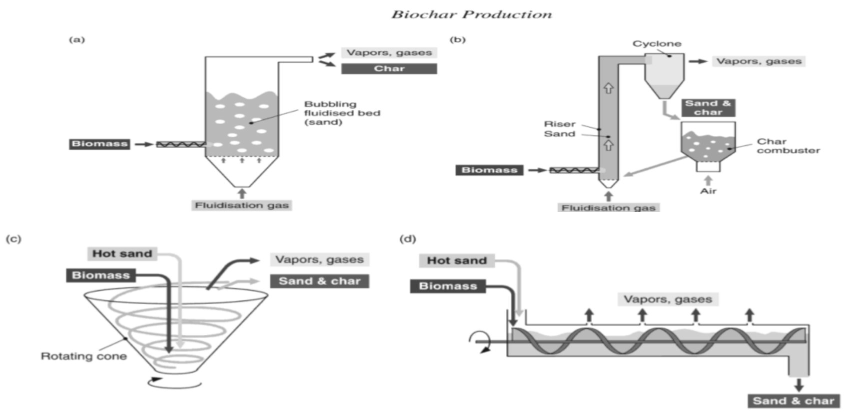

Fig 1 Figure 10.5. Fast pyrolysis reactor types: (a) bubbling fluidized bed, (b) circulating fluidized bed, (c) rotating cone reactor and (d) screw or auger reactor. (A black and white version of this figure will appear in some formats. For the colour version, please refer to the plate section.)

2.Slow Pyrolysis: also called carbonization is done at lower heating rates and minimum solid vapor contact . This process yields maximum char where entire biomass undergoes pyrolysis.

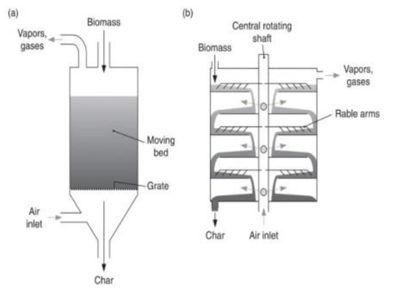

Fig 2

Figure 10.3. Slow pyrolysis continuous kilns: (a) the Schottdorf kiln, (b) Hereshoff multiple hearth furnace (adapted from Thomas et al., 2009).

3.Gasification: Unlike pyrolysis, it makes use temperatures more than 700°C and oxygen. The primary product of gasification is producer gas which is a mixture of combustible gases such as CO_2,CH_4,H_2,CO and lighter hydrocarbons. It only produces less than 10% char by weight.

Properties of Bio-Char

Biochar in improving nutrient retention and soil structure

Through a number of interrelated processes, biochar has a remarkable ability to retain soil nutrients. By trapping vital nutrients like nitrate, phosphate, and ammonium inside its small pores and halting their quick passage through the soil profile, its extremely porous structure acts as a physical reservoir. Together with biochar's large surface area and distinct surface chemistry, this physical trapping produces a large number of exchange sites where positively charged nutrients can attach. Vital cations like potassium, calcium, and magnesium can be efficiently stored and released gradually by biochar due to its high cation exchange capacity, keeping them available in forms that plant roots can easily absorb.

The physical structure of soil is radically altered by biochar, which improves soil health and plant growth. By boosting both accessible water capacity and field capacity, biochar greatly improves water retention when added to soil. The greatest noticeable increases are seen in coarse-textured sandy soils where water normally drains too quickly. During dry spells, this improved capacity to retain moisture offers vital defense against drought stress. By increasing the pore space between soil particles, this improved soil structure also improves aeration and guarantees a sufficient supply of oxygen for root respiration and the aerobic bacteria that power vital nutrient cycling activities. When combined, these structural enhancements produce a more favorable atmosphere that supports the growth of soil organisms and the establishment of strong root systems by plants.

Effect of Biochar on pH, cation exchange capacity, and microbial activity

Because of its alkaline composition and special surface qualities, biochar has a significant impact on soil chemistry and biological activity. Biochar, which is generally alkaline in nature, works well as a liming agent in acidic soils by releasing alkaline minerals such as calcium, magnesium, and potassium hydroxides, carbonates, and oxides that dissolve and balance the acidity of the soil. Exchangeable acidity is further decreased by the binding and sequestration of hazardous hydrogen and aluminum ions from the soil solution by negatively charged functional groups on the surfaces of biochar.

Through a variety of mechanisms, biochar significantly improves soil's cation exchange capacity in addition to modifying pH. Positively charged nutrients like calcium, magnesium, and potassium are drawn to and retained by its large surface area studded with negative charges due to its highly porous design. Biochar gradually increases its negative charge density and nutrient-holding capacity as it ages in soil because surface oxidation produces more oxygen-containing functional groups like carboxyl and hydroxyl groups. The effect of this higher CEC, which varies depending on the feedstock composition and pyrolysis conditions, is to keep essential cations in the root zone instead of letting them leak out. Generally, high-ash feedstocks and herbaceous materials processed at lower temperatures have better cation retention capacities.

Additionally, biochar transforms the soil's microbial landscape by providing favorable conditions for diverse microbial communities. Its porous structure provides protected microhabitats that protect microorganisms from environmental stress, desiccation, and predators, increasing microbial biomass and diversity. New applications of biochar often cause a "priming effect" in which microbes quickly consume available carbon and nutrients, causing metabolic activity throughout the soil. The pH adjustments caused by biochar change the composition of microbial communities, usually favoring populations that are suited to the modified conditions. Additionally, biochar's remarkable adsorption capacity eliminates soil toxins and allelochemicals that might otherwise inhibit microbial growth.

Role of Biochar in Improving Water Retention

Both the mineral and organic components of soil influence its capacity to retain water; however, only the organic fraction can be deliberately managed. Water tends to be held more firmly within smaller pores, which is why clayey soils generally exhibit higher water-holding capacity. The lower bulk density typically associated with increased organic matter content indicates the role of organic matter in improving soil structure and modifying pore size distribution.

Biochar plays a significant role in enhancing various soil physical characteristics, including soil wettability, hydraulic conductivity, infiltration rate, water retention, macro-aggregation, and structural stability. These improvements are closely connected to factors such as surface area, porosity, bulk density, and aggregate stability. Such properties are particularly valuable in tropical regions where they help reduce erosion, alleviate drought effects, prevent nutrient losses, and promote better groundwater quality.

Even small additions of biochar—around 0.5% by weight—can substantially enhance soil water-holding capacity (WHC). In a long-term column experiment, Laird et al. (2010) found that Clarion soil treated with biochar retained about 15% more water overall and exhibited 13% and 10% higher retention at soil matric potentials of -100 kPa and -500 kPa, respectively, compared to untreated soil. Earlier, Tryon (1948) reported that biochar addition improved available water capacity (AWC) in sandy soils, had minimal effect in loamy soils, and slightly decreased moisture content in clayey soils. This variation is likely due to the hydrophobic properties of charcoal and changes in pore size distribution (PSD). Consequently, since biochar tends to enhance moisture retention primarily in coarse-textured soils, careful selection of both the biochar type and soil texture is essential for optimal results.

The Role of Biochar in Enhancing Sandy Soil Water Retention and Drought Resilience

Sandy soils are highly permeable and have poor water and nutrient retention, making crops grown in them more vulnerable to drought and nutrient leaching. With global climate change intensifying temperature fluctuations and altering rainfall patterns, the issue of maintaining soil moisture has become increasingly critical. Among the sustainable soil management strategies, biochar—a carbon-rich product derived from the thermal decomposition of organic materials—has emerged as a promising amendment to improve the physical and hydrological properties of sandy soils.

Biochar’s effectiveness depends largely on its porous structure, surface area, and chemical composition, which vary according to the feedstock type (e.g., wood, manure, crop residues) and pyrolysis conditions. The addition of biochar significantly increases the specific surface area and micropore volume of sandy soils. These micropores (ranging between 0.2–9 µm in diameter) are critical for retaining water against gravity, thereby improving field capacity (FC) and plant-available water content (AWC).

Biochar also modifies soil bulk density and porosity, reducing large interparticle spaces and increasing water-holding pores. This leads to enhanced nutrient retention and reduced leaching, which are crucial for sustainable crop productivity, especially under drought conditions.

Beyond improving water dynamics, biochar acts as a nutrient reservoir, reducing fertilizer leaching and promoting more efficient nutrient uptake by plants. It helps maintain a more stable soil microenvironment, which benefits root development and microbial activity. When combined with organic compost or fertilizers, biochar improves overall soil fertility and water use efficiency, enhancing plant growth under both normal and stress conditions.

Further, developing engineered biochar pellets—enriched with nutrients and designed for easy handling—could enhance biochar's applicability in large-scale agriculture. Utilizing industrial biochar waste from combined heat and power (CHP) systems may also reduce environmental pollution and provide a low-cost, sustainable source of soil amendments.

Environmental and Climatic benefits of biochar

Biochar not only helps in water retention and soil fertility management, but also helps in Carbon sequestration and mitigation of greenhouse gases. Since it is highly stable it reduces decomposition. It locks the atmospheric CO_2 in soil. It also reduces the emission of N_2O and CH_4 from the soil. Thereby reduces greenhouse gas emissions to the atmosphere. It also helps in Climate resilience and sustainable agriculture by improving the soil productivity under changing climatic conditions.

Conclusion

Biochar holds immense potential as a climate-resilient soil amendment, capable of improving sandy soil's water retention, nutrient availability, and drought resistance. Its effectiveness depends on optimizing production and application techniques tailored to specific soil types. With continued innovation in biochar engineering, treatment methods, and field evaluation, biochar can play a transformative role in promoting sustainable agriculture and mitigating the impacts of climate change on soil-water systems.

ISSN : 2583-0910
Agri-India TODAY
visit us at www.agriindiatoday.in

Peer reviewed
monthly newsletter

Article ID : 05/XI/10/1125

BIOCHAR & AGRICULTURAL WASTE VAPORIZATION : TURNING TRASH INTO SOIL TREASURE

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Introduction

After every harvest, dense clouds of smoke rise across the rural landscapes of India. To swiftly prepare the ground for the following harvest, farmers burn tons of crop wastes, such as cotton stalks, banana stems, rice husks, and sugarcane waste. Although it is a frequent sight, it has serious repercussions, including greenhouse gas emissions, air pollution, and the heart breaking loss of priceless organic materials. Science now presents a different picture, one in which agricultural waste is viewed as a benefit rather than a burden. Sustainable agriculture is seeing a revolution thanks to biochar, a carbon-rich substance produced by pyrolyzing agricultural leftovers at low oxygen levels. In a time when climate resilience and soil health are top global priorities, biochar stands at the intersection of tradition, innovation, and environmental responsibility.

Understanding Biochar: Nature's Carbon Vault

In essence, biochar is charcoal for the ground. It is created by heating organic materials in a low-oxygen atmosphere, such as rice husks, banana pseudostems, wood chips, or even fruit peels. By stabilizing carbon, this mechanism stops it from escaping as CO_2 into the atmosphere. A lightweight, porous substance is produced as a result, which functions in the soil like a sponge to absorb nutrients and water while also serving as a home for helpful microorganisms. More than 2,000 years ago, farmers in the Amazon region used comparable methods to produce "Terra Preta," or black earth, soils. Even now, the soils are still fruitful. That ancient wisdom has been improved by modern science. According to studies, biochar increases the physical structure, chemical balance, and biological activity of soil, improving production and restoring fertility in degraded areas.

India's status in Agricultural Waste Challenge

Almost 20% of the more than 500 million tonnes of crop leftovers produced in India each year are burned. Following rice and wheat harvests, large amounts of residue burn in states like Punjab, Haryana, and Uttar Pradesh, which exacerbates pollution and causes major respiratory problems. However, these remnants are undeveloped resources rather than waste. They can retain moisture and minerals for a lot longer than regular soil when turned into biochar, which is a useful soil conditioner. By switching from open burning to pyrolysis, millions of tons of CO_2 emissions might be avoided annually. The core of a circular economy is this: farmers recycle garbage into something useful rather than throwing it away, restoring nutrients to the soil and absorbing carbon in the process.

Turning Waste to Wealth: Scientific Innovations

Simple biochar production has been surpassed by recent advances. In order to create enriched biochar, which functions as a slow-release fertilizer, scientists are now supplementing charcoal with essential elements like nitrogen (N), phosphorus (P), and potassium (K). An innovative example is the process developed by the Institute of Minerals and Materials Technology (IMMT) in Bhubaneswar to convert banana pseudostem waste into potassium-enriched biochar.

This innovation does three things:

1. Reduces massive post-harvest banana waste.
2. Provides farmers with a natural, nutrient-rich soil enhancer.
3. Supports the Government of India's *Waste-to-Wealth* and *Swachh Bharat* initiatives.

Such technology aligns perfectly with India's **National Mission on Sustainable Agriculture (NMSA)** and the **National Policy for Management of Crop Residues (NPMCR)**, which encourage waste recycling and soil rejuvenation.

Biochar's Benefits: For Farmers, Soil, and Climate

Biochar's impact on agriculture is multi-dimensional:

1. **Improved Soil Structure:** Its porous texture loosens compacted soils and enhances aeration, allowing roots to penetrate deeper.
2. **Water Retention :** Biochar can hold up to **five times its weight in water**, a crucial advantage in drought-prone regions.
3. **Nutrient Retention :** It prevents nitrogen and potassium leaching, meaning fertilizers applied stay available to plants longer.
4. **Microbial Habitat :** The pores of biochar act as homes for beneficial soil microbes and fungi, boosting soil biodiversity.
5. **Climate Mitigation :** By locking carbon in a stable form, biochar effectively turns the soil into a carbon sink, helping mitigate climate change.

Policy and Institutional Support

India's scientific and policy ecosystem is strongly backing biochar adoption:

- **ICAR & State Agricultural Universities:** Conduct field demonstrations, soil carbon studies, and awareness programs.
- **NITI Aayog's Waste-to-Wealth Mission:** Promotes technologies that convert agricultural residues into valuable products.
- **National Policy for Management of Crop Residues (NPMCR):** Encourages composting, biochar, and bioenergy over open burning.
- **Private Sector & Startups:** Companies such as *Farm2Energy* and *CarbonCraft* are developing decentralized biochar units.
- **Global Partners:** Organizations like FAO, UNEP, and CGIAR recognize biochar as a key tool for carbon sequestration and climate-smart farming.

Challenges on the Path

While promising, biochar adoption is still in its early stages.

1) **Cost Barriers :** Pyrolysis units can be expensive for small and marginal farmers.

2) **Knowledge Gaps :** Farmers often lack training on production techniques, dosage, and blending with compost or manure.
3) **Standardization Issues :** Biochar quality varies depending on feedstock and pyrolysis temperature, requiring certification systems for consistency.
4) **Market Access :** Currently, there is limited commercialization and value-chain development for biochar products.

To scale adoption, experts recommend financial incentives, demonstration plots, carbon credits, and community-level pyrolysis units managed by Farmer Producer Organizations (FPOs).

The Way Forward: From Pollution to Prosperity

Imagine a time in the future where all crop residue is integrated into a regenerative soil cycle, with no husk, leaf, or stalk being burned. The substance that was once held responsible for pollution may now hold the secret to long-term success. Biochar is a representation of that change. It serves as a link between contemporary ecological science and traditional agricultural knowledge. In addition to lowering emissions and fostering a circular economy where waste is turned into wealth, it aids in the development of healthy soils.

If Integrated across India's farming systems, biochar could:

- Reduce crop residue burning by 80%,
- Cut emissions by millions of tonnes annually,
- Improve soil fertility and water efficiency, and
- Provide additional rural livelihoods through small biochar enterprises.

Conclusion

Biochar is a philosophy of regeneration rather than just a carbon product. It exemplifies the idea that there is no waste in nature only misdirected potential. India has the potential to spearhead the Biochar Revolution by fusing scientific advancement, farmer involvement, and policy assistance, turning waste into output and residues into income. The green answer for the planet's future may lie in the black powder that farmers are holding. Biochar Black may, in fact, be the writing of the farming industry's future.

ISSN : 2583-0910
Agri-India TODAY
visit us at www.agriindiatoday.in

Peer reviewed
monthly newsletter

Article ID : 05/XI/11/1125

BIOCHEMICAL PATHWAYS OF NUTRIENT UPTAKE AND UTILIZATION IN CROPS

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Abstract

Nutrient uptake and utilization are central to plant growth, yield, and stress adaptation. Crops require both macronutrients (nitrogen, phosphorus, potassium) and micronutrients (iron, zinc) for metabolic processes, signaling, and structural development. These nutrients are absorbed from the soil via specialized transporters, translocated through vascular tissues, and metabolized through biochemical pathways regulated by enzymes. This review summarizes the biochemical mechanisms underlying the uptake, transport, and metabolism of nitrogen (N), phosphorus (P), potassium (K), iron (Fe), and zinc (Zn), highlighting enzymatic regulation and cross-talk between pathways.

Introduction

Plants rely on a finely tuned network of biochemical pathways for nutrient acquisition, distribution, and utilization. The efficiency of these pathways influences crop productivity, resilience to stress, and nutrient use efficiency (NUE). Macronutrients like N, P, and K are required in large quantities, whereas Fe and Zn, though needed in smaller amounts, play irreplaceable roles as cofactors in enzymatic reactions. Understanding these pathways has significant implications for sustainable agriculture and biofortification (Marschner, *et al.,* 2012).

The regulation of nutrient uptake and assimilation involves a network of transport proteins, enzymes, and transcription factors**,** which allow plants to adapt to fluctuating soil nutrient availability. Moreover, cross-talk among nutrient pathways ensures coordinated growth; for example, nitrogen status influences phosphorus demand, while zinc and iron uptake often interact due to overlapping transporter families (Fan, *et al.,* 2021 & Bouain, N, *et al.,* 2019).

Given the global challenges of climate change, soil degradation, and over-reliance on chemical fertilizers, understanding these biochemical pathways is essential for improving nutrient use efficiency (NUE), breeding nutrient-efficient crop varieties, and developing sustainable agricultural practices. This review explores the absorption, transport, metabolism, and enzymatic regulation of N, P, K, Fe, and Zn in crops, emphasizing the biochemical processes that integrate nutrient availability with plant growth and productivity

Nitrogen (N) Pathway

Uptake

Nitrogen is absorbed mainly as nitrate (NO_3^-) and ammonium (NH_4^+). Nitrate uptake occurs through members of the NRT1 and NRT2 transporter families, while ammonium is absorbed by AMT transporters (Miller, *et al.,* 2007).

Transport

Nitrate is transported in the xylem to shoots, whereas ammonium is rapidly assimilated in the roots due to toxicity.

Metabolism

Nitrate assimilation begins with nitrate reductase (NR) converting NO_3^- to NO_2^- in the cytosol, followed by nitrite reductase (NiR) reducing NO_2^- to NH_4^+ in plastids. The NH_4^+ ion is then incorporated into amino acids through the GS–GOGAT cycle, involving glutamine synthetase (GS) and glutamate synthase (GOGAT). Glutamate produced here acts as the precursor for amino acids, nucleotides, and chlorophyll (Xu, *et al.,* 2012).

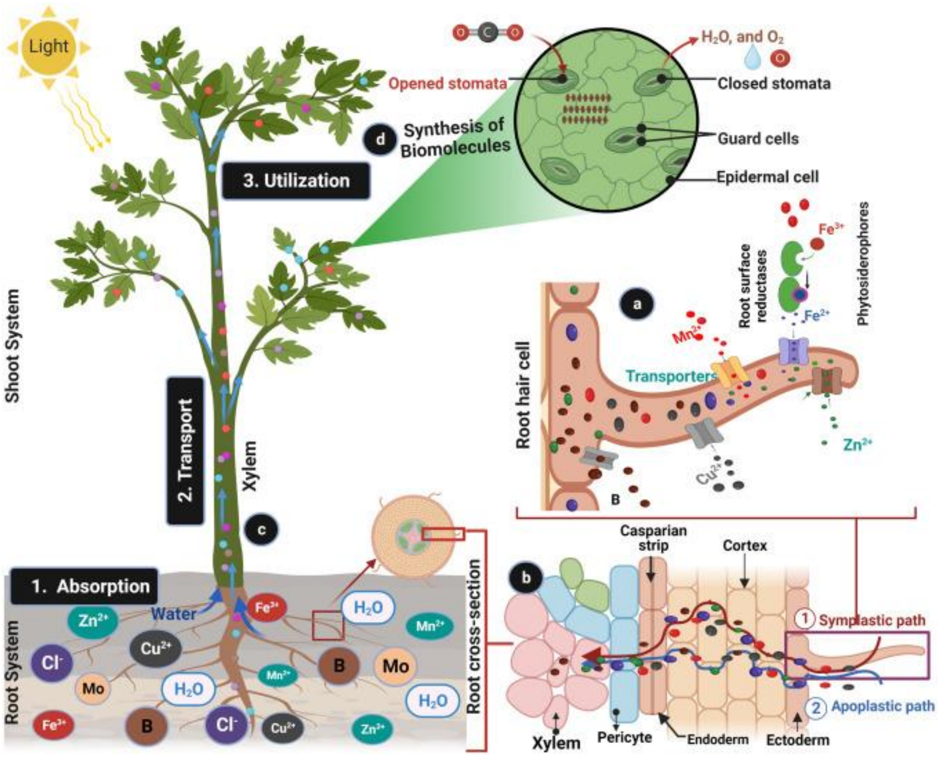

Fig.1: Elucidating the intricate mechanisms of micronutrient absorption, transport, and accumulation in horticultural crops **(**Nazir Ahmed, *et al.,* 2024).

Phosphorus (P) Pathway

Uptake

Phosphorus is absorbed as inorganic phosphate (Pi), mainly in the form of $H_2PO_4^-$ and HPO_4^{2-}. Uptake is mediated by PHT1 transporters, which function under both high- and low-affinity conditions (Raghothama, *et al.,* 1999).

Transport

Pi is transported via the xylem to shoots and is stored as phytate (inositol hexakisphosphate) in seeds for remobilization during germination (López-Arredondo, *et al.,* 2014).

Metabolism

Phosphorus is a structural component of nucleotides, ATP, phospholipids, and phosphorylated intermediates in metabolism. Purple acid phosphatases (PAPs**)** and other phosphatases mobilize Pi from organic compounds in soils and senescing tissues (Raghothama, *et al.,* 1999).

Potassium (K) Pathway

Uptake

Potassium is absorbed as K^+ ions through HAK5 high-affinity transporters under low external K conditions and AKT1 channels under high-K conditions (Wang & Wu, *et al.,* 2013).

Transport

Potassium is highly mobile and moves via both xylem and phloem. It is essential for stomatal opening, mediated by KAT1 and KAT2 channels in guard cells (Shabala & Pottosin, *et al.,* 2014).

Role in Metabolism

Unlike N and P, K is not assimilated into organic molecules but acts as a cofactor for over 60 enzymes, including pyruvate kinase, starch synthase, and RuBisCO. It regulates osmotic balance, charge stabilization, and carbohydrate translocation (Wang & Wu, *et al.,* 2013).

Iron (Fe) Pathway

Uptake

Plants employ two distinct iron uptake strategies:

- Strategy I (dicots and non-graminaceous monocots):
  - Ferric chelate reductase (FRO2) reduces Fe^{3+} to Fe^{2+}.
  - IRT1 transporter mediates Fe^{2+} uptake.
- Strategy II (grasses):
  - Roots release mugineic acid family phytosiderophores, which chelate Fe^{3+}.
  - The complexes are absorbed via Yellow Stripe 1 (YS1) transporters (Kobayashi & Nishizawa, *et al.,* 2012).

Transport

Once absorbed, Fe is chelated with citrate or nicotianamine for translocation through the xylem and stored in ferritin proteins in plastids (Marschner, *et al.,* 2012).

Metabolism

Fe is essential for heme proteins, cytochromes, and Fe-S cluster proteins, which participate in respiration and photosynthesis. It also serves as a cofactor for enzymes like catalase, peroxidase, and aconitase (Kobayashi & Nishizawa, *et al.,* 2012).

Zinc (Zn) Pathway

Uptake

Zn is absorbed as Zn^{2+}, mainly through the ZIP family of transporters, while heavy metal ATPases (HMAs) regulate intracellular distribution and efflux (Broadley, *et al.,* 2007).

Transport

Zinc is translocated in complex with organic acids like citrate and malate or with nicotianamine, enabling mobility in xylem and phloem (Sinclair & Krämer, *et al.,* 2012).

Metabolism

Zinc functions as a cofactor for >300 enzymes, including:

- Carbonic anhydrase (photosynthesis and pH regulation),
- Superoxide dismutase (Zn-SOD) (oxidative stress defense),
- RNA polymerases (gene expression).

Additionally, Zn is involved in auxin metabolism and protein synthesis (Broadley, *et al.,* 2007).

7. Enzymatic and Regulatory Cross-Talk

Nutrient uptake is powered by H^+-ATPase-driven proton gradients, enabling NO_3^-, Pi, and K^+ transport across membranes (Krouk, *et al.,* 2010). Key transcription factors regulate nutrient-responsive genes: NLP7 controls N assimilation, while PHR1 regulates P starvation responses (Bouain, *et al.,* 2019).

Cross-talk exists among nutrients:

- High N supply increases P demand.
- Zn deficiency disturbs Fe homeostasis due to Zn–Fe antagonism.
- K availability modulates N assimilation by influencing nitrate reductase activity (Bouain et al., 2019).

Conclusion

Nutrient uptake and utilization in crops are governed by a complex interplay of transporters, enzymes, signaling molecules, and transcription factors. The pathways for nitrogen, phosphorus, potassium, iron, and zinc not only sustain primary metabolic processes such as protein synthesis, energy transfer, photosynthesis, and respiration but also regulate signalling networks that allow plants to sense and adapt to nutrient availability. Nitrogen and phosphorus are assimilated into organic molecules essential for growth and development, whereas potassium plays an indispensable role in enzyme activation, osmotic regulation, and ion homeostasis. Iron and zinc, although required in smaller quantities, are crucial micronutrients that function as cofactors in redox enzymes, transcriptional regulators, and antioxidant defense systems. Their efficient acquisition and utilization ensure the maintenance of electron transport, DNA replication, auxin metabolism, and stress tolerance.

From an agricultural perspective, unravelling these biochemical pathways has far-reaching implications. Enhancing nutrient use efficiency (NUE) through the manipulation of transporters, enzymes, or transcription factors can reduce fertilizer dependency and mitigate environmental pollution caused by nutrient runoff. Similarly, the knowledge of Fe and Zn transport and metabolism underpins biofortification strategies to improve the nutritional quality of staple crops, thereby addressing global challenges of hidden hunger and malnutrition.

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ISSN : 2583-0910
Agri-India TODAY
visit us at www.agriindiatoday.in
Peer reviewed monthly newsletter

Article ID : 05/XI/12/1125

BLOCK CHAIN & TRACEABILITY IN AGRI-SUPPLY CHAINS: TRUST, SAFETY & PREMIUM MARKETS

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Introduction

When you scan the QR code on a box of mangoes you buy at the grocery store, you can see the farm's location, the farmer's identity, the pesticide records, the harvest date, and even the route taken to arrive to your city. It's not futuristic because it's already happening in several parts of India. This digital transparency is powered by block chain technology, a secure, unhackable digital ledger that records every event or transaction in a supply chain. Block chain has the potential to transform agriculture by promoting confidence in the legitimacy, security, and equity of food transactions. Food transit from farm to fork is being revolutionized by block chain and associated digital tools like QR codes, IoT sensors, and smart contracts in response to customer demands for traceable, organic, and ethical food.

Importance

Traceability is now necessary in the global food industry; it is no longer an option. Exports worth millions of dollars can be disrupted by a single instance of pesticide residue, adulteration, or mislabelling.

- **Consumer trust:** Shoppers now want proof not promises that their food is safe, authentic, and sustainable.
- **Regulations:** The EU, US, and Gulf markets increasingly require digital traceability for imports, especially organic produce.
- **Food safety:** Quick trace-back during contamination events can save time, money, and public health.
- **Fair payments:** Digital records ensure farmers are paid accurately and promptly.

In India, with its fragmented supply chains and millions of smallholders, block chain brings transparency, efficiency, and equity are the three things long missing in traditional systems.

Understanding block chain in simple terms

Imagine block chain as a shared digital notepad where entries are permanent and cannot be removed or changed. A "block" is created by each transaction, whether it is a farmer selling produce, a dealer grading it, or a processor packing it. These bricks create a "chain" by connecting with one another chronologically.

No one person can manipulate the ledger because each participant has a copy. The information is permanent, auditable, and verifiable in terms of its origin, quantity, quality, time, and location.

Agri-supply chains & block chain enables

- **End-to-end visibility:** Every stage from production to retail is recorded.
- **Authentication:** Prevents mislabeling or mixing of organic and conventional produce.
- **Smart contracts:** Automatically trigger payments when conditions are met (e.g., delivery confirmation).
- **Premium market access:** Exporters can prove quality to international buyers easily.

Stepwise manner of working pattern

Let's trace the journey of a block chain enables the product say, a pack of organic Alphonso mangoes from Ratnagiri:

1. **Farm level:** The farmer logs crop details seed source, fertilizers, harvest date using a mobile app or a KVK-supported platform.
2. **Aggregation:** A cooperative verifies produce quality; the batch gets a QR code.
3. **Processing:** Cold storage or packaging data (temperature, handling) is uploaded automatically via IoT sensors.
4. **Logistics:** GPS-tagged trucks record the route and time.
5. **Retail:** The final QR code integrates all this data one scan reveals the entire journey.

The Indian context where innovation meets necessity

India's agri-digitalization is accelerating, with government missions and startups driving blockchain pilots across commodities.

1. Coffee Board of India

One of the earliest adopters — launched a blockchain-based coffee marketplace where consumers can trace beans back to estates in Karnataka or Tamil Nadu, ensuring fair pricing for growers.

2. APEDA (Agricultural & Processed Food Products Export Development Authority):

Promoting blockchain traceability for **organic basmati rice, mangoes, and spices**, especially for EU and Gulf exports.

3. State initiatives:

- **Maharashtra & Andhra Pradesh** are testing block chain for onion and chilli supply chains to ensure fair payments.
- **Kerala** is exploring block chain to certify organic spices and medicinal plants for export.

4. Private startups

Companies like Farmonaut®, Agri10x, and Agri Chain are offering blockchain-based traceability and digital ledgers to farmer producer organizations (FPOs), cooperatives, and agribusinesses. Farmonaut, for instance, helps track crop health via satellite imagery integrated with blockchain records ensuring both physical and digital transparency.

The farmer's perspective transparency pays

For farmers, block chain means more than technology it means trust and fair reward.

Earlier, we sold turmeric to middlemen who mixed it with others and took the premium," says **Ravi Naik**, a turmeric grower from Erode, Tamil Nadu. "Now, with digital traceability, our cooperative sells certified organic turmeric directly to buyers in Europe and we get paid faster and better.

Key benefits farmer's experience:

- Higher prices for traceable, organic, and fair-trade products.
- Faster payments through automated smart contracts.
- Reduced disputes due to clear, verified data.
- Recognition the buyers can see the farmer's name and location, fostering emotional connection.

Economic and export implications

The global organic food market is projected to exceed USD 400 billion by 2030. Indian farmers and Agri-entrepreneurs can claim a slice of that if they can prove traceability and authenticity.

- **Exports:** Block chain ensures compliance with strict residue and labeling norms.
- **Premium markets:** Certified traceable produce fetches 15–25% higher prices.
- **Reduced losses:** Transparent logistics and fewer intermediaries mean more income stays with the producer.
- **Investment attraction:** Traceable systems build confidence among financiers and buyers.

Challenges in scaling block chain in Indian agriculture

While promising, block chain adoption still faces ground-level hurdles:

1. **Data entry reliability:** Garbage in, garbage out — systems rely on accurate, real-time data from multiple players.
2. **Connectivity gaps:** Rural areas still struggle with internet access for real-time syncing.
3. **Cost and complexity:** Smallholders and FPOs need training and affordable solutions.
4. **Interoperability:** Different block chain systems must "talk" to each other to avoid fragmentation.
5. **Trust in digital records:** Farmers and traders must feel confident that technology serves them, not controls them.

Solutions lie in user-friendly mobile interfaces, cooperative-led models, and government-backed open-source platforms that reduce cost barriers.

Policy & institutional support

- **Digital Agriculture Mission (2021–2025):** Encourages use of digital platforms and data interoperability.
- **E-NAM (National Agriculture Market):** Integrating quality certification and traceability modules.
- **APEDA & Spices Board:** Building digital traceability systems for export certification.
- **NABARD & FPOs:** Funding pilot blockchain programs for smallholders.

Steps for trusted, transparent food chains

Imagine a food system where every step from seed to shelf is visible, verifiable, and fair. Block chain makes this vision possible. It replaces opaque, paper-based supply chains with digital trust.

In the coming decade, combining block chain, IoT sensors, and AI analytics will make agriculture more efficient and accountable. Farmers will gain recognition, consumers will gain confidence, and the planet will gain sustainability.

Conclusion

Food is not just about taste or price anymore it's about trust. And in the new Agri-economy, trust is built through technology. By embedding transparency into every transaction, block chain transforms how food is produced, traded, and valued. It bridges the trust gap between farmer and consumer, rural and urban, local and global. From the humble QR code on a mango to a digital ledger tracking organic basmati rice across continents, India’s journey toward trust-based agriculture is well underway.

ISSN : 2583-0910
Agri-India TODAY
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Article ID : 05/XI/13/1125

COLLAGEN-BASED PRODUCTS IN AGRICULTURE: TURNING WASTE INTO WEALTH

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Abstract
Collagen, traditionally known for its role in cosmetics and health industries, is now gaining attention in agriculture as a sustainable bioresource. Derived from animal and agro-industrial waste, collagen-based products such as biofertilizers and soil conditioners enhance soil health, nutrient uptake, and plant growth. This approach not only promotes sustainable farming but also transforms organic waste into valuable agricultural inputs, supporting a circular economy model.

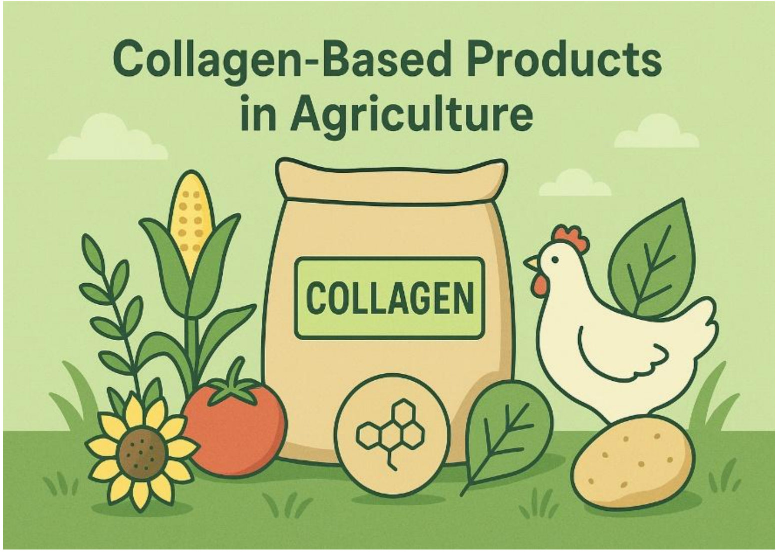
Keywords: Collagen hydrolysate; Biofertilizer; Sustainable agriculture; Waste utilization; Circular economy

Introduction
The word *collagen* usually evokes thoughts of skincare, beauty products, and health supplements. However, this remarkable protein is now making its way into a surprising domain **agriculture**. Researchers and innovators have found that collagen, a protein naturally abundant in animals, possesses tremendous potential to convert waste materials into valuable agricultural resources. This growing interest in collagen-based agricultural products not only promotes sustainable farming but also provides an effective solution to the pressing issue of agro-industrial waste management.

Understanding Collagen and Its Sources
Collagen is the most abundant protein in the animal kingdom, forming the primary structural component of skin, bones, tendons, and connective tissues. It provides elasticity, strength, and resilience to biological systems. In industrial contexts, collagen is extracted mainly from by-products of meat, fish, and poultry processing—such as hides, scales, bones, and connective tissues.

Traditionally, these materials were discarded as waste, posing serious environmental concerns. However, technological advances have enabled the extraction of hydrolyzed collagen, gelatin, and collagen peptides from these sources, giving new life to what was once considered refuse. The result is a growing industry that aligns perfectly with the principles of a circular bioeconomy—where waste materials are recycled into valuable resources.

Collagen’s Role in Sustainable Agriculture
The agricultural sector is increasingly searching for eco-friendly alternatives to chemical fertilizers, synthetic plastics, and conventional animal feed. Collagen-based products provide a natural, biodegradable, and nutrient-rich option that benefits both crops and livestock.



1. Biofertilizers and Soil Conditioners

Hydrolyzed collagen is rich in organic nitrogen and amino acids, which are essential for plant growth. When used as a biofertilizer, it enhances soil fertility by stimulating microbial activity and improving the soil's organic content. Unlike synthetic fertilizers, collagen-based formulations release nutrients slowly, minimizing leaching and ensuring long-term soil health. Farmers using these fertilizers often report better crop vigor, higher yields, and improved soil structure.

2. Seed Coating and Growth Enhancement

Collagen-based biopolymers are used to coat seeds, offering multiple benefits. They create a moisture-retaining layer that aids germination, especially under water-stressed conditions. The natural amino acids in collagen also act as growth stimulants, encouraging root development and early seedling establishment. These coatings are biodegradable and non-toxic, making them suitable for organic farming.

3. Animal Feed Supplements

In livestock and aquaculture industries, collagen hydrolysates are gaining popularity as nutritional supplements. They are easily digestible and contain essential amino acids like glycine and proline, which support bone health, muscle development, and joint flexibility. Inclusion of collagen peptides in feed mixtures enhances the overall health and productivity of poultry, dairy cattle, and fish.

4. Biodegradable Films and Packaging

One of the most exciting applications of collagen lies in bioplastics and edible films. Traditional plastic materials used in farming—such as mulching films and seed trays—pose serious environmental hazards. Collagen-based biopolymers, on the other hand, decompose naturally without leaving harmful residues. They can even be enriched with nutrients to serve as a dual-purpose material: packaging and soil enhancer.

Environmental and Economic Benefits

The use of collagen-based products offers dual advantages: environmental sustainability and economic opportunity.

- **Waste Utilization:** The conversion of animal processing by-products into valuable agricultural inputs reduces the burden of waste disposal.

- **Eco-Friendly Agriculture:** Collagen-based fertilizers and coatings promote organic farming, reducing dependency on synthetic chemicals.
- **Improved Soil Health:** Collagen adds organic carbon to the soil, improving its structure, water retention, and microbial biodiversity.
- **New Income Streams:** Farmers and rural entrepreneurs can establish small-scale collagen extraction or processing units, creating local employment and income opportunities.
- **Carbon Footprint Reduction:** By recycling animal waste and reducing synthetic fertilizer use, collagen-based products help mitigate greenhouse gas emissions.

In essence, collagen enables agriculture to adopt a zero-waste approach—closing the loop between livestock production and crop cultivation.

Research and Technological Advancements

Research institutions are actively exploring innovative extraction methods that make collagen recovery more efficient and environmentally safe. Techniques such as enzymatic hydrolysis and membrane filtration are being used to extract high-purity collagen from fish scales and poultry waste. These methods ensure minimal chemical usage and lower energy consumption.

Furthermore, cutting-edge research is moving toward plant-based recombinant collagen, where genetically modified crops like tobacco or corn are engineered to produce collagen-like proteins. This innovation could revolutionize collagen production by offering a vegan and ethical alternative for agricultural applications.

Challenges Ahead

Despite its promise, the widespread adoption of collagen-based products faces some challenges. The production cost of hydrolyzed collagen remains relatively high compared to synthetic fertilizers. Additionally, farmers need greater awareness of its benefits and proper application methods. Establishing a strong value chain from waste collection to processing and distribution is crucial to make collagen-based agricultural solutions economically viable.

Conclusion

Collagen-based products are redefining the relationship between agriculture, industry, and the environment. By transforming animal by-products into fertilizers, coatings, and bioplastics, collagen embodies the concept of *turning waste into wealth*. It supports sustainable farming, enhances soil and animal health, and reduces the ecological footprint of modern agriculture.

As technology advances and awareness grows, collagen could soon become a cornerstone of green innovation helping farmers cultivate not only crops but also a cleaner, healthier planet.

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ISSN : 2583-0910
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Article ID : 05/XI/14/1125

DEEP LEARNING AND WEATHER DATA FOR PEST AND DISEASE DIAGNOSIS IN AGRICULTURE

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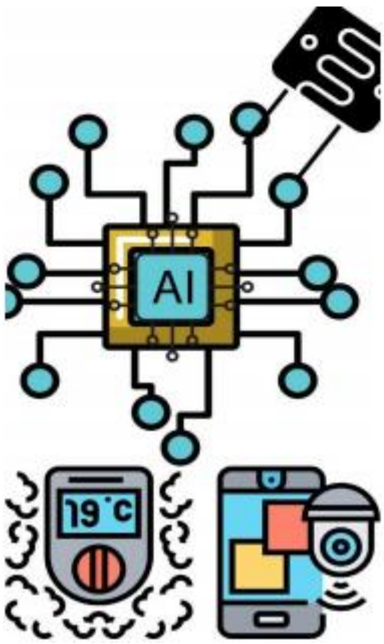
Introduction

Climate change, recurring pest and disease out breaks, and growing input prices are all posing growing challenges to modern agriculture. Traditional methods of handling these risks, which are frequently focused on visual observation and reactionary reactions, can cause significant crop losses and financial setbacks by delaying prompt action. Emerging technologies like Deep Learning, a subfield of artificial intelligence (AI), are showing great promise in addressing these problems. These technologies enable farmers to make proactive, well-informed decisions to save crops and increase farm resilience by combining real-time weather data from climate sensors with early detection capabilities.

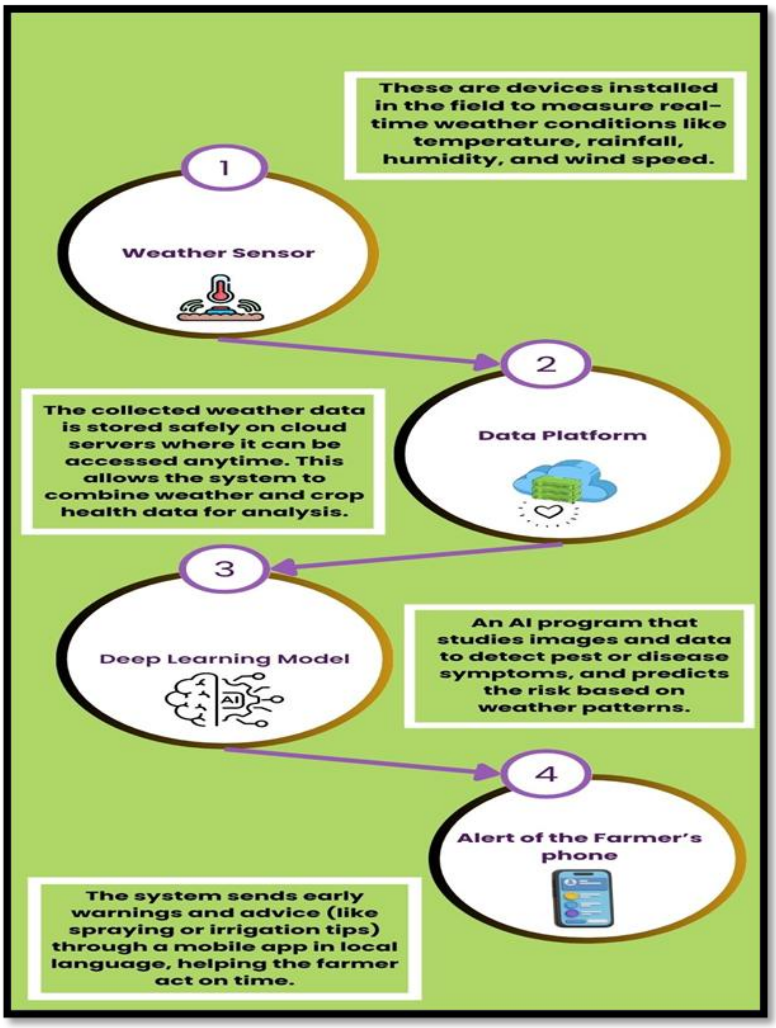


Understanding the Technology: AI, Machine Learning, Deep Learning, and Data Science

The term "Artificial intelligence" (AI) describes the replication of human intellect in devices and systems that can reason, learn, make decisions, and solve problems. Machine Learning (ML), a crucial area of artificial intelligence, deals with techniques that let computers learn from data, spot trends, and make predictions or judgments based on data without explicit programming. Deep Learning (DL), a cutting-edge subfield of machine learning, makes use of artificial neural networks (ANNs) that are fashioned after the structure of the human brain. These networks are capable of processing large datasets and identifying intricate elements in text, audio, and pictures. Deep learning is being used in agriculture to accurately identify and categorize pests and illnesses from crop photos. Data Science plays a complementary role by integrating statistics, programming, machine learning, and data visualization to extract meaningful insights from large datasets. It enhances predictive capabilities and supports informed decisions to optimize agricultural operations.

How Deep Learning Techniques Help Identify Pests and Diseases

Deep Learning enables computer systems to recognize symptoms of plant diseases and pest attacks by training on thousands of annotated images. A farmer can use a smartphone to snap a picture of a sick leaf and upload it via a specific mobile application once the system has been taught. Within seconds, the system can analyze the image and identify the pest or disease.



This enables early detection, which is critical for timely intervention and damage prevention. Moreover, when this image-based diagnosis is combined with location-specific weather data, the system can improve the accuracy of identification and even provide context-aware recommendations.

The Crucial Role of Weather in Pest and Disease Prediction

The emergence and spread of agricultural diseases and pests are significantly influenced by the weather. Rainfall, temperature, relative humidity, wind speed, and other factors all have a significant impact on the virulence and life cycle of diseases and insect pests. Sensors at weather observation stations gather data on various atmospheric characteristics in real time. The results are more precise and location-specific when Deep Learning models are combined with this high-resolution meteorological data. If a farmer reports black spots on banana leaves in an area with high rainfall and high humidity, the system may identify this as a potential instance of Sigatoka, a fungal disease that

thrives in such circumstances. In addition to diagnosis, the system may provide weather-based preventive advice for things like when to apply fungicides, when to schedule irrigation, and other such tasks.

Field-Level Sensors and Digital Agriculture

Government stations are no longer the only places with weather sensors. In order to gather data at the field level, many forward-thinking farmers are already setting up autonomous weather stations in their own fields. Farmers get a sharper and more accurate picture of their agricultural environment because to this localized information, which is frequently more accurate than general area forecasts. Farmers may get real-time pest and disease warnings, irrigation suggestions, crop health monitoring updates, and site-specific agro-advisories by combining this data with cloud-based platforms or mobile applications. This improves decision-making and boosts farm production.

These integrated systems are becoming more and more popular among farmers that raise crops like rice, tomato, brinjal, bananas, and black pepper. These methods have proven particularly useful in areas with significant pest and disease burden and climatic unpredictability, including portions of Kerala, Tamil Nadu, and Maharashtra. The India Meteorological Department (IMD)-supported Agromet Field Units (AMFUs) are essential because they enable village-level agriculture planning and offer localized weather monitoring. In order to help farmers prepare ahead of time, agro-advisories are distributed every Tuesday and Friday based on the medium-range weather forecasts issued by the IMD.

The integration of Deep Learning technology with real-time meteorological data has greatly advanced the objective of climate-smart agriculture. By enabling early warning systems for pest and disease outbreaks, these technologies enable targeted and timely treatments that can significantly reduce crop losses. This approach promotes sustainable resource management, lowers the overuse of chemical pesticides, and boosts agricultural output and farmer revenue. The main benefit is that it shifts the focus from reactive to proactive crop management, empowering farmers to make educated choices before damage is done. In the face of increasing climate unpredictability, these types of innovations are crucial for developing agricultural systems that are robust, flexible, and financially viable.

Aphids on Cowpea

Black pepper Wilt Banana

Sigatoka leaf spot

Article ID : 05/XI/15/1125

EDIBLE PACKAGING: A PALATABLE SOLUTION TO PLASTIC POLLUTION

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Abstract

Edible packaging, made from natural and biodegradable materials like seaweed, rice, proteins, and biopolymers, offers an innovative solution to reduce plastic waste and promote sustainability in the food industry. It not only helps in minimizing environmental pollution but also enhances food safety and shelf life. Despite benefits like eco-friendliness and consumer convenience, challenges such as limited mechanical strength, regulatory hurdles and high production costs still remain. Ongoing research and technological advancements are improving its properties and commercial viability, making edible packaging a promising alternative for achieving future sustainability goals.

Key words: Edible packaging, biopolymers, sustainability, biodegradable films, seaweed packaging, food safety, eco-friendly packaging, circular economy.

Introduction

Edible packaging, made from materials such as seaweed, rice and other edible substances, is emerging as a promising solution to reduce waste and environmental pollution caused by traditional plastic packaging. This innovative approach not only aims to decrease the reliance on petroleum-based resources but also enhances the sustainability of food packaging by being biodegradable and sometimes even consumable. The development and application of edible packaging are gaining momentum, driven by the need for more sustainable practices in the food industry. The following are key aspects of edible packaging, focusing on its materials, benefits, challenges and future prospects.

Materials Used in Edible Packaging

i) Seaweed: Seaweed is a prominent material in edible packaging due to its abundance and sustainability. It contains valuable polysaccharides like alginate, carrageenan and agar, which can be processed into biodegradable films and coatings (Nešić *et al.,* 2024) (Balamurugan *et al.,* 2024). Additionally, rice and other grains are increasingly being explored for their potential in creating edible packaging, offering unique properties that contribute to waste reduction and sustainability in food production (Trafialek & Kolanowski, 2023).

ii) Biopolymers: Other materials include biopolymers derived from proteins, lipids and polysaccharides, which are used to create films that are edible and biodegradable (Janjarasskul & Krochta, 2010) (Ghosh & Katiyar, 2021). These materials not only provide a sustainable alternative to conventional plastics but also enhance the preservation and safety of food products (Rocha *et al.,* 2018). The integration of edible packaging systems in food production represents a significant advancement in sustainable practices, addressing both environmental concerns and the need for effective food preservation (Trafialek & Kolanowski, 2023). The exploration of various natural materials in edible packaging continues to expand, highlighting the potential for innovative solutions to environmental challenges in food production.

iii) Innovative Combinations: Some edible packaging materials are made from combinations of corn protein, cellulose and other natural substances to enhance their mechanical properties and make them more durable (Sufang, 2018). This approach not only utilizes renewable resources but also aims to improve the functionality and consumer acceptance of edible packaging solutions.

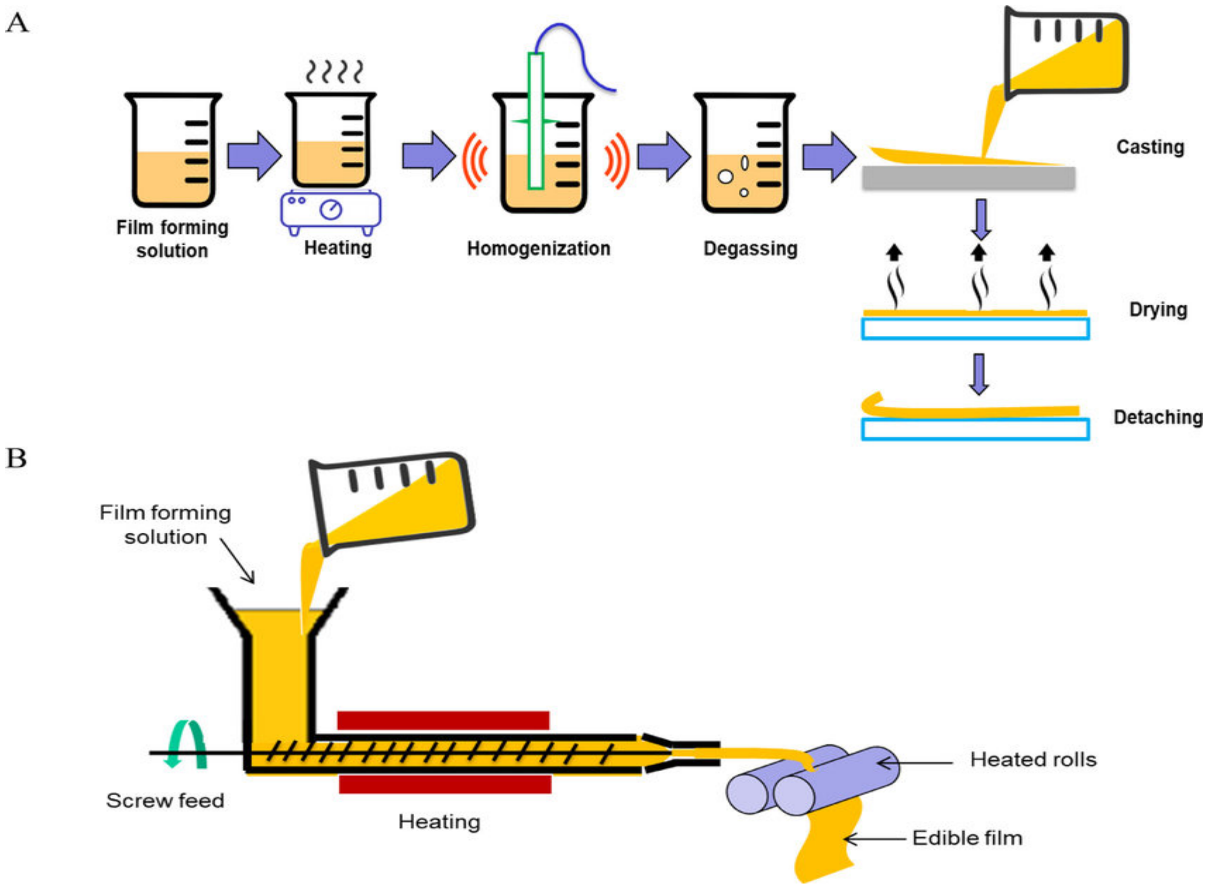

Fig. 1: Schematic representation of the edible film formulation: (A) Casting method and (B) extrusion method. Source: (Kumar *et al.,* 2022)

Benefits of Edible Packaging

i) Environmental Impact: Edible packaging significantly reduces plastic waste, as it is biodegradable and often made from renewable resources. This helps in conserving ecosystems and reducing pollution (Edible Food Packaging- An Overview, 2023) (Neogi & Upadhyaya, 2021).

ii) Food Safety and Quality: These materials can extend the shelf life of food products by providing a barrier against moisture and oxygen, thus maintaining food quality and safety (Trafialek & Kolanowski, 2023).

iii) Consumer Convenience: Products like the Ooho capsules, which encase liquids in a seaweed-based film, offer convenience and reduce waste during events like marathons (Patel, 2019).

4. Challenges and Considerations

i) Mechanical Properties: Edible packaging materials often face challenges related to their mechanical strength and water barrier properties, which can limit their application in certain contexts (Balamurugan *et al.,* 2024).

ii) Regulatory and Consumer Acceptance: There are hurdles related to regulatory approvals and consumer acceptance, as edible packaging must meet food safety standards and gain consumer trust (Janjarasskul & Krochta, 2010) (Neogi & Upadhyaya, 2021).

iii) Cost and Scalability: The cost of production and scalability of edible packaging solutions are significant challenges that need to be addressed to make them commercially viable (Neogi & Upadhyaya, 2021).

Future Prospects

i) Research and Development: Ongoing research is focused on improving the properties of edible packaging through the incorporation of nanotechnology and other advanced materials to enhance their functionality and durability (Ghosh & Katiyar, 2021). The future of edible packaging looks promising as innovations continue to emerge, potentially transforming the food industry and contributing to sustainability goals.

ii) Market Expansion: The market for edible packaging is expanding, with increasing interest from both developed and developing countries. Companies are exploring new materials and methods to make edible packaging more accessible and affordable (Trafialek & Kolanowski, 2023) (Neogi & Upadhyaya, 2021). This growing interest reflects a broader shift towards sustainable practices in the food industry, indicating that edible packaging could play a crucial role in reducing environmental impact.

iii) Sustainability Goals: As the global focus on sustainability intensifies, edible packaging is poised to play a crucial role in reducing the environmental footprint of the food industry (Nešić *et al.,* 2024) (Balamurugan *et al.,* 2024). The integration of edible packaging into mainstream food production could significantly contribute to achieving sustainability goals, addressing both environmental and consumer needs effectively.

Conclusion

While edible packaging presents a promising solution to the environmental challenges posed by traditional packaging, it is important to consider the broader context of its implementation. Factors such as consumer behaviour, regulatory frameworks and economic viability will play critical roles in determining the success and widespread adoption of edible packaging solutions. As research and development continue to advance, these materials have the potential to significantly contribute to a more sustainable future.

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ISSN : 2583-0910
Agri-India TODAY
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Article ID : 05/XI/16/1125

ELECTROHYDRODYNAMIC DRYING: A NOVEL NON-THERMAL TECHNOLOGY

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Introduction

Drying is a thermo-physical and physicochemical operation that deals with the heat and mass transfer from the system (drying materials) to the surroundings. This operation in the food context plays a vital role in preserving the shelf life of the products by removing moisture from the food to a predetermined level to reduce or arrest microbial attacks. Although it has been one of the oldest and most widely used preservation techniques, it's associated to have adverse effects on the physicochemical, nutritional, and sensory attributes of dried foods resulting in the degradation of the overall quality of the products (Lin *et al.,*1998; Gunasekaran, 1999; Jeyamkondan *et al.,* 1999). In light of these concerns, scientists are working on novel non-thermal drying technologies to minimize the deleterious effect on foods caused by heat. Non-thermal technologies are gaining momentum in recent years as it does not generate significant heat but are able to create moisture migration within a short processing time and eventually making the process more efficient, environmentally friendly, and retaining the important properties of the food. Non-thermal drying technologies include Electrohydrodynamic drying (EHD), electrohydraulic discharge, pulsed electric field (PEF), and cold plasma (CP).

EHD is a branch of fluid mechanics that deals with the movement of fluids under the influence of a high-voltage electric field. Whenever a high-voltage electric current flows through an electrode of small radii, the air around the electrode gets ionized and tends to move under the influence of an electric field (Goodenough *et al.,* 2007). This movement of ionized particles is known as primary flow. The ionized particles collide with the neutral air particles transferring their momentum to the neutral particles and driving them toward the collecting electrode where the drying materials are kept for drying (Fig.1). The movement of neutral particles is considered as a secondary airflow and the collective movement of ions and neutral particles is known as "ionic wind or corona wind" which plays a profound role in EHD drying (Bashkir *et al.,* 2020). The EHD drying takes place between the inception voltage (the minimum voltage necessary for causing ionization of air) and the breakdown voltage (the voltage at which volumetric or ohmic heating takes place).

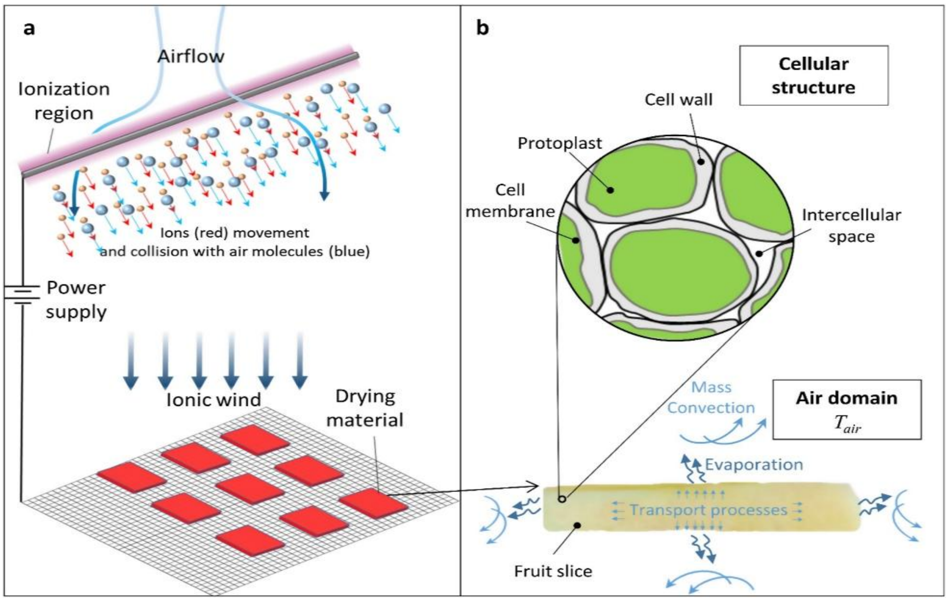

Fig. 1 (a) Schematic of electrohydrodynamic drying setup with a wire-to-mesh configuration; (b) water transport together with the different cellular environment in which the water resides **(**Iranshahi et al., 2022)

Transport phenomenon during EHD drying of biological materials.

Biological materials are composed of aggregated cells with pores in between and these cells are connected to each other by different materials for example middle lamella, in plant tissues, cements the adjacent cells. The cells are comprised of a cell wall, cell membrane, and cytoplasm (Huang *et al.,* 2012). The water is absorbed within the cells and in the porous space (Intercellular pores) between the cells. When EHD drying operation is employed, a series of complex phenomena takes place to remove moisture from the materials. During the entire process of drying all major water transport mechanisms in different regions are encapsulated in Fig. 2

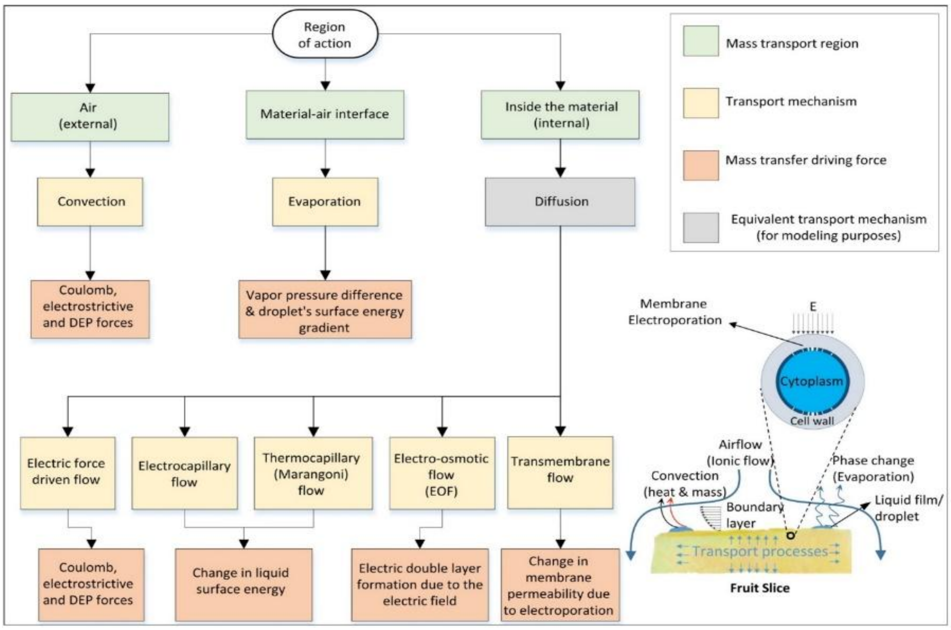

Fig. 2 – Water transport mechanisms classification based on the region of main action and origination together with a schematic illustration of transport mechanisms (Iranshahi *et al.,* 2022)

Convective moisture removal from the drying materials

When the ionic wind interacts with the drying materials, it reduces the thickness of the boundary layer at the material-air interface as a result the mass transfer resistance reduces causing accelerated convective dehydration. This is the only moisture removal phenomenon that occurs in the air region. The main driving force of convective moisture removal is the difference in vapor pressure at the material and the atmosphere (Martynenko *et al.,* 2017). The vapor pressure in the material is enhanced by the different electrically induced forces of ionic wind when interacting with the drying materials. The three forces that interact with the drying materials include coulomb, electrostrictive and dielectrophoretic (DEP) forces (Iranshahiet al., 2020; Velev and Bhatt, 2006). The coulomb force is the net gain momentum of the ionized particles under the influence of an electric field whereas the DEP and electrostrictive forces cause the movement of neutral particles when subjected to a non-uniform electric field owing to the interaction of the particle's dipole and spatial gradient of electric field and/or electric permittivity. The coulomb force is more dominant than the rest of the two forces wherein these two forces are conditional as such that the electrostrictive force is taken into consideration only in a large gradient of air density and the DEP gets into the picture in case of high frequency alternating electric field is applied.

Evaporation at material-air interface

The vapor pressure difference between the surface of the food and the surrounding air is the main driving force accompanied by the droplet's surface energy gradient. When the ionic wind interacted with the water droplets present in the drying material, the water molecules realign themselves in the direction of the electric field. As a result, the hydrogen bond between the molecules gets disintegrated reducing the amount of energy required for evaporation (Atungulu, 2007). The ordered alignment of the water molecules also decreases the entropy (the thermal energy that does not produce useful work) and thus making the EHD drying more efficient. In addition, the energy required for evaporation is taken from the sensible heat of the dried material as well as the surrounding air resulting in a decrease in temperature which is also regarded as evaporative cooling. Due to the realignment of water molecules, the contact angle of the droplet reduces causing a direct negative impact on surface energy as both parameters are directly related (Vancauwenberghe *et al.,* 2013). The low surface tension even assists to evaporate the water molecules with ease.

Water transport mechanism inside the material

The mass transfer mechanism inside the material is different from the mass transfer that occurs in the region of air and material-air interface. The moisture present inside the cells exists in the vapor phase as there is an assumption that no condensation takes place inside the cell's capillaries whereas moisture remains in the liquid state between the intercellular spaces or pores (Prawirantoet *al.,* 2018). Therefore, different types of mass transfer techniques will act in the moisture removal from inside the material to its surface. The following are the different mass transfer mechanisms for water removal during EHD drying:

Electric-driven flow: It deals with the effect of electrical forces on the movement of water vapor present inside the porous membrane. The electrical forces such as coulomb, electrostrictive, and DEP forces drive out the water vapor that exists in the capillaries of the tissues. This movement of vapor is caused due to the generation of uneven charges on the surfaces of the different parts of cells such as the cell wall, cell membrane, etc.

Electrocapillary and thermocapillary flow: In the phenomenon of electrocapillary flow, the effect of the electric field on water available in the intercellular pores of the material is taken into account, here the water is in a liquid state unlike in electric-driven flow where the water present inside the cell exist in vapor phase is of concern. Due to the electro-capillary effect, the interfacial tension is created between the cell wall and the water causing water movement inside the material (Chakraborty, 2014). Thermocapillary flow induces due to the movement of water at the material-air interface and inside the material driven by the temperature gradient (Schonfeld, 2008). The temperature gradient is the result of the difference in the rate of evaporation between the air-liquid interface and the generation of heterogeneous heat inside the material. Due to this heterogeneous heat, the surface tension of the material varied in different parts of the material as a result water tends to move to a cooler position and this movement is called thermocapillary flow. Both the electrocapillary and thermocapillary flow is driven when there is a change in the liquid’s surface tension.

Electro-osmotic flow (EOF): The electric charge in different parts of the material also induces EOF. The charges affect the ion distribution of water present in the food material to form a layer called an electrical double layer (EDL) (Li, 2004). The EDL is composed of two layers: compact layers (sessile balanced charges) and diffuse layers (mobile charges) where the counter ions are densely distributed. The electrical field induces electrical forces that drive the counterions in the diffuse layer to thrust the fluid movement. This movement of fluid due to the formation of EDL is EOF and the phenomenon is known as electro-osmosis.

Transmembrane flow: The Ionic wind interacts with the food material and increases the natural potential difference (generally 1 kV in various food materials) across the cell membrane. Consequently, the existing size of the pores increases or the new pores are created causing accelerated transmembrane water flow. The phenomenon of creating new pores and the enhancement in the size of the existing pores is called electroporation. An increase in the transmembrane flow is mainly associated with the increase in permeability of the membrane and the electrokinetic effects (Smith and Weaver, 2011).

Application of Electrohydrodynamic drying (EHD) in the food industry

Electrohydrodynamic (EHD) drying has gained considerable attention in the food sector due to its non-thermal nature, which helps preserve sensitive bioactive compounds and structural integrity of dried products. Unlike conventional thermal drying methods, EHD is particularly suitable for heat-sensitive biomaterials such as perishable fruits and vegetables, herbs, medicinal plants, as well as nutraceutical and functional food ingredients like probiotics, enzymes, and starter cultures. By minimizing thermal degradation, EHD drying ensures superior product quality in terms of color, flavor, texture, and nutritional value, making it highly relevant for the production of high-value functional and specialty foods.

Effect of pre-treatment on EHD

Most conventional drying techniques require pre-treatments to enhance efficiency, and similar approaches have been explored for electrohydrodynamic (EHD) drying. For example, Ni et al. (2020a) reported that ultrasound, sucrose ester solution, and alkaline treatments improved the EHD drying of goji berry by reducing the blocking effect of its waxy outer layer. In a related study, ultrasonic pre-treatment at 200 W for 20 min at 35 °C significantly enhanced the drying rate and preserved product quality (Ni et al., 2020 a,b). Since mass transfer in most food materials during

EHD is diffusion-limited, simple pre-treatments such as peeling, slicing, and blanching have also been shown to accelerate drying and improve final quality (Alemrajabi et al., 2012 Taghian Dinani et al., 2015a). However, the necessity and effectiveness of such pre-treatments largely depend on the food matrix, particularly its composition and physicochemical properties such as thermal, dielectric, and microstructural characteristics (Martynenko and Kudra, 2019).

Effect on drying kinetics

A comparative study on banana slices reported distinct drying patterns under electrohydrodynamic (EHD) and microwave (MW) drying (Esehaghbeygi et al., 2014). MW drying followed a two-stage process, beginning with a constant rate period and transitioning to a falling rate period, whereas EHD drying occurred entirely in the falling rate period, indicating dominance of internal moisture transfer. EHD also demonstrated superior energy efficiency and product quality. Similarly, Ding et al. (2015) observed that increasing the applied voltage during EHD drying of carrot slices enhanced drying rates, while ensuring better retention of carotene and higher rehydration ratios compared to oven drying. In another study on tomato slices, Esehaghbeygi and Basiry (2011) compared EHD with air drying and reported differences in quality attributes and energy requirements, noting a slight increase in surface temperature with lower applied voltages. Bardy et al. (2016) further compared drying kinetics of methylcellulose gel and mango slices under forced convection and EHD, finding that EHD significantly reduced drying time in mango and improved energetic efficiency by nearly two-fold compared to methylcellulose gel.

Effect on microstructural properties

EHD drying has been shown to influence the microstructural and physicochemical characteristics of food materials. Singh et al. (2015) reported that EHD treatment significantly altered wheat protein conformation by affecting hydrogen bonding patterns, leading to noticeable shifts between low- and high-frequency bands. Differential scanning calorimetry (DSC) analysis of EHD-dried mushroom slices further revealed reductions in enthalpy at both high and low electric field intensities, which were attributed to the aggregation of denatured proteins (Taghian Dinani et al., 2015b). Similarly, Cao et al. (2004) observed that EHD treatment affected fissuring, drying behavior, and germination rate of rough rice, with comparable results also reported for wheat. In another study, Esehaghbeygi (2012) demonstrated that high-voltage electric fields (HVEF) applied during batch drying of rice accelerated the drying process but also increased breakage susceptibility. These findings suggest that while EHD enhances drying efficiency, its impact on protein structure, textural integrity, and grain stability must be carefully considered to optimize process conditions.

Effect on shrinkage

The drying behavior of radish slices under different drying methods was investigated by Bajgai and Hashinaga (2001a), who reported that EHD drying was more effective than convective and ambient methods. Radish slices dried using EHD exhibited reduced shrinkage, indicating greater retention of natural components, along with lower solid losses during soaking, improved water absorption, and better color quality. Moreover, the drying rate under EHD was approximately 1.5 times faster than that of control treatments. Similarly, Bai and Sun (2011) examined the effect of EHD on shrimp and found that it significantly reduced shrinkage, minimized solid loss, and enhanced water absorption, rehydration ratio, and sensory attributes such as color and texture. Their findings highlighted that EHD not only accelerates drying but also ensures superior product quality compared to conventional drying approaches.

Effect on color

Li et al. (2006) reported that EHD treatment of okara cake led to noticeable browning, while Martynenko and Zheng (2016) observed negative effects on the color of apples during EHD drying. In a related study, Chen and Martynenko (2018) produced blueberry leather and evaluated how variations in pureeing and drying methods influenced the quality of the final product.

Overall, EHD-induced ionic wind has been reported to be more efficient than mechanically induced convective drying, making it particularly suitable for perishable solid and semi-solid foods with high moisture content. The key advantage of EHD over conventional drying technologies lies in its higher drying efficiency coupled with lower energy consumption, and with precise control of product and process variables, notable improvements in both product quality and energy savings can be achieved.

Conclusion

Conventional drying technologies often cause considerable deterioration of the organoleptic and nutritional quality of foods, primarily due to exposure to high temperatures. In this context, electrohydrodynamic (EHD) drying emerges as a promising non-thermal technique, particularly suitable for high-value foods and products containing heat-labile components. This review provides updated insights into the mechanisms of EHD drying and its diverse applications in the food industry, while also highlighting the need for a deeper understanding of the underlying science. As a novel approach, EHD has been compared with conventional drying techniques and explored in combination with them to achieve specific advantages. Although large-scale commercialization requires further research, integrating EHD with established drying methods could unlock synergistic benefits in terms of product quality, energy efficiency, and environmental sustainability. Overall, EHD demonstrates proven potential as an energy-efficient technology that significantly reduces drying time while preserving the functional and sensory attributes of food.

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ISSN : 2583-0910
Agri-India TODAY
visit us at www.agriindiatoday.in

Peer reviewed
monthly newsletter

Article ID : 05/XI/17/1125

FRONTIER SCIENCES AND TECHNOLOGIES IN AGRICULTURE FOR DEVELOPED INDIA

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Introduction

Agriculture has served as the foundation of India's economy for centuries, sustaining the livelihoods of over half the population. But the challenges, such as population growth, climate change, soil degradation, and the demand for higher food production, are increasing rapidly. However, the introduction of advanced agricultural techniques and frontier sciences is becoming critical in shaping a developed India. These innovations are transforming the agricultural landscape, enhancing productivity, ensuring food security, and promoting sustainable farming practices. The global population is projected to rise to 9.7 billion by the year 2050, posing a monumental challenge: how to meet the growing demand for food without depleting our natural resources. This requires agricultural production to increase by 70% over the next three decades (Hemathilake *et al.,* 2022), necessitating a shift from traditional farming methods to innovative, sustainable approaches.

This topic explores frontier sciences and technologies that are transforming agriculture. These innovations address challenges such as resource shortages, climate change, and inefficiencies in traditional practices.

1. Challenges in Traditional Agriculture

Traditional agriculture faces several constraints, including:

- **Limited resources:** Depleting arable land and water resources.
- **Environmental impact:** Overuse of chemical fertilizers and pesticides leads to soil degradation and pollution.
- **Low productivity:** Dependence on conventional methods often results in lower yields.
- **Climate change:** Unpredictable weather patterns and global warming exacerbate agricultural risks.

Frontier technologies to overcome existing challenges:

Frontier sciences offer tools and technologies to overcome these challenges, laying the foundation for a robust and efficient agricultural sector.

Biotechnology and Gene Editing

Biotechnology has paved the way for the advancement of genetically modified (GM) crops engineered for resistance to pests, diseases, and extreme weather conditions. GM crops like golden rice, Bt cotton, and herbicide-tolerant rice have shown improved yields and reduced the need for chemical inputs. The future lies in genetic engineering and gene-editing technologies such as CRISPR, advanced CRISPR-based tools like Base Editing and Prime Editing. These technologies could potentially develop crops with enhanced nutritional content and better resistance to pests and diseases.

Table 1. Summary of crop improvement using different Genome Editing Tools

Genome Editing Tools	Accomplishments (Global)	Possible solutions to hurdles (India)
CRISPR (clustered regularly interspaced short palindromic repeats)	• Around **80 crop varieties** (41 food, 15 industrial, 6 oil, 8 ornamental, 1 fiber, and feed crop) have been developed. • **Banana**: Slow browning for prolonged shelf-life • **Rice:** Yield, disease resistance, and drought tolerance • **Wheat**: Resistance to powdery mildew	**India has been actively researching and developing the following gene-edited crops using the CRISPR/Cas9 system:** • Drought-tolerant rice and maize • Beta carotene-rich banana • High oleic and low linoleic acid groundnuts • Blast-resistant rice • Stress-tolerant tomato • CSIR-NBRI's Flagship Program
ZFNs (Zinc-finger nucleases)	• **Soybean and Corn**: Herbicide-resistant • **Mushrooms**: Non-browning • **Tomato**: High-yield • **Rice, wheat, mustard, and millets**: High-nutrition	
TALENs (Transcription activator-like effector nucleases)	• **Rice:** Resistant to bacterial blight • **Cassava:** Resistance to cassava mosaic virus (CMV) • **Soybean**: Herbicide tolerance • **Wheat**: Gluten-Free	

One of the most promising advancements is in biotechnology and gene editing. Techniques such as Genetic Modification (GMOs) and CRISPR allow for:

- **Enhanced crop resilience:** Developing varieties resistant to pests, diseases, and adverse weather.
- **Higher nutritional value:** Biofortification to combat malnutrition.
- **Reduced dependency on chemicals:** Traits like pest resistance reduce the need for pesticides.

For instance, crops engineered through CRISPR can withstand drought conditions or thrive in saline soils, ensuring stable food supplies in challenging environments.

Crop Improvement by the hands of Omics technology

Omics technology has revolutionized crop improvement by providing comprehensive insights into the genetic, proteomic, transcriptomic, and metabolomic profiles of plants. By integrating data from these advanced molecular tools, researchers can identify key genes and pathways involved in traits like yield, stress tolerance, and disease resistance. Techniques such as genome sequencing, transcriptome analysis, and metabolite profiling allow for precise manipulation of plant characteristics through marker-assisted selection, genomic editing, or transgenic approaches. This broad understanding accelerates the development of resilient, high-performing crop varieties, addressing global food security challenges while ensuring sustainability in agriculture.

Table: Summary of crop improvement using different omics technologies

Crop	Genomics	Proteomics	Transcriptomics	Metabolomics
Rice	Yield, pest resistance, drought tolerance	Stress response and grain quality improvement	Drought and pest resistance (**BPH** and **WBPH**)	Enhancing nutritional content (**Golden Rice 2.0** with higher iron and zinc)

Crop	Genomics	Proteomics	Transcriptomics	Metabolomics
Maize	Disease resistance (**Maize Lethal Necrosis**), drought tolerance	Protein content and disease resistance	Stress responses	Improving protein quality and stress tolerance
Wheat	Yield, disease resistance (**Rust**), drought tolerance	Fiber quality improvement and stress resistance	Drought (**Deguo 2**), heat (**K7903**)	Improving protein quality and nutritional content

Role of Omics Sciences

Omics sciences, including genomics, proteomics, and metabolomics, are essential for:

- **Crop improvement:** Pinpointing genes that govern desirable traits.
- **Disease resistance:** Developing diagnostic tools to combat crop diseases.
- **Animal biotechnology:** Enhancing livestock health through advanced vaccines and diagnostics.

The integration of big data analytics further accelerates the application of omics technologies, enabling precision in agricultural interventions.

Nanotechnology in Agriculture

Nanotechnology holds immense promise in agriculture by improving the delivery of nutrients and pesticides in a more targeted and efficient manner. Nano-pesticides and nano-fertilizers have the potential to enhance crop productivity. It is also revolutionizing agricultural practices by offering solutions for crop production, protection, and post-harvest management. Applications include:

- **Nano-fertilizers:** They improve nutrient delivery and reduce wastage, and enhance crop yields. As of December 2024, the Government of India has approved several nano-fertilizers under the Fertilizer Control Order (FCO) of 1985. These include nano liquid formulations of urea, di-ammonium phosphate (DAP), zinc, and copper. To support the production of these nano-fertilizers, six nano urea plants with a combined annual capacity of 26.62 crore bottles (500 ml each) and four nano DAP plants with a total annual capacity of 10.74 crore bottles (500/1000 ml each) have been established across the country.
  The government is actively promoting the application of nano-fertilizers among farmers through various initiatives, including awareness camps, field demonstrations, and the provision of drones to women's self-help groups for efficient application. These efforts aim to enhance crop yield and quality, address micronutrient deficiencies, and reduce dependency on conventional chemical fertilizers.
- **Nano-pesticides:** Target-specific solutions, which minimize environmental harm. As of December 2024, the Government of India has not officially approved any nano-pesticides under the Insecticides Act, 1968. However, several products utilizing nanotechnology for pest control are available in the Indian market. These products are often categorized differently, such as disinfectants or crop protectors, and may not require registration under the Insecticides Act.

Here are some notable nano-based pest control products available in India:

1) Nanocon **(**organic pesticide)
2) Nanopot Smart Plant Protector
3) NanoBee Agro-Kill

- **Soil health management:** Nanosensors monitor soil properties in real time, enabling precision farming. An innovative example is the diatom-based photoluminescent immunosensor developed at the University of Allahabad for early detection of Karnal bunt in wheat. This technology allowed for timely interventions, reducing crop losses.

Animal Biotechnology

Animal health is a critical component of sustainable agriculture. Biotechnological advancements in this field, such as:

- **Vaccines and diagnostics:** Improved disease control reduces losses.
- **Genetic engineering:** Enhancing productivity and disease resistance in livestock.
- **Nanotechnology for drug delivery:** Targeted therapies reduce antibiotic use.

Precision Agriculture

Precision agriculture employs Artificial Intelligence (AI), the Internet of Things (IoT), and drones to:

- **Optimize resource use:** Precise application of water, fertilizers, and pesticides.
- **Enhance productivity:** Data-driven decision-making increases efficiency.
- **Monitor crops:** Real-time data collection improves disease and pest management.

These technologies empower farmers to maximize yields while conserving resources, contributing to both sustainability and profitability.

Climate-Smart Agriculture

In the face of climate change, climate-smart agriculture focuses on:

- **Carbon sequestration:** Practices such as agroforestry and soil carbon storage mitigate greenhouse gas emissions.
- **Resilient crops:** Developing varieties that adapt to changing climates.
- **Renewable energy:** Biofuels and solar-powered farms reduce reliance on fossil fuels.

These strategies ensure food security while minimizing environmental impacts, creating a sustainable agricultural framework.

Robotics and Automation

Automation and robotics are transforming labor-intensive tasks in agriculture. Applications include:

- **Harvesting robots:** Precision harvesting reduces waste and enhances efficiency.
- **Weed control:** Robots equipped with AI target weeds without harming crops.
- **Data analysis:** Automated systems offer valuable insights into crop health, soil conditions, and weather patterns.

By reducing manual labor, these technologies improve productivity and reduce costs for farmers. These innovations contribute to the overall efficiency and sustainability of livestock farming.

Empowering Farmers through Digital Extension

Digital platforms play a pivotal role in bridging knowledge gaps and providing essential resources to farmers. Key benefits include:

- **Knowledge sharing:** Access to best practices and expert advice.
- **Market access:** Digital tools connect farmers with buyers, ensuring fair prices.
- **Data-driven decision-making:** Information on weather, soil health, and crop conditions aids in planning and resource management.

By harnessing digital technologies, farmers can make informed decisions, enhancing productivity and income.

The Future of Agriculture

Innovation and education are the twin pillars of a hunger-free and prosperous India. Frontier sciences offer immense potential to:

- Address global food demand sustainably.
- Mitigate the impacts of climate change.
- Enhance the economic viability of farming.

Collaboration among government agencies, research institutions, and the private sector are essential to scale these technologies and ensure their accessibility to farmers worldwide.

Conclusion

The transformation of India's agricultural sector is pivotal to the journey towards a developed nation. Frontier Sciences offers transformative solutions to tackle traditional agricultural challenges, while digital tools empower farmers with informed decision-making and enhanced market connectivity. By embracing a collaborative blend of biotechnology, omics technologies, nanotechnology, and other cutting-edge innovations, we can ensure a sustainable and food-secure future. It is our collective responsibility to support and advocate for these advancements, fostering a brighter future for generations to come.

ISSN : 2583-0910
Agri-India TODAY
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Peer reviewed
monthly newsletter

Article ID : 05/XI/18/1125

GENOME EDITING IN RICE: ADVANCING FOOD SECURITY AND CLIMATE-RESILIENT AGRICULTURE

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Abstract

Rice, a staple food for more than half of the global population, plays a critical role in ensuring global food security. However, climate change, declining productivity, and increasing pest and disease pressures threaten its sustainable production. Recent breakthroughs in genome editing technologies such as CRISPR/Cas9, TALENs, and ZFNs have provided new avenues for enhancing rice productivity, resilience, and nutritional quality. These tools allow precise modifications of specific genes responsible for yield, stress tolerance, and grain quality, leading to faster and more predictable crop improvement compared to conventional breeding.

Keywords: Rice improvement, CRISPR/Cas9, Genome editing, Climate resilience, Food security, Biotechnology.

Introduction

Rice (*Oryza sativa* L.) is central to the diet of billions across Asia, Africa, and Latin America. As a primary source of calories and livelihood for smallholder farmers, its production is closely tied to global food security. The challenges posed by climate change, biotic stresses (pests and pathogens), and abiotic stresses (drought, salinity, and flooding) threaten the stability of rice yields.

Conventional breeding methods have contributed significantly to the development of high-yielding and disease-resistant varieties; however, these processes are time-consuming and limited by genetic barriers. Genome editing technologies, particularly CRISPR/Cas9, offer a more efficient and precise approach for developing improved rice varieties that can withstand changing climatic conditions and contribute to sustainable agricultural systems.

Genome Editing: A Transformative Tool in Crop Improvement

Genome editing refers to targeted alterations of specific DNA sequences within an organism's genome. The most widely used tools CRISPR/Cas9 (Clustered Regularly Interspaced Short Palindromic Repeats associated protein 9), TALENs (Transcription Activator-Like Effector Nucleases), and ZFNs (Zinc Finger Nucleases) enable scientists to precisely knock out, insert, or modify genes responsible for desirable traits.

CRISPR/Cas9, in particular, has revolutionized plant biotechnology due to its simplicity, high efficiency, and cost-effectiveness. In rice, CRISPR has been successfully applied to improve yield-related genes, enhance resistance to pathogens, and develop tolerance to drought and salinity.

Applications of Genome Editing in Rice

1. Enhancing Yield and Productivity

The global demand for rice is expected to increase by 25% by 2030, necessitating higher yields without expanding cultivated land. Genome editing has identified and modified key yield-related genes, such as Gn1a (grain number), DEP1 (dense and erect panicle), and GS3 (grain size).

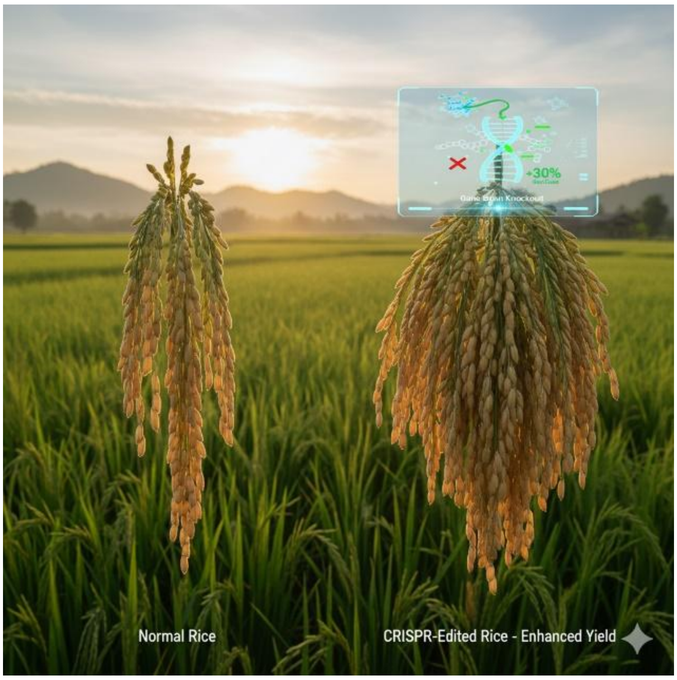


Fig: Normal and CRISPR-edited rice panicles showing grain number improvement

For instance, CRISPR-mediated knockout of *GS3* results in larger grains and increased yield potential. Similarly, editing *Gn1a* enhances cytokinin activity in panicles, leading to more spikelets per panicle.

2. Developing Climate-Resilient Rice Varieties

Climate resilience involves the ability of rice plants to maintain yield stability under environmental stresses. Genome editing allows precise modification of genes associated with drought, salinity, and submergence tolerance.

- **Drought Tolerance:**
  CRISPR/Cas9 targeting *OsSAPK2* and *OsbZIP46* genes enhances drought response by improving osmotic adjustment and reducing water loss.

Fig: Abiotic stress tolerance mechanisms (drought, salinity, and flood) in genome-edited rice.

- **Salinity Tolerance:**
  Modification of *OsRR22* and *OsHKT1;5* genes enables the plant to maintain ion balance under saline conditions.
- **Flooding Tolerance:**
  Editing of *SUB1A* and related genes leads to improved submergence tolerance, critical for rainfed lowlands of Asia.

3. Improving Nutritional Quality

Rice is often criticized for its low micronutrient content. Genome editing offers opportunities to biofortify rice with essential nutrients such as iron, zinc, and vitamin A.

For example, knockout of *OsAAP6* enhances grain protein content, while modifying *OsNAS3* increases iron and zinc accumulation in grains. Recent experiments with CRISPR have led to increased β-carotene (provitamin A) content, contributing to the fight against "hidden hunger."

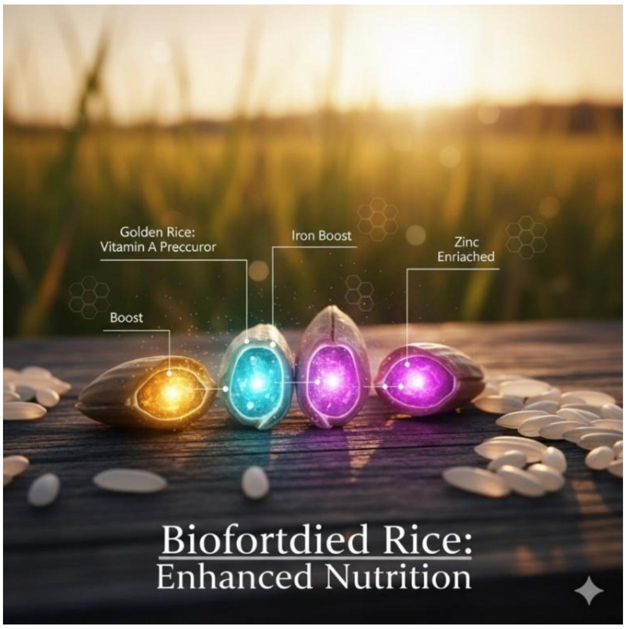


Fig: Cross-sectional view of biofortified rice grains showing nutrient enrichment.

4. Disease and Pest Resistance

Major rice diseases like bacterial blight, blast, and sheath blight cause substantial yield losses. Genome editing provides a quick route to develop resistant varieties by targeting susceptibility (S) genes.

- *Xa13*, *OsSWEET11*, and *OsSWEET14* have been edited to confer resistance to bacterial blight (*Xanthomonas oryzae*).
- *Pi21* gene knockout confers durable blast resistance (*Magnaporthe oryzae*).

Unlike conventional breeding, where resistance genes are introduced through multiple backcrosses, CRISPR/Cas9 allows direct modification of target loci without disturbing the genetic background.

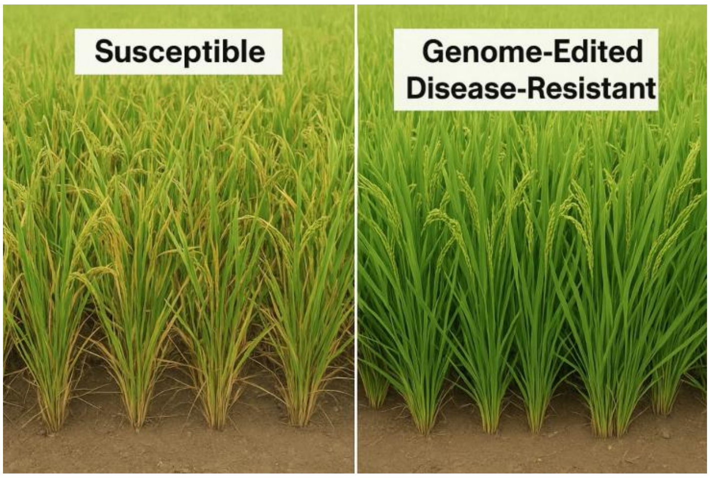
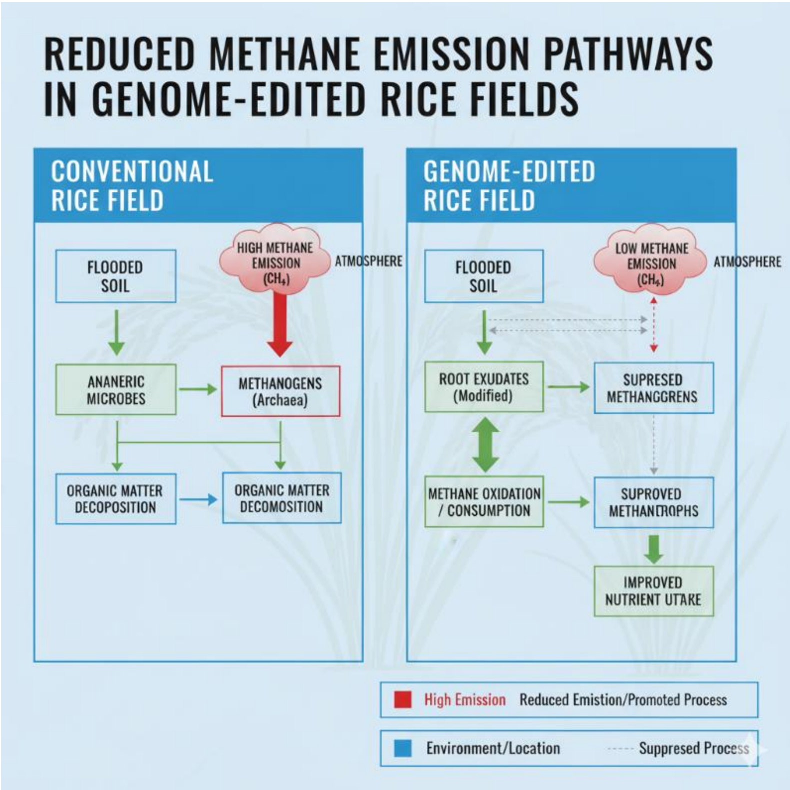


Fig: Field comparison of susceptible and genome-edited disease-resistant rice plants.

5. Reducing Greenhouse Gas Emissions

Rice paddies contribute significantly to global methane emissions due to anaerobic soil conditions. Genome editing can be used to modify genes involved in carbon and nitrogen metabolism to reduce methane production.

Editing the *OsNRT1.1B* gene enhances nitrogen-use efficiency, while regulating root exudate production genes can reduce methane-emitting microbes in paddy soils. Such innovations align with the goals of climate-smart agriculture and sustainable rice production systems.



Ethical, Regulatory, and Socioeconomic Considerations

While genome editing offers transformative potential, it raises ethical and policy-related questions regarding biosafety, intellectual property, and public acceptance.

Globally, countries like Japan, the United States, and India have begun developing simplified regulatory pathways for genome-edited crops that do not contain foreign DNA, distinguishing them from traditional genetically modified organisms (GMOs).

In India, the Department of Biotechnology (DBT) and ICAR support CRISPR research for rice improvement under the “Genome Editing Mission.” Ensuring transparency, farmer participation, and equitable access to technology will be essential for public trust and adoption.

Future Prospects and Challenges

The future of rice improvement lies in integrating genome editing with digital and precision agriculture tools such as artificial intelligence, genomics-assisted breeding, and big data analytics.

However, challenges persist in:

- Efficient transformation and regeneration of edited plants
- Avoiding off-target effects

- Harmonizing global biosafety regulations
- Promoting farmer and consumer awareness

Collaborative efforts among researchers, policymakers, and private sectors will accelerate the deployment of genome-edited rice varieties that contribute to both food and environmental sustainability.

Conclusion

Genome editing stands as a powerful frontier in modern plant science, offering precision, speed, and sustainability in rice improvement. It not only enhances productivity and nutritional value but also builds resilience against climate stresses and diseases. By integrating scientific innovation with supportive policies and public engagement, genome-edited rice can play a pivotal role in achieving food security and climate-resilient agriculture for future generations.

The path forward involves harmonizing technology with ethics, ensuring that genome-edited rice varieties are accessible, safe, and beneficial to all stakeholders especially smallholder farmers who depend on this vital crop.

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ISSN : 2583-0910
Agri-India TODAY
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Article ID : 05/XI/19/1125

GENETICALLY MODIFIED CROPS: TECHNOLOGIES, BENEFITS AND CONTROVERSIES

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Abstract

Genetically Modified crops are biotechnologically modified crops which has benefited the food economy of world. Currently, 76 nations and territories have adopted GM foods, while in India only common cultivation of one crop is allowed up to date *i.e.*, bt-cotton. Technologies are advancing in terms of genetic modifications in 21st century genome editing is gaining more importance. GM crops have various advantages like, pest resistance, stress tolerance, high nutritional values. However, controversies about GM crops such as Séralini *affair (2012), bt-rice in Europe, GM crops in India leads to either partial or full ban on GM crops. Proper regulation on production of biotechnologically engineered crops will be an effective way to meet future demands of rising population and changing climate.*

Keywords: GM crop, genome editing, controversies*, Séralini* affair, biotechnologically engineered crops

Introduction

Genetically modified (GM) crops are crop plants whose genetic material has been altered through genetic engineering techniques to enhance existing characteristics or to introduce new traits that are not naturally found in that particular crop species. The two terms transgene and transgenic crop hold the utmost importance in field of genetically modified crops. Transgenic plants referred to as plants in which gene or nucleic acid is altered using the technologies available to introduce a novel trait and to make a plant ecologically and economically fit for use, whereas transgene is a segment of nucleic acid which is use for transforming the crop plants.

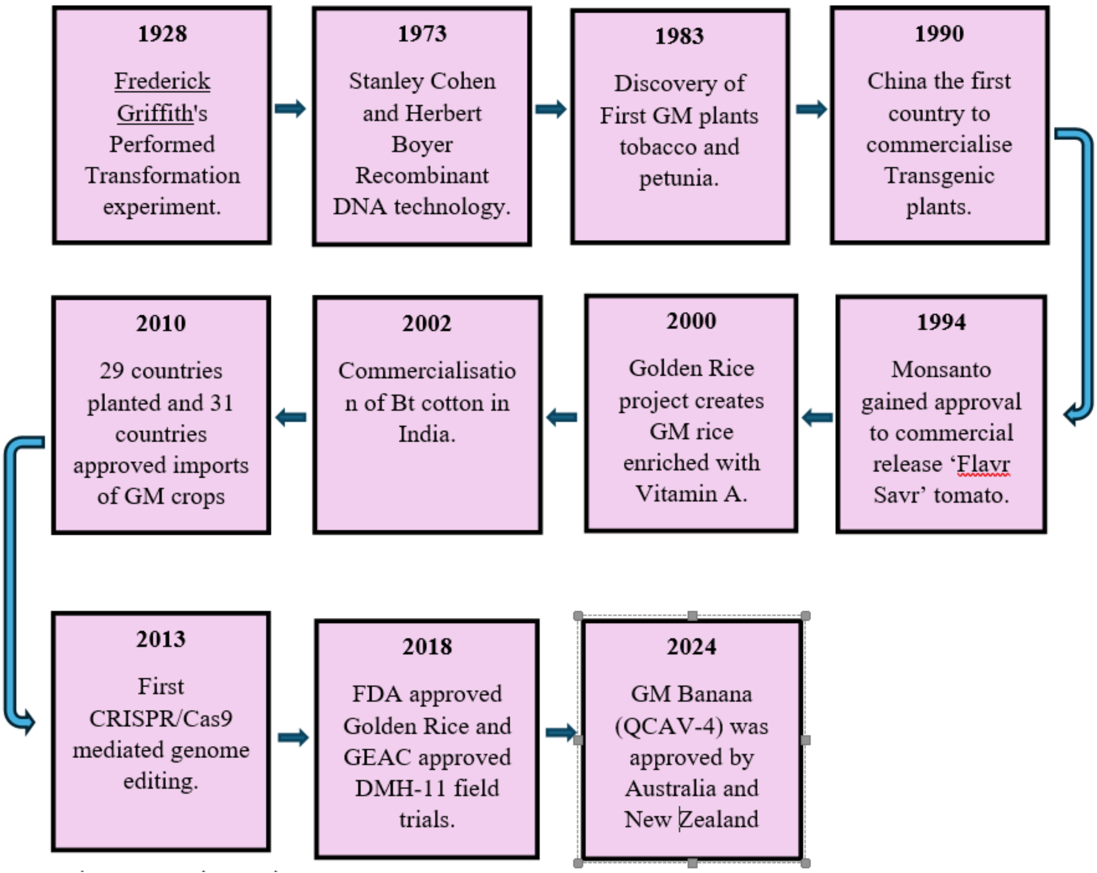
According to Qaim (2009), genetically modified crops can be grouped into three waves:

- First generation: Target agronomic performance, like improved resistance to insects, diseases, and environmental stresses.
- Second generation: Enhance product quality, including boosted nutritional value, altered composition, or longer shelf life.
- Third generation: Engineered as bio-factories to produce specific pharmaceuticals, vaccines, or industrial compounds.

The genetical engineering to modify a crop started in the year 1977, with the discovery of *Agrobacterium tumefaciens* that stably insert Ti plasmid DNA (T-DNA) into host plant cell genome (Chilton *et al.,* 1977). Following that, it was first revealed that a specific gene sequence could be introduced into plant cells using recombinant DNA and transformation technology. (Bevan *et al.,*

1983; Fraley *et al.,* 1983; Murai *et al.,* 1983). The first transgenic plants, *viz.*, antibiotic-resistant tobacco and petunia, were developed in 1983 (Fraley *et al.,* 1983). In 1994, Food and Drug Administration (FDA) approved the commercialisation of transgenic tomato, 'Flavr Savr' in the USA, with the property of longer shelf life or delayed ripening developed by Calgene (Monsanto).
GM technology is still making its way into many countries with 29 cultivating countries so far and 72 have issued 4,485 regulatory approvals (ISAAA, 2019). Technologies like *Agrobacterium* mediated gene transfer, biolistic gene gun, CRISPR/Cas9 and TALENS are used to alter the genome sequence in the crops to modify them. The introduction of GM crop is a game changer in field of agriculture as it paved a pathway to decrease the use of pesticide and other harmful chemical spray which imbalances the ecosystem, it also increases the production of crops with enhanced nutritional contents.

Timeline of Genetic Engineering of Crops



(Biswas *et al.,* 2021)

Techniques Behind Geneticlally Modified Crops

Technologies behind genetically modified crops:

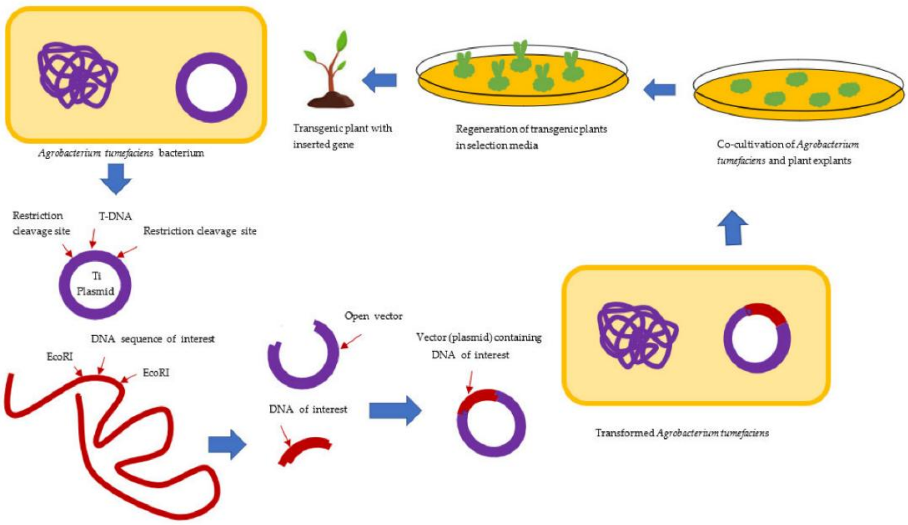
Some commonly used technologies to develop genetically modified crops are mentioned below.

1. Gene delivery methods

***Agrobacterium*-Mediated Transformation**

Agrobacterium-Mediated Transformation is a technology use to create transgenic plants**.** *Agrobacterium* genetically alters plant hosts by delivering a specific DNA segment from its tumor-inducing (Ti) plasmid into the plant genome (Gelvin 1998)**.** In its natural form, this transferred T-

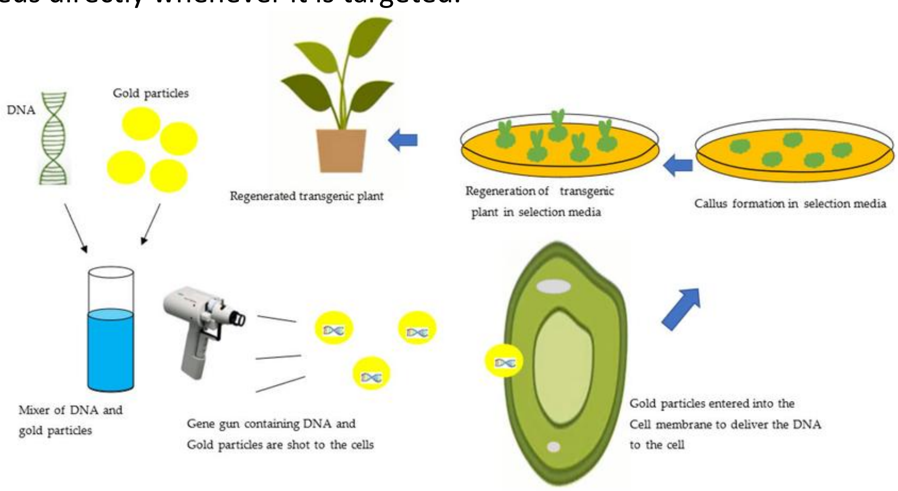
DNA contains oncogenes and opine metabolism genes; their expression in plant cells triggers tumor-like growth and the synthesis of opines—amino acid derivatives that primarily serve as nitrogen sources for the bacterium **(**Gaudin *et al.,* 1994)**.** Engineered *Agrobacterium* strains, in which the native T-DNA is replaced with target genes, have become the most effective tools for introducing foreign DNA into plants and generating transgenic species**.**



Agrobacterium-mediated genetic transformation of the plant. (Ghimire *et al.,* 2023)

Biolistic Gene Gun

Introducing genes into plants is a cornerstone of genetic engineering. Among available methods, direct DNA delivery especially particle bombardment offers several advantages over *Agrobacterium*-based approaches. By shooting DNA straight into cells, tissues, or organs capable of regeneration, these techniques can achieve transformation largely independent of plant genotype, avoiding *Agrobacterium*'s host range limitations and many tissue culture regeneration challenges. In microprojectile bombardment, DNA-coated metal particles are accelerated to high speed to penetrate plant cells and introduce functional DNA. (Leech *et al.,* 2000). High-velocity particles are introduced into cells to undergo transformation. A device known as a particle gun can accelerates these particles. The particle has the ability to pass through multiple cell layers and enter the nucleus directly whenever it is targeted.



Biolistic method of genetic transformation of the plant. (Ghimire *et al.,* 2023)

2. Genome Editing

CRISPR/Cas9 (Clustered Regularly Interspaced Short Palindromic Repeat)

CRISPR/Cas9, introduced from the type II adaptive immune system of bacteria and archaea, creates targeted double-strand breaks in DNA. These breaks are then fixed by the cell's own repair pathways. **(**Steinert *et al.,* 2016). It provides a deliberate, rapid way to create sequence variation. In plants, targeted genome editing can be used to refine virtually any key trait such as yield, nutritional profile, and product quality (including protein or oil composition) and to enhance tolerance to environmental stresses like drought or salinity.

TALENS (Transcription activator-like effector nucleases)

TALENs are engineered by fusing the Fok-I nuclease domain to DNA-binding domain from TALE proteins of Xanthomonas (Joung and Sander, 2013). They can be used to insert new resistance genes and to build multi-gene stacks by placing several genes at a single genomic locus, preventing segregation during breeding. This capability is key for achieving durable, long-term disease resistance.

ZFNs (Zinc Finger Nucleases)

Zinc-finger nucleases (ZFNs) are site-directed nucleases built by combining zinc-finger DNA-binding modules with a Fok-I nuclease domain. Their extensive history of reliable performance, well-characterized specificity, and established Intellectual property rights makes them a compelling option for genome editing in biotechnology product development. ZFNs are relatively small proteins compared to many CRISPR systems, easing delivery constraints for plant transformation (*Agrobacterium* T-DNA size limits, viral vectors, or tightly packed biolistic stacks) (Urnov *et al.,* 2010).

Case Study on Bt cotton

Bt cotton is the only commercialized crop cultivated in India since 2002, which results in robust increase in cotton production, export and textile industry. It is the only approved GM crop for commercial cultivation in 2002 by the Genetic Engineering Appraisal Committee (GEAC) of Ministry of Environment, Forest and Climate Change.In India, cotton is preyed on by both caterpillars from the Lepidoptera order and sap-sucking insects from the Hemiptera order. Indian farmers have a long-standing tradition of successfully cultivating native 'desi' cotton species, primarily Gossypium arboretum, but the problems began in 1990s with the spread of hybrids (Prasad, 1999). The hybrids were input intensive and also lacked resistance against insects and pest which results in agro-ecological instability along with entomological instability among farmers.

In 2002, the sale of Bt seeds was authorized in central and southern India, leading to the introduction of three Mahyco seeds that contained the single *Cry1Ac* gene. These seeds experienced minimal adoption initially. By 2005, Bt technology received approval for northern India, and that same year, seeds featuring a combination of *Cry1Ac* and *Cry2Ab* genes were launched nationwide. The uptake of Bt cotton began to rise significantly in 2005, resulting in the disappearance of conventional brands from stores in many regions. All Bt seeds were hybrids, and during these years, there was also a swift transition from varieties to hybrids: the proportion of cotton area dedicated to hybrids increased from 32.9% in 1996–1997 to 71.47% in 2009–2010 (Suresh *et al.,* 2013) and reached 93.0% in 2011. (Mayee & Choudary, 2013).

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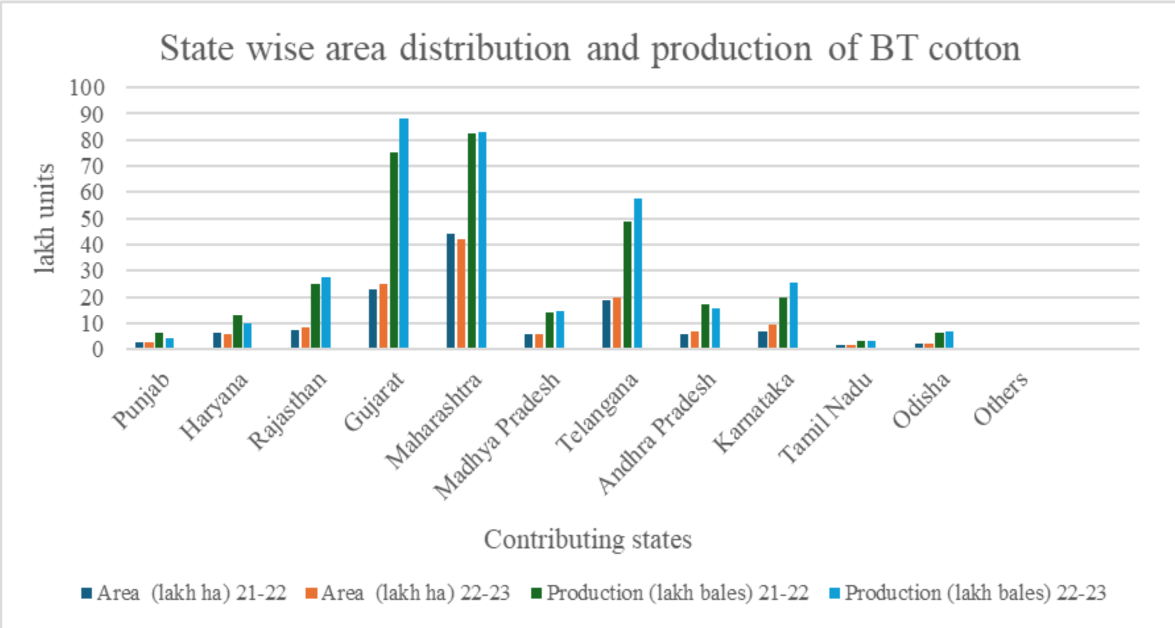

Genetically Modified and Genome Edited crops

Golden rice

Globally, an estimated 1.02 billion individuals suffer from severe micronutrient deficiencies, with vitamin A being the most deficient nutrient (Wirth *et al.,* 2017). The main objective of Golden Rice's development is to address vitamin A deficiency. *Agrobacterium* tumefaciens-mediated plant transformation was used to enhance the product quality and produce golden rice. As a joint project of the Philippine Rice Research Institute and the International Rice Research Institute (IRRI), golden rice was created by Ingo Potrykus and Peter Beyer and improved the production of mannose and the level of provitamin A. A daily intake of around 75 grams of golden rice contains enough provitamin A to meet the complete dietary requirement (Paine *et al.,* 2005).

With the ultimate goal of releasing a stacked variety containing beta-carotene, iron, and zinc, IRRI is working on high iron and zinc rice (HIZR), which can help address several micronutrient deficiencies that impact over two billion people globally (IRRI).

Roundup ready Soybean

The glyphosate-resistant *Agrobacterium* strain CP4 (CP4 EPSPS) was the source of the Roundup-ready soybean variety used in genetically engineered crops. After being cloned, the CP4 EPSPS gene was introduced into soybeans. By joining the 5' end of the CP4 EPSPS gene to a petunia-derived chloroplast transit peptide, the gene was modified for plant expression. Three bacterial genes, two CP4 EPSPS genes, and a marker gene as *E. coli*'s beta-glucuronidase producer (GUS) were all present. The gene gun, also known as the particle-acceleration technique, was used to inject the DNA into the soybeans.

A 1999 evaluation of Roundup Ready soybean crops revealed that their production was 6.7% lower than the best conventional varieties (Benbrook, 1999). When other qualities are incorporated into soybeans by traditional breeding, this "yield drag" exhibits the similar trend (Caviness and Walters, 1971). Monsanto asserts that later patented varieties produce 7–11% more than its initial, underperforming variety, bringing them closer to those of traditional cultivation.

Genome Editing: DRR Rice (Dhan) 100 (Kamala) and Pusa DST Rice 1

At Indian Institute of Rice Research (ICAR-IISR), Dr. Satendra Kumar Mangrauthia and his colleagues utilized CRISPR/Cas mediated genome editing to create DRR Rice 100 (Kamala). A ltering cytokinin metabolism strategically, promotes the growth of the reproductive system. Its yield is 19% higher than that of the Samba Mahsuri. Thanks to a more robust root system architecture (RSA), it has a strong culm for lodging resistance, moderate drought tolerance, and prolonged performance under low nitrogen and phosphorus inputs. These traits make it appropriate for farming areas with limited resources and those under climate stress.

Since its genome contains no foreign DNA, Pusa DST Rice 1 is genome edited on the MTU 1010 variety rather than a genetically modified variety. Created by ICAR-IARI (Indian Institute of Agricultural Research) using CRISPR/Cas technology with SDN-1 (Site Directed Nuclease) to create small double strand breaks with insertions, deletions or substitution of nucleotides. It has shown resilience to drought and salinity stress conditions.

DMH 11

One of the most important crops in terms of oil content is mustard, which is also one of the most produced oil seeds in India. Professor Deepak Pental of Delhi University developed the Dhara mustard hybrid-11, usually referred to as DMH-11. Its primary goal was to lessen India's reliance on imported edible oil. Because it is the result of crossing two different parents, it is known as a hybrid crop. Because its DNA has been altered using engineering methods, it is also known as a trans genetic crop. A popular Indian mustard variety known as "Varuna" was crossed with a mutant "early heera-2" to create DMH-11. When compared to the best varieties, such Varuna, census data from DMH-11 indicates an average yield increase of up to 28%.

It was created with transgenic technology, which involves Bar gene, Barnase and Barstar gene. In that Barnase gene is responsible for male sterility in mustard, while Barstar gene restores fertility conditions. The Bar gene, derived from *streptomyces hygroscopicus* is responsible for Glufosinate resistance of DMH-11, by producing enzyme phosphinothricin-N-transferase. This enzyme then acts as detoxifying agent for phosphinothricin which is an active compound of Glufosinate.

Status of Genetically Modified Crops in World And India

Globally, 76 nations and territories adopted genetically modified technology in 2023, while 27 countries planted 206.3 million hectares of GM crops, leading to 3.05% increase from the year before (Agbio Investor 2024). With a total planting area of over 3.4 billion hectares, the area dedicated to GM crop cultivation has increased 121-fold since 1996 and now makes up around 13.38% of the world's total agricultural area (1,542 million hectares). 91% of the world's genetically modified crops were grown in the top five countries in terms of planting area: the United States, Brazil, Argentina, Canada, and India. The GM crops that were planted worldwide in 2023 included rice, wheat, soybean, corn, canola, sugar beet, alfalfa, sugarcane, eggplant, and cotton. The two most prevalent crops were still GM soybean (100.9 million hectares) and GM corn (69.3 million hectares). The largest area of genetically modified crops, namely GM corn, soybeans, and cotton, is found in Central and South America. Cotton is a key component of India's industrial and agricultural economies and has long been used as a raw material for textiles and fiber. This crop provides a living for almost 8 million farmers, the majority of whom are small and medium-sized (with farms smaller than 15 acres and an average of 3–4 acres of cotton holdings). Bollgard I, India's first genetically modified cotton hybrid, was introduced by Monsanto-Mahyco in 2002. It contained Bacillus thuringiensis (Bt) genes that produce *Cry1Ac*, which was used to combat the pink bollworm (*P. gossypiella*) pest (Choudhary and Gaur, 2015). Only 36% of farmers initially accepted the new GM crop, but after Bt-cotton was approved nationally, this number quickly increased to 46% in 2004 (Kathage and Qaim, 2012). Subsequently, Monsanto-Mahyco approved and introduced Bollgard-II, a Bt-pyramid that confers resistance to bollworm by producing the two toxins *Cry1Ac* and *Cry2Ab*. This led to an increase in the adoption of Bt cotton among cotton growers in India. Despite difficulties, Bt-cotton's introduction has substantially benefited Indian farmers and agricultural sector.

Advantages of Genetically Modified Crops

I. **Advancement of gene editing technique: CRISPR/Cas9**

CRISPR/Cas based gene editing precisely modifies the existing genes to bring novel characteristics, instead of introducing a foreign DNA element from a different species into the plant genome. Researchers have improved disease resistance in rice, potatoes, and wheat by using CRISPR/Cas technique. The phytoene desaturase gene in muskmelon (CmPDS) was successfully knocked out by CRISPR/Cas9, marking the first study to use CRISPR/Cas9 genome editing on the species. A 2022 study, for example, discovered that rice treated with CRISPR was resistant to bacterial blight without lowering yield.

II. **Pest resistance and herbicide tolerance**

First, the sustainability of agricultural operations is mentioned in relation to biodiversity. The most widely used genetically modified crops are those that are resistant to pests, such as bollworm-resistant bt cotton. By reducing insect damage and increasing cotton profit for small landholders by 50%, Bt has resulted in a 24% increase in cotton yield per acre. Genetically modified crops have demonstrated resistance to potent herbicides and help stop the harm that herbicide use brings to the environment. Ex- Glyphosate-tolerant soybean.

III. **Biofortification and Nutritional Enhancement**

A staple crop that is widely consumed, 90% of the world's rice is produced in Asian nations. One sustainable method of reducing hunger is through staple biofortification. In rice, notable progress has been made globally to enhance grain zinc, iron, and protein. Currently, 37 sustainable rice cultivars 16 from India and 21 from other nations are biofortified with iron, zinc, protein, and pro-vitamin A. A major step forward in the fight against vitamin A deficiency, which causes night blindness, was made in 2021 when the highly debated Golden Rice, which is genetically modified to produce vitamin A, was authorized for commercial cultivation in the Philippines.

Golden rice, which is high in vitamin A, aids in the global fight against hunger (Key S, 2008). Additionally, field research is currently underway in Sub-Saharan Africa for genetically modified maize and cassava varieties that are rich in vitamins and essential amino acids.

IV. **Drought tolerance**

In extreme environmental conditions like drought, genetically modified plants have a higher chance of surviving. Because crops are designed to endure weather extremes and fluctuations, they will produce adequate yields of high-quality crops even in the event of unfavourable or severe weather conditions. Ex: Rice's resistance to critical water conditions due to a mutation in the Arabidopsis HARDY gene, which increases rice's water efficiency by speeding up photosynthesis and reducing transpirational loss (Karaba A, 2007).

V. Pharmaceutical

Edible plant vaccines made from genetically modified crops could potentially be able to protect people against a wide range of infectious diseases, from cholera to perhaps AIDS (Moffat A.S, 1995). As a low-cost edible oral vaccination, the AIDS virus HIV-1's glycoprotein gene, gp 120, was inserted into genetically modified maize.

VI. Phytoremediation

Pollution of soil and water is still a concern everywhere in the world. It is possible to genetically modify plants, such as poplar trees, to remove pollutants or heavy metals from soil and water (Reichenauer and Germida, 2008). The grey poplar trees' ability to produce phyto-chelatine and detoxify organic contaminants is increased by excessive expression of γ-ECS (from *Escherichia coli*).

Controversies Surrounding Genetically Modified Crops

Genetically modified crop is the most controversial topic all over the world besides of its extensive advantages like higher crop yields, lower use of chemical insecticides and herbicides, reduced CO_2 emissions, greater farmer earnings, and better consumer health (Klümper and Qaim 2014; Brookes and Barfoot 2018). However critics had said that GM crops are unfit for human use due to its allergic effects. Scientists also reported about the upcoming potential risks from GMOs including vertical gene transfer, horizontal gene transfer, hybridization, and resistance against pest infestation.

Experiments carried out by researchers at the University of Caen in France, with support from the GEKKO Foundation in Germany, revealed that the toxins produced by bt corn (Mon810) can have a significant effect on the survival of human cells. (Abbas, 2018).

The potential health risks of toxicity and allergenicity linked to transgenic crops have long been a matter of debate. For example, Cry9c-expressing "StarLink" maize was approved in the USA in 1998 for animal feed and industrial use, but not for human consumption because of its potential allergenicity, owing to the protein's high stability and possible interaction with the immune system (Bucchini and Goldman, 2002). In 2000, Aventis was forced to recall StarLink maize globally after residues of the Cry protein were detected in food products (EPA, 2017). One of the most controversial studies in this field was published by Séralini *et al.* (2012), which reported potential health risks such as increased tumor development, chronic kidney disease, liver congestion and necrosis in male rats, and higher mortality in female rats fed with transgenic NK-603 Roundup Ready maize. However, this study quickly became known as the "Séralini affair," as it faced strong criticism for its flawed experimental design and questionable statistical methods, ultimately leading to its retraction Hence, there is bann over bt- corn due to its controversial status.

Moreover, in some European countries such as Poland, the opposition to the distribution and cultivation of GM crops is high (upto 60%). European union has banned the export of rice from China due to improper experimentation and not considering biosafety test. After the reports collected the EU stopped the import of the GM rice (Bt Shanyo 63) and had tightened its security for regulations of import of GM rice.

Recently, Ajay Srivastava the founder of Global Trade Research Initiative (GTRI) has raised banned for genetically modified product in the India and US trade pact by mentioning the key fact that trade of gm food will weaker the India's fragment of agriculture sector as it can lead to mixing of genetically modified seeds or by products (Times of India 2025, July).

Future Perspectives

Population is increasing rapidly and to meet the demands of rising populations for foods scientist are needed to be more evolve with the technologies that can cope up the rising demands of foods along with the resistivity to changing climate. Government should focus more on research and development sectors along with private sectors for production of genetically modified crops via genome editing techniques. With the emerging new era of technologies in 21st century, molecular biology with advancement in gene editing can lead to ease in genetic improvement of crops.

Conclusion

GM crops are specifically modified crop and are resultant of biotechnological engineering. Over the centuries the advancement in technologies, from gene delivery methods to genome editing (CRISPR/Cas9, TALENS, ZFN) has ease the production of these modified crops. Several crops have been genetically modified according to environment and consumers needs like, golden rice, roundup ready soyabean and DMH -11. Advantage of using such crops is non-neglectable as the possess biotic and abiotic stress resistance, high nutritional values. Any new innovation has its own controversies and benefits. Hence, GM crops hold the power to strengthen the food economy of world and to make agriculture more sustainable.

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ISSN : 2583-0910
Agri-India TODAY
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Peer reviewed monthly newsletter

Article ID : 05/XI/20/1125

INSECTS AS EARLY WARNING SYSTEMS FOR ECOLOGICAL DISTURBANCES

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Imagine walking through a forest just after a rainfall. The ground exhales a damp, earthy scent; raindrops cling to the leaves and countless small creatures stir into motion. Dragonflies sweep over clearings with precise, helicopter like movements, beetles burrow beneath fallen logs and ants follow their well-worn trails in tireless lines. To the casual observer, these may seem like simple rhythms of nature, but to scientists, they carry meaning. Insects respond quickly to changes in their surroundings and their abundance, diversity and even body form provide valuable clues about environmental quality. A decline in certain groups may indicate polluted waters, while sudden population shifts can signal soil degradation or the early effects of climate change. In this way, insects function as bioindicators, living biological markers that integrate and translate environmental changes into measurable ecological responses, often preceding detection by conventional monitoring systems.

Bioindicators and their importance

A bioindicator is a group of species whose presence, absence, or changes in abundance and physiology reveal the condition of their environment. Researchers can track both natural variations and human-driven impacts on habitats, communities and ecosystems by observing these organisms and helping to determine whether such changes are positive or harmful (Parmar *et al.,* 2016). In ecology, species that respond in measurable ways to environmental shifts are called indicator species, acting as biological signposts that reflect overall ecosystem health (Landres *et al.,* 1988). Using bioindicators is especially valuable in environmental monitoring because they can provide early warnings of ecological change, offer a cost-effective way to evaluate environmental quality, support biodiversity assessments and often show a high degree of sensitivity and specificity to pollutants (Chowdhury *et al.,* 2023). The classification of these bioindicators is as follows (Fig 1).

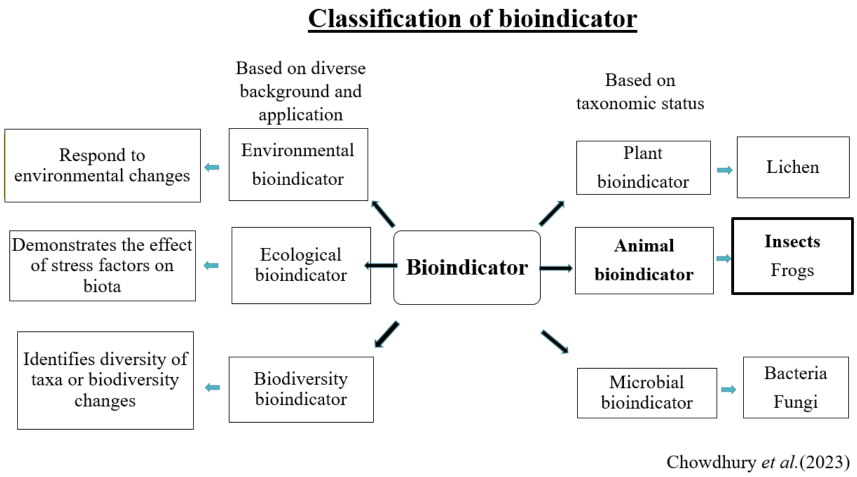

Fig 1 Classification of bioindicators

Insects as bioindicators

Insects are considered highly effective bioindicators because they react quickly to environmental stress, occur in large numbers and have short generation times, which enables us early detection of possible ecological change. They are also relatively easy to collect and identify and their species richness, diversity, ecological fidelity and sensitivity to even small shifts in conditions make them reliable for assessing overall ecosystem health (Chowdhury *et al*.,2023; Peck *et al.,*1998). Different groups of insects reflect different aspects of the environment. For example, Collembola, Ephemeroptera, Odonata and Plecoptera are closely related to water quality, while Lepidoptera and Hymenoptera give clues about habitat condition and floral resources. In contrast, Coleoptera, Diptera and Isoptera are often linked to soil health, decomposition and pollutant accumulation. On whole, these insect groups provide a broad yet detailed picture of ecosystem dynamics, helping us detect both natural changes and human impacts across multiple ecological scales.

Insect orders as indicators of environmental pollution

Insects, owing to their ecological sensitivity and diversity, are widely used as bioindicators of different types of pollution. Certain aquatic groups, such as Ephemeroptera, Plecoptera, Trichoptera and Odonata, are strongly related to water quality, where their presence or absence reflects oxygen availability, organic load and heavy metal contamination (Table 1). For soil ecosystems, insects orders like Collembola, Coleoptera and Hymenoptera indicate changes caused by pesticides, heavy metals and organic pollutants, making them reliable markers of soil health and decomposition processes (Table 2). Similarly, in the case of air pollution, groups such as Lepidoptera, Hymenoptera and Hemiptera serve as sensitive indicators, with shifts in morphology, population density or pollutant accumulation revealing changes in atmospheric conditions (Table 3). Collectively, these insect orders highlight how different taxa can be linked to specific environmental stressors, offering valuable insights into ecosystem quality and anthropogenic impacts.

Table 1: Insect orders as water pollution indicators

Order	Common name	Indicator of	Water quality indication	Reference
Ephemeroptera	Mayflies (naiads)	Oxygen availability	High population indicates good water quality	Parikh *et al.,* 2021
Plecoptera	Stoneflies (naiads)	Clean, oxygen-rich water	Excellent abundance depeicts unpolluted water	
Trichoptera	Caddisflies (larvae)	Pollution sensitivity	High abundance indicates pure water	
Diptera	Midges/Chironomids	Organic matter	High indicates Poor/degraded water quality	Lafont and Durbec,1990
Hemiptera	Sea Skaters	Heavy metal pollution	Cadmium accumulation in tissues	Cheng *et al.,* 1976
Odonata	Dragonflies and Damselflies (naiads)	Water quality	High abundance indicates fresh water	Corbet, 1999

Table 2: Insect orders indicating soil pollution

Order	Common name	Indicator of	Soil quality indication	Reference
Collembola	Springtails (*Folsomia candida* and *Sinella curviesta*)	Soil acidity, pesticides, heavy metals	Declined reproduction and body size in adults in high copper concentrated soils.	Chowdhury *et al.,* 2023; Liu *et al.,* 2018
Hymenoptera	Red wood ant (*Formica lugubris*)	Heavy metal accumulation	Accumulates Al, Cd, Co, Cu, Fe, Ni, Pb, and Zn in worker bodies and nests, reflecting soil metal contamination.	Skaldina *et al.,* 2018
Coleoptera	Ground beetles (Carabidae)	Pesticides, heavy metals, radioactive waste	Used in monitoring pollutants from herbicides, insecticides, metals, and radioactive substances.Morphological changes (shorter elytra length and body size) under pollution stress was observed.	Chowdhury *et al.*, 2023; Lagisz, 2008

Table 3: Insect orders indicating soil pollution

Order	Common name	Indicator of	Air quality indication	Reference
Lepidoptera	Pine beauty moth (*Panolis flammea*) & Pine looper moth (*Bupalus piniarius*)	Industrial pollutants in food plants	Reduced pupal size in polluted areas indicates industrial contamination and plant stress.	Heliövaara *et al.,* 1990
Hemiptera	Aphids	Elevated CO_2 levels	Aphid population density increases when host plants are exposed to high atmospheric CO_2.	Cannon, 1998
Hymenoptera	*Polistes* wasp larvae	Heavy metal (Lead) accumulation	Larval fecal mass accumulates Pb up to 36× body concentration, serving as a local air metal pollution indicator.	Urbini *et al.,* 2006
Hymenoptera	Honey bees	Pesticides, heavy metals, radionuclides	Mortality indicates pesticide residues; chemical residues detected in bees, wax, and honey signal contamination.	Porrini *et al.,* 2003; Barganska *et al.*, 2016
Hymenoptera	Honey bees	Trace	Accumulate heavy	Di Fiore *et al.*,

Order	Common name	Indicator of	Air quality indication	Reference
		elements (Be, Cd, Co, Cr, Ni, Pb, Cu, V)	metals and pollutants in bodies and hive products across rural and urban environments.	2022

Caddisfly larva

Honey bee

(https://northyubaguide.com/stonefly-facts/)

Advantages and disadvantages of insect bioindicators

Insects serve as efficient bioindicators due to their ability to provide early warnings of environmental change, cost-effective monitoring compared to specialized systems and direct assessment of ecological and toxicological impacts (Parmar *et al.,* 2016). However, their reliability can be constrained by natural population fluctuations, climatic disturbances, biotic interactions such as predation or parasitism and seasonal inactivity of certain species (Lenhard & Witter, 1977).

Future thrust

Future research should prioritize exploring the underutilized potential of insects as bioindicators for assessing environmental quality across diverse ecosystems. Comprehensive studies are required to identify, validate and standardize specific taxa as reliable indicators of distinct environmental parameters. Integrating insect based monitoring into early warning systems could enhance the prediction and mitigation of ecological risks. Furthermore, elucidating the links between environmental change and insect behavioural or physiological responses will not only strengthen ecological monitoring frameworks but also support longterm economic planning and the development of sustainable industrial practices.

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ISSN : 2583-0910
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Article ID : 05/XI/21/1125

INVASIVE SPECIES: HIDDEN ENEMIES OF AQUATIC ECOSYSTEMS

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Abstract
Aquatic invasive species pose critical threats to freshwater and marine ecosystems globally, causing billions in annual economic damage. These non-native organisms, introduced via ballast water, aquarium releases, and intentional stocking, rapidly establish populations that outcompete natives, alter habitats, and disrupt food webs (Ricciardi & MacIsaac, 2011). This article examines invasion mechanisms, biodiversity impacts, and management challenges, highlighting examples like zebra mussels, Asian carp, and lionfish. Understanding these consequences is essential for developing effective strategies in our increasingly globalized world (Gallardo *et al.,* 2016).

Keywords: Aquatic invasive species, ballast water, zebra mussels, Asian carp, lionfish, biodiversity loss, ecosystem disruption, marine invasion, freshwater ecology, biological control

Introduction
Aquatic ecosystem invasion by non-native species represents a pressing 21st-century environmental challenge. Unlike habitat loss or pollution, invasive species work insidiously, establishing undetected until reaching critical population levels that trigger irreversible changes (Simberloff *et al.,* 2013). Aquatic environments are particularly vulnerable due to interconnected water systems and numerous transport pathways. Globalization has exponentially increased introduction rates through shipping ballast water containing thousands of organisms and aquarium trade facilitating exotic species movement into natural waterways (Padilla & Williams, 2004). Economic costs are staggering—damages and control efforts exceed $100 billion annually in the United States alone, with aquatic invaders comprising substantial losses (Pimentel *et al.,* 2005).

Invasion Pathways
Commercial vessels represent the primary invasion vector, discharging ballast water that inadvertently transfers approximately 7,000 species daily globally (Molnar *et al.,* 2008). Zebra mussels (Dreissena polymorpha), introduced to the Great Lakes via European ballast water in the late 1980s, have caused billions in damage by clogging pipes, smothering native mussels, and altering nutrient cycles (Karatayev *et al.,* 2015). The ornamental trade serves as another significant pathway—lionfish (Pterois volitans), likely from 1990s Florida aquarium releases, became one of the most damaging Western Atlantic marine invasions (Morris & Whitfield, 2009). Human waterway modifications like the Suez Canal have enabled over 300 species migrations, while aquaculture operations serve as stepping stones when cultured species escape (Galil *et al.,* 2015).

Ecological Impacts
Invasive species possess competitive advantages enabling native organism domination. Asian carp escaped from aquaculture constitute up to 80% of biomass in invaded U.S. rivers, fundamentally

restructuring communities by outcompeting native fish for plankton (Irons *et al.,* 2007). Some invaders transform habitat structure—water hyacinth (Eichhornia crassipes) forms dense mats blocking sunlight and reducing oxygen, creating anoxic conditions causing fish kills (Villamagna & Murphy, 2010). Invasive species also introduce novel pathogens; Eurasian crayfish brought crayfish plague to North America, causing dramatic native crayfish declines (Holdich *et al.,* 2009). Additionally, invasive-native interbreeding threatens genetic integrity—escaped farmed Atlantic salmon reduce wild population fitness and local adaptation over generations (McGinnity *et al.,* 2003).

Socioeconomic Consequences

Financial burdens extend across sectors. Power plants and water facilities spend millions annually removing zebra mussels, while fisheries suffer losses when invasives reduce target populations (Lovell *et al.,* 2006). Property values decline along invaded waterways, and tourism experiences reduced visitation. Some invaders pose direct health threats—dense plant mats breed disease-carrying mosquitoes, certain species harbor transmissible pathogens, and invasive jellyfish cause beach closures (Purcell *et al.,* 2007). Indigenous communities face cultural losses when invasives displace traditional fishery species, while recreational activities suffer from degraded water quality and diminished biodiversity.

Management Challenges and Strategies

Identifying invasives during initial establishment offers the best eradication opportunity, but aquatic environments present detection challenges as many species are small, cryptic, or indistinguishable from natives (Geller *et al.,* 2010). Environmental DNA (eDNA) techniques have emerged as powerful early detection tools. Established aquatic invasives are notoriously difficult to control—physical removal is labor-intensive, chemical control raises non-target concerns, and biological control risks introducing additional problems (Simberloff & Stiling, 1996). Prevention represents the most effective approach: ballast water regulations requiring treatment before port entry have reduced introductions regionally (Bailey *et al.,* 2011), while education campaigns discourage aquarium releases and biosecurity measures minimize escapes.

Case Studies

Since 1988, zebra mussels colonized eastern North America waters, their filtering paradoxically harming ecosystems by removing plankton essential for larval fish while infrastructure damage costs exceed $1 billion annually (Connelly *et al.,* 2007). Caribbean lionfish invasion demonstrates single predator capacity to restructure reef communities, with studies showing 80-90% native fish reductions within two years (Green *et al.,* 2012). Venomous spines deter predators and females produce over 2 million eggs annually, making widespread eradication impossible despite management efforts promoting consumption and removal tournaments.

Conclusion

Aquatic invasive species represent persistent, growing threats to ecosystem health worldwide. Global trade, climate change, and human activities facilitate unprecedented introduction rates. Success requires multi-faceted approaches emphasizing prevention through strengthened ballast water regulations, restricted high-risk species trade, and improved biosecurity. Early detection systems employing eDNA enable rapid response, while public engagement remains critical as human activities drive most introductions. Aquatic invasions' hidden nature—operating beneath surfaces, unnoticed until severe impacts manifest—makes them particularly insidious enemies.

However, increased awareness, scientific understanding, and coordinated management offer hope for protecting aquatic biodiversity and vital ecosystem services for future generations, fundamentally addressing challenges to economic prosperity, food security, and global human wellbeing.

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ISSN : 2583-0910
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Article ID : 05/XI/22/1125

MARINE HEATWAVES: IMPACTS, VULNERABILITY, AND MANAGEMENT STRATEGIES FOR MARINE ECOSYSTEMS

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Introduction

One of the significant consequences of climate change is the increasing frequency and intensity of extreme weather and climate events. One such extreme event that was characterized by prolonged periods of anomalously high ocean temperatures that can occur at any time of the year, posing substantial threats to marine ecosystems and coastal economies is marine heatwaves (MHWs). Marine heatwaves (MHWs) are prolonged periods of anomalously elevated sea surface temperatures that deviate significantly from the seasonal mean. These extreme thermal events have emerged as a critical aspect of ocean climate variability, exerting profound impacts on marine ecosystems by disrupting species distribution, altering primary productivity, and triggering large-scale habitat degradation such as coral bleaching and seagrass loss. Marine heatwaves (MHWs) are driven by a complex interplay of local oceanic and atmospheric processes, including variations in air–sea heat fluxes and horizontal temperature advection. Their occurrence and intensity can further be modulated by large-scale climate variability, such as the El Niño–Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD), and other remote influences transmitted through atmospheric and oceanic teleconnections.

Different Events of MHWs

Marine heatwave (MHW) events are increasing in both frequency and intensity over time. Recent analyses indicate that, under current climate conditions, approximately 87% of observed MHWs can be attributed to anthropogenic warming. This underscores the strong influence of human-induced climate change on the occurrence of extreme ocean temperature events. Between 1925 and 2016, marine heatwave (MHW) dynamics exhibited marked intensification globally. During this period, the frequency of MHW events increased by 34%, their average duration extended by 15%, and the total number of MHW days worldwide rose by 54%, reflecting a clear trend toward more persistent and widespread ocean warming extremes. Outbreaks of marine heatwaves (MHWs) have been reported across various regions of the world. Notable events include the Mediterranean Sea during the summer of 2003, linked to the European heatwave, as well as occurrences in the South China Sea, the Bering Sea, and major ocean basins such as the Pacific, Atlantic, Indian, and Arctic Oceans. The most extreme MHW occurred in the northeast Pacific Ocean between 2013 and 2015, with sea surface temperature anomalies reaching up to 6 °C. This warming is due to reduction in cloud cover and increased solar radiation, emphasizing the influence of atmospheric conditions on ocean heat extremes.

Ecophysiological and Marine Individual-Level Responses to Thermal Stress

The latitudinal distributions of most marine species generally reflect the spatial projection of their thermal niche. Temperature exerts a fundamental influence on physiological processes, including photosynthesis and respiration, and consequently regulates key aspects of ecological performance such as growth, reproduction, phenology, and survival. Individuals respond negatively to marine heatwaves (MHWs) in ways that can range from sublethal impacts on core physiological processes to complete mortality. Elevated temperatures often lead to increased basal metabolic rates, raising energy demands. In many cases, this heightened demand surpasses the metabolic capacity of the species, potentially compromising survival, growth, and reproduction. Such physiological stress highlights the vulnerability of marine organisms to extreme thermal events. In addition, individuals may employ physiological adjustments to depress their metabolism and conserve energy for cellular protection and repair. As a result, energy deficits can develop, typically increasing with the intensity and duration of marine heatwaves (MHWs). When these deficits are not offset by increased energy acquisition, other aspects of physiological performance are negatively affected. To cope, individuals may modify their behavior, relocate, or further adjust their physiology. However, if their buffering capacity is exceeded, MHWs can have severe consequences for individual performance

Vulnerability of Marine Ecosystems to Thermal Extremes

The marine environment encompasses diverse ecosystems that sustain rich biodiversity across both coastal and open ocean habitats. These ecosystems offer vital resources and services that support human societies, with a substantial portion of the global population relying directly on the ocean and coastal regions for their livelihoods, food security, and overall well-being. However, these ecosystems are increasingly under threat from a range of human-induced stressors, among which marine heatwaves (MHWs) have become particularly concerning. The rising frequency and intensity of MHWs disrupt the delicate balance of marine environments, leading to habitat degradation, loss of biodiversity, and altered ecosystem functioning. Such changes not only endanger marine species but also compromise the essential goods and services that oceans provide, ultimately affecting the social and economic stability of coastal communities worldwide. The vulnerability of marine ecosystems to marine heatwaves (MHWs) is influenced not only by the intensity and duration, but also by the ecosystem's inherent sensitivity and adaptive capacity.

Impacts of Marine Heatwaves (MHWs) on Marine Ecosystem Services

Category	Service Type	Impact of Marine Heatwaves (MHWs)
Provisioning	Living resources (non-food)	Extreme ocean temperatures cause widespread mortality, local extinctions, and range contractions among diverse marine taxa, reducing availability of biological materials.
	Food resources	Alterations in the distribution and abundance of commercially valuable fish and invertebrates disrupt fisheries and food supply chains.
Regulating	Carbon sequestration and storage	Decreased growth and high mortality of seagrasses and other primary producers results in reduction of carbon burial and long-term sequestration capacity.
	Moderation of extreme events	Loss of complex reef and kelp structures simplifies benthic habitats, changes hydrodynamics and sediment transport, and weakens natural coastal defences.
	Nutrient cycling	Increased water-column stratification and elevated temperatures reduce phytoplankton productivity and nutrient turnover; loss of seagrass and kelp further disturbs carbon and nitrogen cycling.

Impacts of Marine Heatwaves (MHWs) on Marine Ecosystem Services		
Category	**Service Type**	**Impact of Marine Heatwaves (MHWs)**
	Biological control	Anomalous warming promotes the spread and establishment of invasive non-native species, altering community structure and ecosystem stability.
Habitat / Supporting	Habitat provision	Mortality of habitat-forming species (corals, seagrasses, macroalgae) leads to habitat simplification, loss of structural complexity, and declines in biodiversity.
Cultural	Tourism and recreation	Heat-impacted coastal areas become less attractive for tourism and recreation, reducing their socioeconomic and aesthetic value.

Strategies to Control Marine Heatwaves and Prevent Habitat Loss

1. Global-Scale Climate Mitigation

Reduce greenhouse gas emissions: The primary driver of MHWs is global climate change. Rapid decarbonization through reduced fossil fuel use, increased renewable energy adoption, and improved energy efficiency is essential to limit ocean warming.

Implement international climate agreements: Stronger adherence to frameworks like the Paris Agreement can help stabilize global temperatures and reduce the frequency and intensity of MHWs.

Enhance carbon sequestration: Protecting and restoring blue carbon ecosystems (mangroves, seagrasses, salt marshes) enhances carbon uptake and moderates local ocean temperature anomalies.

2. Local and Regional Adaptation Measures

Habitat restoration and protection: Restoring degraded seagrass beds, coral reefs, and kelp forests can enhance ecosystem resilience by stabilizing sediments, improving water quality, and providing thermal refuges for species.

Marine protected areas (MPAs): Well-designed MPAs help reduce local stressors (e.g., overfishing, pollution), allowing ecosystems to better withstand heat stress.

Reducing coastal pollution: Minimizing nutrient runoff and sedimentation decreases eutrophication and light limitation, improving the ability of habitats like coral and seagrass to recover after MHWs.

3. Monitoring and Early Warning Systems

Ocean observing networks: Satellite data and in-situ temperature monitoring systems (e.g., NOAA Coral Reef Watch) can detect emerging heatwaves and provide early warnings.

Predictive modeling: Climate models can forecast potential MHW events, enabling managers to take pre-emptive action such as temporary fishing closures or coral shading interventions.

4. Ecosystem-Based Management

Integrated Coastal Zone Management (ICZM): Balancing human activities like fishing, tourism, and development can reduce cumulative stress on marine ecosystems.

Restoring food web balance: Protecting keystone species helps to maintain habitat structure after heat disturbances.

5. Research, Education, and Policy Support

Scientific research: Continued study of MHW dynamics, thresholds, and biological responses helps refine management approaches.

Community engagement: Local stewardship and awareness programs empower communities to participate in conservation and monitoring efforts.

Policy integration: Linking ocean management with climate adaptation policies ensures coordinated action across governance levels.

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Article ID : 05/XI/23/1125

ISSN : 2583-0910
Agri-India TODAY
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Peer reviewed monthly newsletter

APPLICATION OF NANOTECHNOLOGY FOR WATER PURIFICATION IN AQUACULTURE

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Abstract

Maintaining high water quality is essential for the health and productivity of aquaculture systems. However, increasing pollution, feed residues, and microbial contamination have made this a growing challenge. Nanotechnology offers innovative and effective solutions for purifying and managing aquaculture water through its unique nanoscale properties such as high surface area, strong reactivity and enhanced adsorption capacity. This article reviews how different nanomaterials such as nanofiltration membranes, nano adsorbents, photocatalysts, nano sensors, and antimicrobial nanoparticles are being applied to remove pollutants, heavy metals, and pathogens from aquaculture environments. These technologies not only improve water quality but also reduce dependence on chemicals and antibiotics, supporting a more sustainable and ecofriendly aquaculture industry. Despite their potential, concerns about nanoparticle toxicity, high cost, and lack of clear regulations remain key challenges. Future research focus on developing safer, biodegradable nanomaterials and integrating nano sensors for smart, real time water monitoring.

Keywords: Nanotechnology, Water purification, Nanosensors, Water quality management

Introduction

Aquaculture has grown rapidly over recent decades to meet rising global demand for seafood. However, this growth brings challenges: disease outbreaks, feed waste accumulation, nutrient loading, and deteriorating water quality all threaten productivity and sustainability. Effective water purification and management are therefore critical to maintain healthy aquatic environments and high yields. The term “nanotechnology” refers to materials, devices or systems that operate at the nanoscale (typically <100 nm) and benefit from unique physical, chemical and biological properties such as large specific surface area, quantum effects and enhanced reactivity. These features enable novel approaches for water treatment: adsorption, filtration, catalysis, sensing and antimicrobial action. When applied to aquaculture systems- ponds, recirculatory aquaculture systems (RAS), tanks- nanotechnology can help maintain water quality, remove pollutants, reduce pathogenic load and improve overall sustainability. This article explains the application of nanotechnology in water purification within aquaculture, covering key technologies (nano filtration membranes, nano adsorbents, photocatalysis, nano sensors and antimicrobial nanomaterials), their advantages, case studies, (especially toxicity and scalability) and future prospects.

Water quality challenges in Aquaculture

Water quality is one of the most important determinants of aquatic animal health, growth and survival. In aquaculture systems, water may be loaded with:

- Nitrogenous wastes (ammonia, nitrite, nitrate) from feed break down and excretions, which can become toxic to fish accumulation is high.
- Phosphates, causing eutrophication, algal blooms and oxygen depletion.
- Heavy metals (e.g., lead, cadmium, mercury, copper) arising from feed, sediments or external pollution.
- Organic contaminants, such as antibiotics, pesticides and hormones, especially in intensively managed systems.
- Pathogens (bacteria, viruses, parasites), which thrive in poorly managed water.

Nano technology solutions for Aquaculture water purification

Nano filtration (NF) membranes have pore sizes typically in range of 1-10nm, which allow them to remove small dissolved ions, organic molecules and micropollutants while retaining much of the essential salts or nutrients. In aquaculture, NF membranes can be integrated in recirculating systems to remove nitrates, phosphates, heavy metals and other dissolved contaminants.

For example, advanced membranes incorporating graphenr, carbon nanotubes (CNTs) or nano metal oxides benefit from high permeability, fouling resistance and selectivity. The review by Tripathy *et al.,* describes how nanocomposite membranes (metal/ metal-oxide +polymer) improved removal of heavy metals and organic compounds. Such membranes help maintain water clarity, reduce nutrient loads and there by support healthy aquaculture production cycles.

Nanofiltration and nano membrane

Process: During nanofiltration, pressure is applied to contaminated water, forcing it through a specialized membrane. The membrane acts as a barrier that allows only certain molecules and ions to pass while blocking larger and unwanted contaminants .

The contaminants removed by nanofiltration are illiustrated and listed in the above image:

- **Bacteria**: Microorganisms that can cause disease and affect water quality.
- **Colloids**: Very fine particles that do not settle naturally and cause turbidity.
- **Suspended particles**: Larger particles that float in water and can include dirt, debris, or organic material.
- **Viruses**: Much smaller than bacteria, these can be hazardous to health.
- **Proteins**: Organic molecules that may be present in contaminated water.

- **Monovalent ions**: Ions with a single positive or negative charge (like sodium or chloride).
- **Multivalent ions**: Ions with more than one positive or negative charge (like calcium or sulfate)

Nanofiltration membrane

The membrane used is highly selective, removing contaminants down to 0.001 microns in size. As water passes through, the membrane effectively captures almost all bacteria and viruses, most organic matter, divalent ions (multivalent ions), and up to 90% of monovalent ions. This shows that after filtration, only some of the smallest can pass through. Bacteria, viruses, proteins, and larger ions are retained and do not make it into the filtered water.

Nano adsorbents

Nanoadsorbents exploit the large surface to volume ratio of nano particles to bind or trap contaminants via adsorption, ion exchange, or surface complexation. Examples include iron oxide nano paricles (Fe_3O_4), nano- zeolites , carbon nanotubes, graphene oxide, chitosan nanoparticles and others. In one study targeting RAS water, nano-porous absorbents were to reduce ionic species (e.g., ammonia) and derived batch-reactor parameters for controlling water quality.

Another case: Biosynthesized iron oxide nanoparticles(Fe_2O_3) immobilized in a cryogel were used to remove cadmium from tilapia culture water, improving fish physiology and reducing metal accumulation. Nano adsorbents can be used either in pre-treatment (before water enters culture tanks) or within the water loop to continuosly scrub contaminants. They are especially useful to treat heavy metals, ammonia, phosphates and micropollutants.

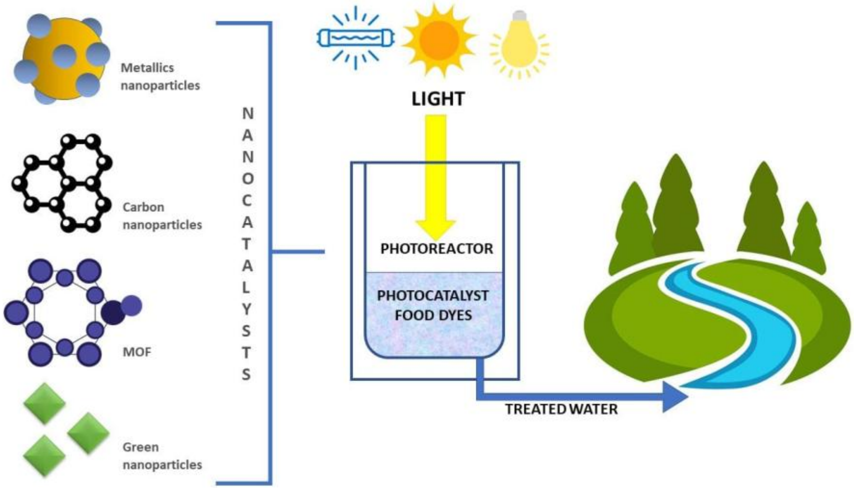
Nanocatalysts

Classification of major material types utilized as nanocatalysts. Nanocatalysts are catalysts whose active components or structures are in the nanoscale range (typically 1 to 100 nanometers). Their small size gives them a high surface area- to- volume ratio, leading to enhanced catalytic efficiency, selectivity, and often, stability compared to their bulk counterparts.

The six principal categories shown in the diagram are:

- **Graphene based materials:** These utilize graphene, a single layer of carbon atoms arranged in a two dimensional hexagonal lattice, or its derivatives (like graphene oxide or reduced graphene oxide). Their extraordinary electrical conductivity and extremely high surface area make them excellent supports or active components for various catalytic reactions.
- **Metals and metal oxides:** This category includes nanoparticles of pure metals (e.g., Pt, Au, Pd, Ag) and their corresponding oxides (e.g., TiO_2, ZnO, Fe_3O_4). These are among the most widely used nano catalysts, playing crucial roles in hydrogenation, oxidation, and photocatalysis.

- **Zeolites:** Zeolites are crystalline aluminosilicates with well defined porous structures. Their precise pore sizes and internal surface acidity makes them highly selective catalysts, particularly in petrochemical and refining processes. Nanoscale or modified zeolites offer improved mass transport and accessibility to active sites.
- **Carbon nanotubes (CNTs):** These are cylindrical nanostructures m:ade of carbon. They can act as excellent catalyst supports due to their high mechanical strength, thermal stability, and large surface area. The inner and outer walls can be functionalized or loaded with active species.
- **Metal organic framework (MOF):** MOFs are a class of porous crystalline materials consisting of metal ions or clusters coordinated to organic ligands. They possess exceptional porosity and tunable structural features, making them ideal candidates for selective catalysis, separation, and storage.
- **Clay based materials:** This category involves natural or modified clay minerals (like montmorillonite or bentonite) that are often layered and possess ion-exchange capabilities. When used as nano catalysts or catalyst supports, they are attractive due to their low cost, abundance and large surface area.



Photocatalysis

Photocatalytic nanomaterials, such as titanium dioxide (TiO_2) nanoparticles, zinc oxide (ZnO) nanoparticles or doped variants, exploit light (UV or visible) to produce reactive oxygen species (ROS) that degrade organic pollutants, disinfection by-products, antibiotics, harmones and other micropollutants. This means that feed residues, pesticide runoff, antibiotic traces and other organic loads can be broken down into benign products (CO_2.H_2O) instead of accumulating. For e.g., a nanomaterials study observed ZnO nanoparticles for dehalogenation reactions and degradation of microbial matter via ROS generation. Such systems can be integrated as part of water recirculation loops or as side- stream treatment units in installations.

Treatment

- **The medium:** A container, labeled **photoreactor**, holds the contaminated water, which is a mixture of the photocatalyst (the chosen nanocatalyst) and the food dyes (the contaminants).
- **The energy source (light):** The process is driven by light energy, indicated by a sun (natural light), a fluorescent lamp (UV light), and an incandescent bulb (visible light). The photocatalyst absorbs the light energy (photons), leading to the generation of electron-hole pairs. These

pairs initiate redox reactions with water and oxygen, producing highly reactive species (like hydroxyl radicals, -OH).

- **The reaction:** These reactive species chemically break down and mineralize the organic dye molecules into harmless substances like CO_2 and H_2O. This process is known as photocatalytic degradation.
- **Treated water:** Following the reaction, the water is separated from the catalyst and released as treated water.
- **Environmental remediation:** The treated water is flowing into a clean environment.

Nano sensors for water monitoring

Devices that use nanomaterials to detect physical, chemical or biological parameters. Made from materials like carbon nanotubes, gold nanoparticles, quantum dots, and metal oxides. Provides high sensitivity, selectivity, and rapid response due to their nanoscale properties.

Principle: The fundamental princile used in nanosensors for water monitoring in aquaculture is the high surface area- to- volume ratioof nanomaterials, which leads to an amplified signal upon interaction with the target analyte. The specific working principles of nanosensors are actegorised based on their signal transduction mechanisms:

Electro chemical nanosensors

These are the most common and rely on the measurement of an electrical signal (current, voltage, or resistance) resulting from a chemical or physical interaction.

Principle: Nano materials like nanoparticles are used to modify the electrode surface. When the target analyte (e.g., ammonia or heavy metals)interacts with the active nanomaterial, it causes a measurable change in the electrical properties of the electrode, such as resistance or conductivity.

Example: A metal Oxide Semi-conductor (MOS) nano sensor, where gases like ammonia adsorb onto the surface of metal oxide nanowires, changing the electrical resistance proportional to the gas concentration.

Optical nanosensors:

These sensors measure changes in light properties (absorption, emission, or scattering) to detect the analyte.

Principle: They utilize nanomaterials like quantum dots or fluorescent nanoparticles that are functionalized to react with a specific analyte.

For example, In DO sensor, an oxygen-sensitive fluorescent dye is embedded in a nano-layer. Oxygen molecules quench (reduce) the intensity or change the lifetime of the dye’s fluorescence when exposed to light.

Example: Fluorescent - based nano sensors for DO or pathogens, where the presence of the target molecule directly affects the light emission of the nanomaterial, providing a high sensitive signal.

Surface plasmon resonance (SPR)

Principle: These sensors monitor changes in the refractive index near a surface coated with metallic nanoparticles (like gold or silver). When an analyte binds to the functionalized surface, it changes the local refractive index, which is detected as a shift in the SPR signa.

Antimicrobial nanoparticles.

Nanoparticles of silver (AgNPs), copper oxide (CuO), zinc oxide (ZnO) and other metals exhibit strong antimicrobial and anti-biofilm effects. They can be used in aquaculture water systems to suppress pathogenic bacteria (e.g., Vibrio, Aeromonas), reduce biofilm formation on tanks or pipes, and minimize antibiotic usage. For example, in aquaculture wastewater treatment, silver and zinc oxide nanoparticles showed removal efficiencies for ammonia (>98%) and significant microbial count reductions. By using antimicrobial nanomaterials judiciously (with careful monitoring for toxicity), water quality can be enhanced and disease incidence reduced.

Advantages of Nanotechnology in Aquaculture Water Purification

1. High efficiency & selectivity: Nanomaterials offer improved removal of trace pollutants, heavy metals, micropollutants and pathogens compared with many conventional methods
2. Reduced footprint & energy consumption: Some nano-membrane and nano adsorbent systems operate under milder conditions, saving energy and space.
3. Enhanced water reuse: In recirculating aquaculture systems (RAS), cleaner water means less fresh-water input, lower effluent discharge, and more sustainable operations.
4. Better animal health and productivity: By sustaining higher water quality and reducing disease-pressure, growth rates, survival and feed conversion can improve.
5. Flexibility and modularity: Nano-based treatment units can be retrofitted into existing systems or scaled for various sizes of operations.

Conclusion

Nanotechnology holds significant promise for enhancing water purification in aquaculture. Through nanofiltration membranes, nano adsorbents, photocatalytic nanomaterials, nano sensors and antimicrobial nanoparticles, aquaculture systems can maintain higher water quality, reduce pollutant loads, improve animal health and increase productivity. However, the path to large-scale adoption is challenged by toxicity concerns, cost and regulatory issues. With responsible development, pilot implementation and robust risk management, nanotechnology can become a key component of sustainable aquaculture water management meeting the global demand for seafood while preserving aquatic environments.

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ISSN : 2583-0910
Agri-India TODAY
visit us at www.agriindiatoday.in

Peer reviewed
monthly newsletter

Article ID : 05/XI/24/1125

AGRICULTURE-LINKED HUMAN NUTRITION: PATHWAYS, CHALLENGES AND POLICY PRIORITIES

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Abstract

India is grappling with a dual burden of malnutrition, persistent undernutrition on the one hand and rising overweight and obesity on the other. Agriculture plays a pivotal role in shaping dietary diversity, food security and affordability of nutritious foods. However, challenges such as climate change, soil degradation and socio-economic inequalities are impeding progress. Crop diversification, bio-fortification, reduction of post-harvest losses and better integration between agriculture and health policies are essential to strengthen the agriculture-nutrition nexus. Priority actions for 2025-30 should focus on nutrition-sensitive agriculture, targeted social protection and community level interventions. This article highlights how agriculture-related human nutrition in India is a key driver of food, and nutrition security.

Introduction

Agriculture plays a central role in shaping human nutrition, as the quality and diversity of crops grown directly determine the nutritional adequacy of the diet. The types of crops, cultivation methods, post-harvest care and food distribution, calorie availability and the amount of essential nutrients, etc. directly affect nutrition. Improvements in agricultural productivity have led to a significant reduction in hunger over the past decades, but malnutrition and micronutrient deficiencies remain persistent challenges in many regions. Despite high production of staple cereals, dietary diversity remains low, resulting in widespread deficiencies of iron, zinc, vitamin A and other micronutrients even with adequate calorie intake.

Agriculture and nutrition are deeply intertwined. In India, agriculture is the main source of livelihood for almost half the population and continues to influence food availability and affordability. Intensive agriculture involves mono-cropping, excessive use of chemical fertilizers and soil erosion which reduce the amount of nutrients in the crops. Biofortified foods reduce the consumption of bioavailable food, while post-harvest losses and processing methods such as milling and refining further reduce the nutritional quality of food. The positive side is that biofortified foods are also used in biofortified foods. (Biofortified) Innovations such as crop rotations, integrated farming systems and crop diversification have shown promising results in improving nutrient availability and addressing the problem of “underlying hunger”. In addition, inclusion of animal-source foods through livestock and aquaculture can increase protein and micronutrient intake. Clearly, despite significant progress in food production and food security programmes, malnutrition remains a persistent challenge. Therefore, a re-evaluation of the agriculture-nutrition interface is necessary from research and policy perspectives to develop strategies that move beyond calorie adequacy to nutrient adequacy and health security.

Agriculture-related human nutrition challenges

Agriculture and nutrition are deeply interconnected. Several challenges hinder the effective integration of agriculture and nutrition. Soil erosion reduces nutrient content in crops. Climate change affects crop yields and micronutrient density. Limited crop diversity and overreliance on staple cereals reduce diet quality. Post-harvest losses due to poor storage and processing lead to nutrient losses. Finally, socio-economic barriers prevent poor households from accessing nutrient-rich foods even when they are available.

Several challenges hinder the effective integration of agriculture and nutrition. Soil erosion reduces nutrient content in crops. Climate change affects crop yields and micronutrient density. Limited crop diversity and overreliance on staple cereals reduce diet quality. Post-harvest losses due to poor storage and processing lead to nutrient losses. Finally, socio-economic barriers prevent poor households from accessing nutrient-rich foods even when they are available.

Factors causing malnutrition

The drivers of malnutrition in India are complex and interconnected. Poverty and income inequality limit access to diverse diets, while climate change and soil degradation reduce agricultural productivity and threaten nutritional security. Post-harvest losses, especially of perishable foods such as fruits and vegetables, reduce the supply of essential micronutrients. Gender inequality limits women's control over resources and decision-making, limiting the potential for improved maternal and child nutrition. Cultural dietary preferences and gaps in health and sanitation services further exacerbate this challenge.

Impact of agricultural practices on nutrition

***Monoculture and dietary diversity*: Many farmers practice mono-cropping or growing the same crop in the same field year after year, which in turn causing environmental and economic risks as displayed in Figure 1. Focusing** primarily on staple crops can reduce dietary diversity. Excessive reliance on grains can lead to protein and micronutrient deficiencies, leading to malnutrition despite adequate calories.

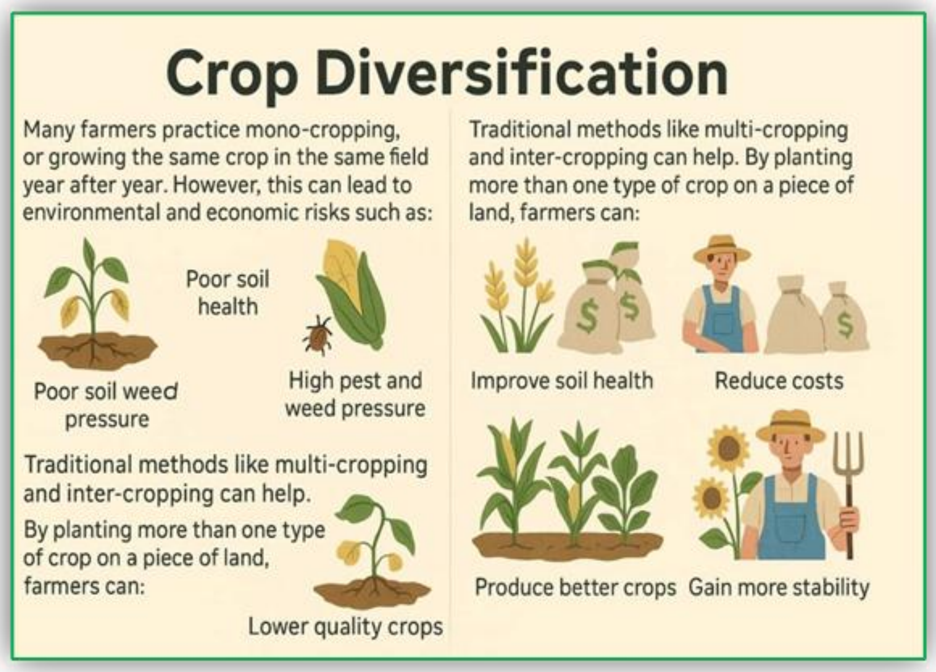

Fig.1.Impact of mono-cropping vs. multi-cropping on soil health, crop productivity and quality

Soil erosion and loss of nutrients: Continuous mono-cropping and excessive use of chemical fertilizers can reduce soil fertility. Crops grown on nutrient-poor soils may have low micronutrient content, reducing nutritional quality for consumers.

Post-harvest and processing effects: Modern agricultural systems often involve storage, grinding, and refining practices that destroy essential nutrients (e.g., polished rice loses vitamin B and fiber). Long-distance transport and improper storage can reduce the vitamin content of fruits and vegetables.

***Use of agricultural chemicals*:** Excessive pesticides and fertilizers can contaminate food and water, posing health risks. Certain practices can affect the microorganisms present in soil and crops, indirectly affecting human gut health and nutrient absorption.

Current status of malnutrition in India

Recent surveys show that India faces challenges in tackling malnutrition. According to the National Family Health Survey-5 (NFHS-5) and subsequent projections for 2023-24, about 35% of children under five years of age are stunted, 19% are wasted and 32% are underweight. Anemia remains a serious concern, affecting over 57% of women of reproductive age and 67% of children under five years of age (**Fig. 2**). Although progress has been made, the dual burden of malnutrition and rising obesity highlights the need for agriculture-nutrition integration.

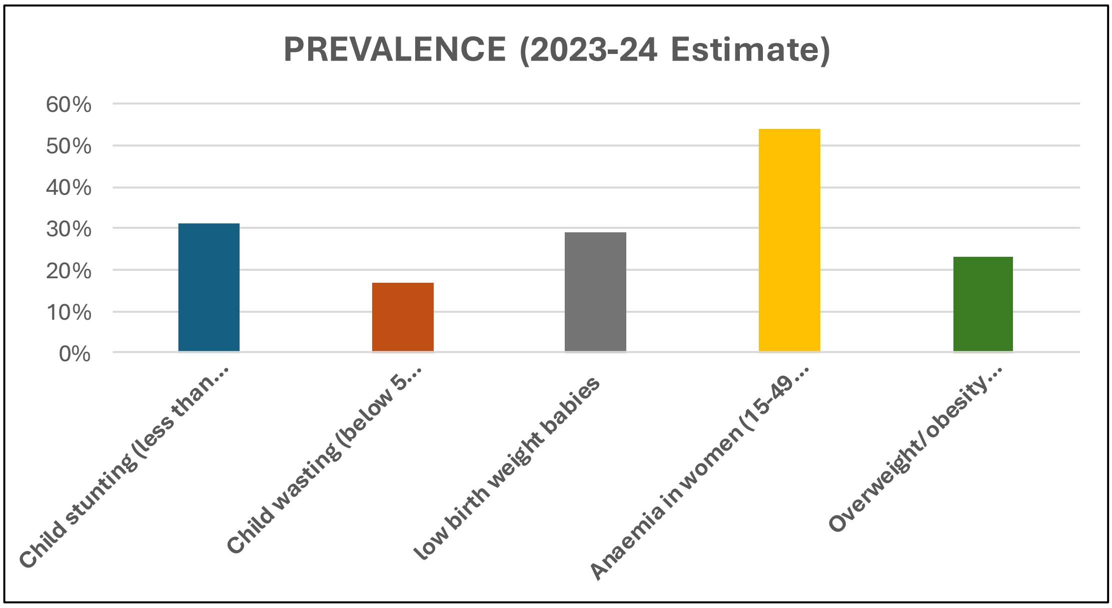

Fig.2. Impact of malnutrition on human health
Source: National Family Health Survey-5 (NFHS-5)

Agriculture and nutrition are deeply interlinked, as the quality and diversity of crops grown directly determine the nutritional adequacy of the diet. In India, agriculture is the main source of livelihood for nearly half the population and continues to influence food availability and affordability. Despite significant progress in food grain production and food security programmes, malnutrition remains a persistent challenge. Therefore, a re-evaluation of the agriculture-nutrition interface is necessary from research and policy perspectives, to develop strategies that move beyond calorie adequacy to nutrient adequacy and health security.

Relationship between agriculture and human nutrition
Agriculture is not only the basis of human livelihood but also a major determinant of nutrition and health. Agriculture affects nutrition outcomes through multiple channels. It determines food availability at the household and community levels, shapes dietary diversity, and provides income to purchase nutritious foods. Empowerment of women in agricultural systems also directly affects household nutrition outcomes.

Increased food availability: High-yielding varieties, improved irrigation and mechanisation have increased the quantity of staple crops like rice, wheat and maize. Greater availability of staple foods reduces calorie deficiency and hunger, especially among lower-income populations. Crop diversification (including legumes, vegetables and fruits) increases access to micronutrients such as iron, zinc, vitamin A and folate. Adequate production of cereals, pulses, fruits and vegetables ensures food security. However, mono-cropping or low-diversity cropping systems may provide calories but lack essential nutrients, leading to hidden hunger or micronutrient deficiencies.

Soil nutrients and crop nutritional quality: Soil rich in micronutrients such as iron, zinc and selenium produces nutrient-rich crops. However, depleted soils result in reduced levels of essential vitamins and minerals in crops, increasing the risk of malnutrition, anaemia and stunted growth.

Diversification of crops: Growing a mix of cereals, legumes, fruits and vegetables improves dietary diversity. Similarly, integrating animal husbandry such as milk, eggs and fish increases protein and micronutrient intake. Crop diversity and soil health are important to ensure that diets are rich in essential micronutrients. For example, iron-enriched millets and zinc-enriched rice developed through biofortification demonstrate how targeted agricultural research can address hidden hunger. Similarly, diversified farming systems that incorporate pulses, fruits, vegetables and livestock are more likely to provide a balanced diet than single-crop cereal production.

Benefits of crop diversification are shown in **Fig.3**.

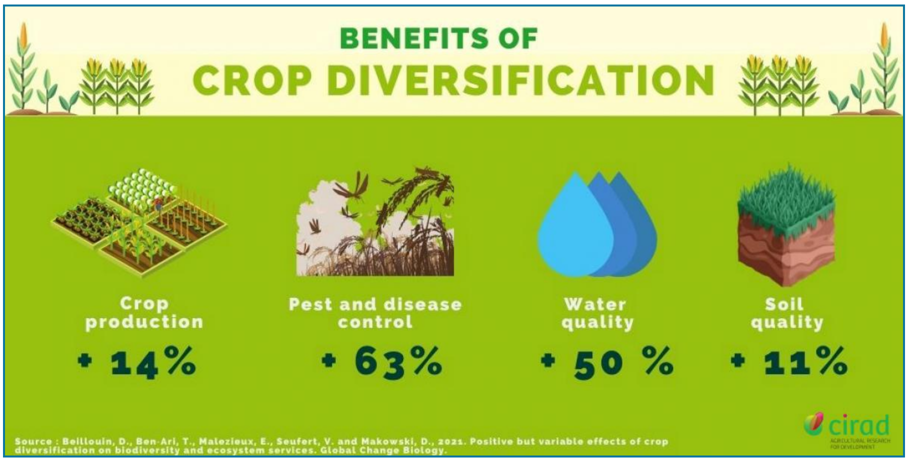

Fig.3. Benefits of crop diversification on yield and related parameters.

Bio-reinforcement (Biofortification) **: A real need**

- Biofortification improves the nutritional quality of food crops by increasing the number of essential vitamins and minerals in them, making them healthier to eat. It helps fight malnutrition, especially in low-income areas, by providing critical nutrients such as iron, zinc and vitamin A directly through staple foods without any supplements. Biofortified crops can reduce health problems caused by deficiencies such as anemia and vision loss, improving the overall health of vulnerable groups such as children and pregnant women.

- This process is highly cost-effective because after the initial development of biofortified seeds, the benefits last for multiple growing seasons with no additional recurring costs. Biofortification also helps farmers by enabling them to grow more nutritious and valuable crops, which can fetch them better prices and improve food security in their communities. In addition, many biofortified crops are more resilient to diseases, pests, and environmental stresses, leading to better nutritional outcomes as well as agricultural sustainability.
- Currently, India has bio-fortified several crops to address nutritional deficiencies and improve public health. The major bio-fortified crops grown in India include rice, wheat, maize and millets, which have higher iron, zinc and protein content. In addition, there are also bio-fortified pulses such as lentil, chickpea, fieldpea, urad and moong, which are grown for higher protein, iron and zinc content. Several oilseeds, including mustard, soybean, sesame and groundnut, have also been developed with improved nutritional profiles.

In horticultural crops, sweet potatoes and potatoes have been bio-fortified for higher content of vitamin A and iron; Amaranthus and Greater Yam are grown for enhanced micronutrient content; also, select crops such as cauliflower, okra, banana, guava, grapes and pomegranate now have higher vitamin and mineral content. Since 2014, the Indian Council of Agricultural Research (ICAR) has released 142 bio-fortified varieties, including 124 field crops and 18 horticultural crops, and over 10 million hectares of area has been covered under these varieties to help reduce malnutrition.

Examples of biofortified crops in India:

- ***Millet:*** Increased iron content
- ***Wheat* :** Zinc bio-fortification
- ***Rice:*** Zinc bio-fortified varieties
- ***Potatoes:*** High in iron, zinc, and vitamin C.
- ***Corn, sweet potatoes, lentils, black eyed peas* :** Improves iron, zinc or vitamin A levels.

India has released several bio-fortified rice and wheat varieties that are now available for cultivation to address malnutrition and improve nutritional security, which are detailed below:

Bio-fortified rice varieties

- *CR Dhan 310* (high protein, first of its kind in India);
- *CR Dhan 411 (Swarnanjali),* high protein 'Swarna')
- *CR Paddy 315* (High Zinc: 25 ppm)
- *DRR Paddy 45* (High Zinc)
- *DRR Dhan 48* (high zinc)
- *DRR Paddy 49* (High Zinc)
- *DRR Paddy 63* (High Zinc)
- *Surbhi* (high zinc)
- *Zinko Rice MS* (High Zinc)
- *Chhattisgarh Zinc Rice-1* (High Zinc)

- *Chhattisgarh Zinc Rice-2* (High Zinc)
- *CR Paddy 311 Mukul* **(** High Protein and Medium Zinc)
- *CR Dhan 324 Abhay Nutritious* (High Protein: ~11%, Zinc: ~23 ppm)
- *Spurthi* (zinc-enriched, releasing in 2023)

Bio-fortified wheat varieties

- *PBW 872* (iron: 42.3 ppm, zinc: 40.7 ppm);
- *Pusa Ojaswi (HI 1650)* (Zinc: 42.7 ppm);
- *Karan Vrinda* (DBW 371) (Protein: 12.2%, Iron: 44.9 ppm); **Karan** *Varun (DBW 372)* (Protein: 12.2%, Zinc: 40.8 ppm);
- *advanced (HD 2967/HD 3406)* (protein: 12.25%);
- *Macus saccas (Macus 6768)* (Protein: 12.0%, Iron: 41.2 ppm, Zinc: 45.1 ppm);
- *Pusa Wheat 3369 (HD 3369* ***)*** (Iron: 40.6 ppm);
- *Karan Aditya (DBW 332* **)** (Protein: 12.2%);
- *Pusa Vakula (HI 1636)* (zinc: 44.4 ppm);
- *HUW 838* (zinc: 41.8 ppm);
- *MP(JW) 1358* (Protein: 12.1%, Iron: 40.6 ppm);
- *DBW 327 (Karan Shivani* ***)*** (Zinc: 40.6 ppm);
- *DBW 303 (Karan Vaishnavi)* (Protein: 12%);
- *PBW 771* (Zinc: 41 ppm);
- *PBW 752* (protein: 12%);
- *HPBW 01* (iron: 40 ppm, zinc: 41 ppm);
- *Pusa Tejas Durum* (Protein: 12%; Iron: 41 ppm; Zinc: 43 ppm);
- *WB 02* (Zinc: 42 ppm, Iron: 40 ppm, Protein: 12.4%)

These varieties have been developed and released by ICAR and associated national research institutes, and have been recommended for diverse agro-ecological regions across the country for both yield performance and improved nutritional quality.

Agricultural innovations such as biofortified crops (iron-fortified beans, zinc-fortified wheat, vitamin A-fortified sweet potatoes) directly improve nutrient intake. Such crops combat “underlying hunger,” which occurs even when calorie intake is adequate but micronutrient intake is inadequate.

Impact of agricultural practices on nutrition

The way food is produced—crop choice, cultivation methods, input use, post-harvest management—directly affects the availability, quality, and nutrient composition of food. Modern agricultural practices can have mixed effects on human nutrition while increasing productivity. Understanding these relationships is critical for developing strategies that ensure both food security and nutritional security.

Agricultural practices affect not only yields but also the nutritional quality and resilience of food systems under climate stress (**Table 2**).

Table 2. Effect of agricultural practices on nutrition

Agricultural Practices	Effects on human nutrition
Chemical-intensive farming	Soil and crops may be deficient in micronutrients; pesticide residues affect health

Agricultural Practices	Effects on human nutrition
Organic Farming	Increases soil fertility, crop nutrient content, and reduces chemical exposure
Crop rotation and intercropping	Improves soil health and provides dietary diversity
Irrigation and Water Management	Ensures consistent crop yields and a stable food supply

Here is a brief overview of **the effects of agricultural practices on nutrition.**

Sustainable for balanced nutrition Agriculture Methods

Below are the key points related to sustainable agricultural practices for balanced nutrition related to agriculture:

- The amount of nutrients in crop produce can be increased through balanced crop nutrition.
- Prohibit burning of crop residues to improve soil health and crop nutrition, so as to increase the nutrient content in crop products.
- Organic farming, integrated pest management (IPM) and agroforestry can maintain soil health and improve nutrient density in crops.
- Reducing chemical residues in crops can reduce exposure to harmful substances and promote long-term health.

Role of Livestock and Fisheries: Integrating animal husbandry and aquaculture provides high-quality protein, essential fatty acids, and micronutrients such as vitamin B12, iron, and calcium. Agricultural practices that neglect animal and fish protein sources can further exacerbate nutrient deficiencies.

Socio-economic and policy dimensions: Small farmers' access to diverse seeds, extension services and markets affects nutritional outcomes. Subsidies often favour staple crops such as rice and wheat over nutrient-rich crops, affecting food availability and diversity. Policies promoting "nutrition-sensitive agriculture" are emerging to link production choices directly to improved nutrition.

Agriculture and nutrition: Government initiatives

The Government of India has launched several initiatives to link agriculture with nutrition.

- *Poshan Abhiyaan:* Nutrition campaign and health interventions integrate nutrition programmes with agriculture for children and women. And HarvestPlus for iron, zinc and vitamin A crops.
- *National Food Security Mission (NFSM)* - Diversification of food grains through pulses and millets.
- *Soil Health Card Scheme-* To promote balanced fertilizer for crop nutrient quality.
- *Bio-fortification Programmes* : Bio-fortification programmes led by ICAR and CGIAR promote the adoption of micronutrient-rich crops.
- *Soil Health Card Scheme* helps to ensure balanced nutrient utilization for higher crop nutrition.
- *National Food Security Mission:* National Food Security Mission focuses on pulses, millets and diversified crops to improve the quality of diet.

Policy priorities for agriculture-nutrition nexus are presented **in Table 3.**

Table 3: Agriculture-linked nutrition: Policy-related Preferences

Priority Sector	**Recommended Action**
Soil Health	Expand Soil Health Card Scheme, promote micronutrient management
Bio-reinforcement	Mainstreaming bio-fortified crops in the public distribution system and school meals
Crop Diversification	Promote pulses, millets, fruits and vegetables
Nutrition Awareness	Strengthen *Nutrition Campaign*, Women and Child Nutrition Education
Post-harvest losses	Cold chains, storage and processing facilities
Nutrition-sensitive agriculture	Crop diversification, bio-fortification, more focus on pulses, fruits, vegetables
Climate Resilience	Sustainable practices, soil health restoration and water-use efficiency
Social Security	Strong safety nets, fortified foods in ICDS and PDS, maternal nutrition support
Integration	Convergence of agriculture, health and nutrition programmes at the local level

Nutri-Cereals

Different Nutri-Cereal crops grown in India are displayed in **Picture 1.** Nutri-cereals are important in human nutrition because they are rich in fibre, protein, vitamins (especially B vitamins), and minerals (like iron, calcium, zinc) (**Table 4**), offering benefits such as managing diabetes, regulating blood sugar and pressure, and supporting cardiovascular health. They also contain beneficial phytochemicals with antioxidant properties and are a good source of complex carbohydrates that are digested slowly, providing sustained energy. They provide essential macro- and micronutrients, including dietary fibre, protein, carbohydrates, and vitamins and minerals like calcium, iron, potassium, and magnesium. The high fibre content aids digestion, promotes gut health, and helps in weight management. Their lower glycemic index and resistant starch content lead to a slower release of glucose, making them excellent for managing diabetes and regulating blood sugar levels.

Nutri-cereals can help lower cholesterol, regulate blood pressure, and reduce the risk of cardiovascular diseases. They contain bioactive compounds like polyphenols and anthocyanins that act as antioxidants, fighting inflammation and protecting against chronic diseases. Many nutri-cereals are naturally gluten-free, making them suitable for individuals with celiac disease or gluten sensitivities.

Picture 1. Nutri-Cereal crops grown in India

Table 4. Nutritional values of Nutri-Cereals

Crop	CHO (g)	Protein (g)	Fat (g)	Crude fiber (g)	Ash (g)	Ca (mg)	P (mg)	Fe (mg)	Zn (mg)	Mg (mg)
Finger millet	72.6	7.7	1.5	3.6	2.7	344	250	6.3	2.3	130
Foxtail millet	60.9	12.3	4.3	8	2.7	31	290	2.8	2.4	81
Proso millet	60.9	12.5	1.1	5.2	3.3	14	206	0.8	1.4	81
Barnyard millet-	65.5	6.2	4.4	13.6	2.2	20	280	8	3	137
Little millet	65.6	10.4	1.3	7.6	1.3	16.1	220	1.3	3.7	133
Kodo millet	66.2	8.9	2.6	5.2	1.7	15.3	188	2.3	0.7	147
Pearl millet	70.0	8.5	2.7	2.6	2.0	50.0	450	7.5	3.1	137
Sorghum	70.7	10.4	3.1	2.0	1.8	25	520	5.4	1.7	165
Finger millet	72.6	7.7	1.5	3.6	2.7	344	250	6.3	2.3	130
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Pearl millet	70.0	8.5	2.7	2.6	2.0	50.0	450	7.5	3.1	137
Sorghum	70.7	10.4	3.1	2.0	1.8	25	520	5.4	1.7	165

Policy Brief: Recommended Priority Actions (2025-30)

An integrated and multi-sectoral approach is needed to address malnutrition through agriculture. Nutrition-sensitive agriculture should be mainstreamed into national policies, while agriculture and health sectors must work together to achieve results. Expanding bio-fortified crops, reducing post-harvest losses, and promoting dietary diversity through awareness and production strategies are central to this agenda. The policy priority implementation strategies for agriculture-nutrition nexus are given below:

To improve agriculture-related human nutrition, crop diversification and cultivation of nutrient-rich crops should be promoted, including cultivation of fruits, vegetables, legumes, pulses, oilseeds and bio-fortified varieties, while adopting inter-cropping and crop rotation systems to simultaneously enhance soil fertility and dietary diversity.

- Agricultural policies should be made more nutrition-sensitive by reforming subsidies to encourage the production of nutrient-rich foods rather than just staple cereals, supporting government seed programmes for micronutrient-rich varieties, and integrating nutrition indicators into agricultural planning and monitoring frameworks.
- Balanced fertilisation and integrated soil fertility management should be implemented to maintain nutrient-rich soil, while precision agriculture technologies, including organic farming, compost and nano-fertilisers, should be promoted to enhance nutrient absorption efficiency and crop quality.
- Post-harvest losses should be minimised by improving storage, transportation and cold chain infrastructure, and food processing methods should be adjusted to retain essential vitamins and minerals, including the development of community-based processing units to preserve local nutrient-rich crops.
- The integration of livestock and aquaculture within agricultural systems should be strengthened to provide high-quality proteins, essential fatty acids and micronutrients, while nutrition education programs should raise awareness among farmers and consumers about dietary diversity, nutrient-sensitive agricultural practices and the impact of food choices on household nutrition.
- Finally, research and monitoring efforts should be expanded to study nutrient retention, bio-fortification, sustainable agricultural practices, and the links between agricultural production and nutrition outcomes, as well as regular tracking of micronutrient deficiencies and dietary diversity at regional and national levels.
- By implementing these measures in a coordinated manner, agricultural systems can be transformed to not only meet calorie requirements but also provide essential nutrients, thereby reducing malnutrition, improving public health, and strengthening long-term food and nutrition security

Approaches to agriculture-related human nutrition support

1. **Promote bio-fortified crops and nutrient-rich farming systems.**
2. **Strengthen soil health programs with a nutrition-sensitive approach.**
3. **Encourage crop diversification and include millets, pulses, fruits and vegetables in public food schemes.**
4. **Integrate agriculture and nutrition planning at the state and district levels.**
5. **Address post-harvest losses with improved storage and processing infrastructure.**
6. **Increase area under Nutri-cereals.**
7. **Climate-resilient agriculture**
8. **Increase community nutrition awareness by linking dietary diversity to agricultural practices.**
9. **Effective implementation of these priority areas can accelerate progress towards reducing malnutrition and also enhance agricultural sustainability and resilience.**

The way forward

The way forward requires an integrated and multi-sectoral strategy that strengthens the link between agriculture and human nutrition. Agriculture must move beyond calorie adequacy to ensuring dietary diversity, micronutrient adequacy and long-term health outcomes. To achieve this, several priority actions are recommended.

- Nutrition-sensitive agriculture should be mainstreamed into all agricultural programmes, rural development missions and state-level agricultural policies. This will ensure that food systems are designed not only to increase productivity but also to improve the nutritional status of the population.
- There is a need to expand research, seed multiplication and dissemination of biofortified crop varieties so that farmers can adopt nutrient-rich crops on a large scale. These include cereals rich in zinc and iron, sweet potatoes and maize rich in vitamin A, and pulses rich in calcium and protein.
- Soil management should be improved through balanced fertilisation, use of organic matter and nano-fertilisers so that crops are rich in essential micronutrients. Along with this, crop diversification should be promoted, with special emphasis on millets, pulses, fruits and vegetables, which are naturally rich in vitamins and minerals.
- Resilient cropping systems must be developed to meet the challenges of climate change to ensure food and nutrition security even under stressful conditions. Improved irrigation management, drought-tolerant varieties and integrated farming systems will play a key role in this.
- Post-harvest management, food fortification and strengthening value chain linkages are essential to reduce nutrient losses and make nutritious food accessible to all sections of society. Public food distribution systems should include more nutrient-rich crops besides rice and wheat.
- Nutrition education campaigns should be intensified at the community level to encourage a diverse diet, especially among women, children and vulnerable sections. Local food-based solutions, kitchen gardens and school meal diversification will be important in this regard.
- Strong synergies between the agriculture, health and education sectors should be promoted. Coordinated action between ministries and departments will help integrate agricultural practices, nutrition interventions and public health outcomes into an integrated framework for sustainable nutrition.
- Policy and socio-economic factors also play an important role, as agricultural subsidies and production incentives traditionally favour staple crops over nutrient-rich foods, and small farmers often lack access to diverse seeds, extension services and markets, limiting the potential for nutrition-sensitive agriculture. Therefore, achieving human nutrition security requires agriculture to move beyond simply increasing calorie production to focusing on nutrient-sensitive practices, sustainable agricultural methods and systems that enhance dietary quality and diversity.

The above action plan emphasizes the shift from food security to nutrition security, making agriculture the cornerstone of better health and well-being in India.

Summary

India is at a critical juncture in its fight against malnutrition. Although some progress has been made in reducing stunting and underweight, gaps remain in tackling the growing challenge of anaemia, wasting and obesity. Integrating nutrition goals into agricultural strategies, and supporting policies that emphasise sustainability, diet quality and equity will be essential. *Achieving the goals of the Nutrition Abhiyaan*, the Sustainable Development Goals and India's national development priorities by 2030 will require coordinated, community-led and evidence-based action that places nutrition firmly at the centre of agricultural policy.

Conclusion

Agriculture is the backbone of human nutrition. By focusing on soil health, crop diversity, bio-fortification and sustainable agricultural practices, food systems can directly improve diet quality and human health and help reduce hidden hunger. Integrating agriculture and nutrition policies is crucial to address these issues. Coordinated action between agriculture, health and nutrition sectors is essential to ensure a healthier and more resilient India.

ISSN : 2583-0910
Agri-India TODAY
visit us at www.agriindiatoday.in

Peer reviewed
monthly newsletter

Article ID : 05/XI/25/1125

NANOTECHNOLOGY FOR TRANSFORMING AGRICULTURAL WASTE INTO VALUE-ADDED PRODUCTS

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Abstract

Agricultural waste presents major environmental challenges, with harmful practices like crop burning contributing to severe pollution. Conventional waste management methods often fail to effectively utilize these residues. Nanotechnology offers innovative solutions by converting agricultural waste into high-value products such as nanocellulose and biochar. These advancements not only minimize environmental impact but also foster a circular economy by generating economic opportunities. Addressing challenges like scalability and cost-effectiveness requires supportive policies, collaboration between industries and academia, and enhanced public awareness. Nanotechnology transforms agricultural waste into valuable resources, promoting sustainability and resource efficiency.

Introduction

The global population is projected to hit 9.7 billion by 2050, challenging the agricultural sector to meet the growing demand for 70% more food. This increased production must occur amidst climate change, which threatens agricultural productivity through extreme weather conditions. These dual pressures are straining agricultural systems and resulting in increased agricultural waste. Types of agriculture-based waste (Fig. 1), such as Crop residues, food-processing waste, and animal byproducts, are accumulating at alarming rates, causing environmental challenges and complicating waste management (Divyabharathi *et al.,* 2024).

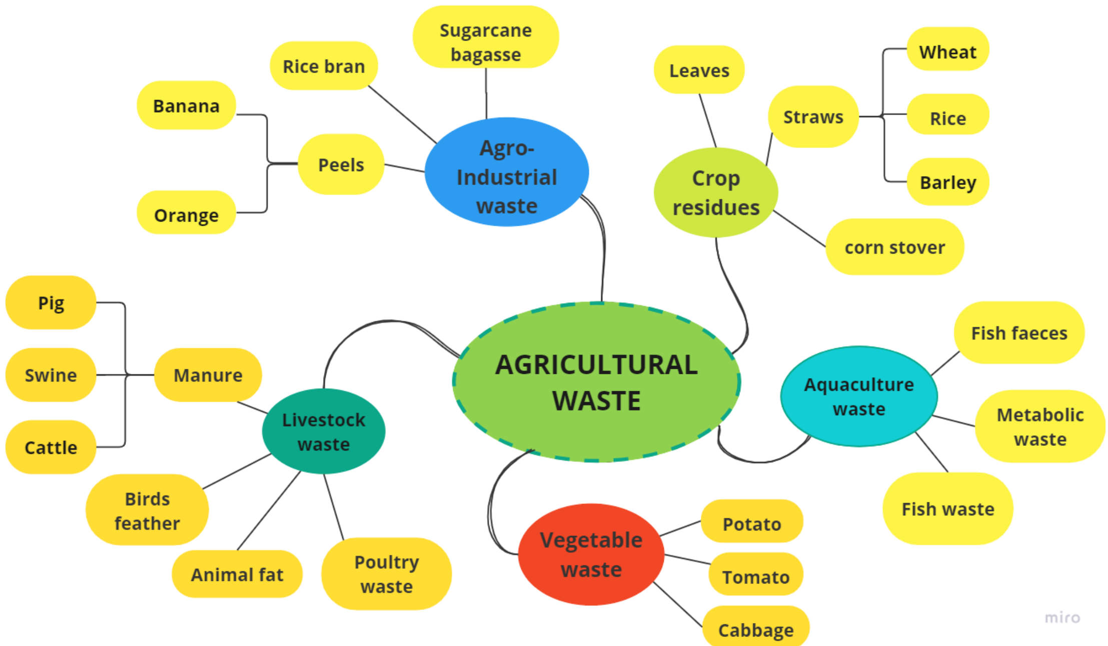

Fig. 1. Types of agriculture-based waste

Mismanagement of agricultural waste is a major global issue, with traditional disposal methods wasting resources and contributing to greenhouse gases, soil degradation, and climate change. Across the world, regions like China, India, and parts of Africa face significant challenges, with India annually produces around 130 million tonnes of paddy straw, much of which is burned, causing severe environmental damage (Koul *et al.,* 2022).

Nanotechnology operates at the nanoscale, specifically involving materials that range from 1 to 100 nanometers. It has significantly advanced in different industries, such as food, cosmetics, and healthcare, over the past decades. This emerges as a promising solution to the problem of agro-waste by enabling the efficient and eco-friendly conversion of agricultural waste into valuable products or resources, such as biofuels, biopigments, and bioplastics, etc. Integrating these advancements within the circular bioeconomy and nanotechnology allows agricultural waste to become an economic asset rather than a burden. This approach reframes waste as a catalyst or driver for sustainability and economic growth, aligning environmental conservation with profit and positioning nanotechnology as a key player in achieving a resilient and greener future.

Transforming Agricultural By-Products: A Nanotechnology-Driven Perspective

Agricultural waste, once considered an environmental burden, is now increasingly recognized as a valuable resource with substantial economic and environmental potential, especially considering rapid advancements in Nanotechnology. By enabling the manipulation of materials at the nanoscale, Nanotechnology provides transformative pathways to convert agricultural by-products into high-value, high-performance materials (Fig. 2) (Aydin *et al.,* 2023). These innovations enhance the efficiency of waste conversion processes, turning residual biomass into commercially viable and environmentally beneficial products.

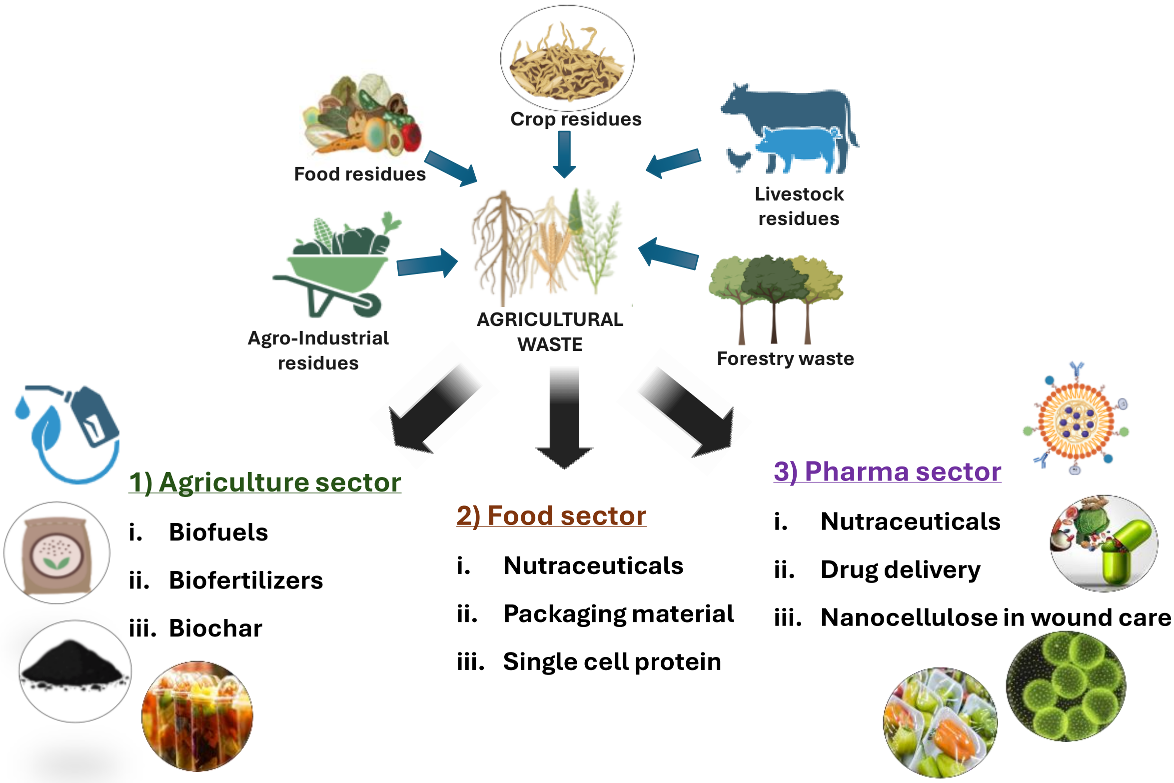

Fig. 2. Conversion of agricultural waste into high-value products

Key applications of Nanotechnology include the production of biofuels for renewable energy (Ingle *et al.,* 2023), nanofertilizers that improve nutrient uptake and reduce runoff, and nanopesticides that minimize chemical use while enhancing crop protection (Ghodake *et al.,* 2024). Agricultural residues are also being used to produce biochar for water purification and soil improvement, carbon nanomaterials for energy storage and environmental remediation, and nanocellulose for biodegradable packaging and advanced functional materials.

The multifaceted role of nanomaterials in upcycling agricultural waste into a wide range of value-added products (Table 2). Nanotechnology addresses critical environmental challenges while opening new opportunities for economic growth. As research advances, the focus is shifting toward scaling up these technologies for real-world applications in agriculture and industry. Looking ahead, nanotechnology is strengthened to play a transformative role in converting agricultural waste into valuable assets, fostering sustainability, resource efficiency, and inclusive development.

Table 1. Nanomaterials for upcycling agricultural waste into valuable products

Sr. No.	Source of Agricultural Waste	Nanomaterials	Value-added product/Application of nanomaterials	References
1	Mesquite *(Prosopis juliflora)*	Nanocomposite of Ag-grey Mg alloy	Nano-reinforced lightweight materials for use in automotive and aerospace applications	Arundeep & Yuvaraj, 2024
2	Pomegranate peels	ZnO NPs	Photocatalysis in wastewater treatment	Verbič et al., 2022
3	Potato peels	Cellulose NPs	Material for smart packaging	Ramesh and Radhakrishnan, 2019
4	Oil palm wastes	Cellulose nanofiber	Bio-aerogel scaffold	Das *et al.,* 2023
5	Groundnut shells	Carbon NPs	Nano fertilizers and pesticides	Farmand *et al.,* 2022
6	Sawn timbers	Nanocellulose	Bio-composite membrane	Peña-Ortiz *et al.,* 2023
7	Banana peels	Pectin NPs	Seedling growth and seed germination	Li *et al.,* 2022
8	Tea waste	Fe NPs	Remediation of chlorinated VOCs	Rónavári *et al.,* 2023
9	Oil palm wastes	Cellulose nanofiber	Antimicrobial agent against *E. coli* and *S. aureus*	Yahya *et al.,* 2023
10	Groundnut shell	ZnO, ZnO-Carbon Dot Nanocomposite, and Carbon Dots	Antibiotics against *E. coli*, *S. aureus*, *B. subtilis,* and *C. violaceum*	Akpeji *et al.,* 2024
11	Sea asparagus *(Salicornia ramosissima)*	Cellulose nanofiber	Material for strengthening	Lima *et al.,* 2022

Sr. No.	Source of Agricultural Waste	Nanomaterials	Value-added product/Application of nanomaterials	References
12	Coffee wastes	Ag NPs	Phenol compound removal; Functional nanodevices; Photocatalytic applications	El-Desouky *et al.,* 2023
13	Banana leaves	Nanocellulose	Regeneration of tissues	Manurung *et al.,* 2024
14	Red onion peels	Nanocellulose	Wound healing potential	Datta *et al.,* 2024
15	Cow dung	ZnO NPs	UV protection	Shubha *et al.,* 2022
16	Tea waste	MgO NPs	Adsorbent in industrial wastewater treatment	Chu *et al.,* 2023

Innovative Interdisciplinary Approaches: Converting Agricultural Waste into Sustainable Nanomaterials

The integration of nanotechnology, biotechnology, and green chemistry is leading to transformative advancements in sustainability, particularly in the recycling of agricultural waste (Soares *et al.,* 2024). Through the convergence of these scientific disciplines, researchers are developing innovative and sustainable nanomaterials to address both environmental and economic challenges. This interdisciplinary collaboration is facilitating the development of high-performance, eco-friendly materials, positioning agricultural waste as a valuable resource within the circular economy. Additionally, the hybrid materials emerging from this approach show great potential for applications in diverse sectors such as biomedicine and food packaging. By fostering cross-disciplinary innovation, these developments not only enhance waste management practices but also contribute to a more sustainable and environmentally responsible future (Saxena *et al.,* 2025).

Advantages of nanotechnology in waste transformation

Nanotechnology offers an eco-friendly approach to convert agricultural waste into high-value, sustainable products. It reduces waste, lowers emissions, and promotes efficient resource use, minimizing environmental impact. Economically, it opens new prospects through revenue generation, job creation, and cost savings across agricultural and industrial sectors. By turning waste into profitable materials such as nanofertilizers, bioplastics, or advanced composites, nanotechnology supports sustainable economic growth and strengthens rural economies. Ultimately, it plays a crucial role in advancing a circular economy, where waste is not discarded but repurposed into valuable assets, aligning environmental responsibility with economic opportunity.

Challenges and limitations of Nanotechnology for Transforming Agricultural Waste into Valuable Goods

Nanotechnology offers significant potential in transforming agricultural waste into valuable products, but several critical challenges must be addressed to utilize its benefits. Technical barriers such as scaling up nanotechnological processes, managing the diversity of biomass feedstock, synthesizing nanomaterials efficiently, and reducing high production costs pose major obstacles. Additionally, regulatory and safety concerns, such as the toxicity of nanomaterials, limited knowledge of their long-term effects, inadequate regulatory frameworks, and risks to environmental and occupational health, further complicate progress. Addressing these issues requires a diverse or multifaceted approach, including increased investment in research and development, harmonization of regulatory standards, expanded safety research, public education initiatives, and market-driven incentives. By systematically overcoming these barriers, nanotechnology can play a vital role in the sustainable and profitable utilization of agricultural waste, delivering far-reaching economic, environmental, and social benefits.

Future directions and research opportunities

Advancements in nanotechnology aimed at supporting a circular economy focused on transforming agricultural waste into high-value and sustainable nanomaterials. Current research emphasizes the development of innovative nanocatalysts, biodegradable nanocomposites, and environmentally friendly synthesis methods for applications in biofuels, energy storage, and precision agriculture. Goals include improving control over nanomaterial properties, such as particle size and morphology, to enhance functionality. Scalability and energy-efficient production methods, like green synthesis, are emphasized to make large-scale manufacturing viable. Standardization of these materials is essential for maintaining quality and supporting market stability. Interdisciplinary collaboration is key to transforming agricultural waste into valuable resources, promoting sustainability and resource efficiency across diverse industries.

Conclusions

Nanotechnology transforms agricultural waste from an environmental issue into a valuable resource by utilizing nanocatalysts, green chemistry, and biodegradable nanocomposites. This innovative approach allows agricultural residues to be upcycled into various products, including biofuels, nanofertilizers, bioplastics, and advanced energy storage solutions. By reducing waste and creating economic opportunities, it supports the circular economy and promotes sustainable growth. Ultimately, nanotechnology enhances resource conservation and positions agricultural waste as a key contributor to economic and environmental resilience.

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ISSN : 2583-0910
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Article ID : 05/XI/26/1125

PLANT IMMUNE RESPONSES AGAINST PATHOGENS AND THEIR AGRICULTURAL IMPLICATIONS

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Abstract

Plants, although sessile, have developed highly sophisticated immune systems to counter a wide spectrum of pathogenic threats. These responses are governed by both local and systemic defense mechanisms, primarily categorized into pattern-triggered immunity (PTI), effector-triggered immunity (ETI), and systemic responses such as systemic acquired resistance (SAR) and induced systemic resistance (ISR). Modern advances in molecular biology and omics technologies have greatly expanded our understanding of plant-pathogen interactions and are increasingly informing breeding and biotechnological interventions to boost crop resilience. This article reviews the layered architecture of plant immunity, the role of molecular signals, recent research developments, and how these insights are reshaping sustainable agriculture.

Introduction

Plants are constantly exposed to a diverse array of microbial pathogens including bacteria, fungi, viruses, nematodes, and oomycetes. Unlike animals, plants lack specialized mobile immune cells; instead, they rely on innate immunity embedded within each cell to detect and respond to pathogenic threats (Jones and Dangl *et al.*, 2006). Over millions of years, this system has evolved into a highly sophisticated multi-layered defense mechanism that includes both local and systemic responses, enabling plants to survive in dynamic ecosystems.

The concept of plant immunity was historically limited to observable resistance phenotypes, such as hypersensitive response (HR). However, molecular studies over the past two decades have revolutionized our understanding of how plants detect and resist pathogens. The zigzag model proposed by (Jones and Dangl *et al.*, 2006) provided a pivotal framework, describing two principal layers of immune recognition: pattern-triggered immunity (PTI) and effector-triggered immunity (ETI)**.** In PTI, conserved microbial signatures known as pathogen-associated molecular patterns (PAMPs) are recognized by cell surface-localized pattern recognition receptors (PRRs). In ETI, specific pathogen effectors are recognized by intracellular nucleotide-binding leucine-rich repeat (NLR) receptors, triggering a stronger and more localized immune response.

In the face of rapidly evolving pathogens and the increasing need for sustainable agriculture, leveraging plant immune knowledge to breed resistant varieties and develop biological control methods has become a cornerstone of modern plant science **(**Dangl *et al.*, 2013; Naseem *et al.*, 2020)**.**

Layers of Plant Immunity: Plants employ a two-layered immune system to defend against pathogens.

Pattern-Triggered Immunity (PTI)

Pattern-Triggered Immunity (PTI**)** is the first line of defense in the plant immune system. It allows plants to recognize and respond to general features of pathogens, known as PAMPs (Pathogen-Associated Molecular Patterns). PTI represents basal immunity initiated upon the detection of pathogen-associated molecular patterns (PAMPs) or damage-associated molecular patterns (DAMPs) **(**Boller, T., & Felix, G *et al.*, 2009). PTI is broad-spectrum: effective against many pathogens. PRRs such as FLS2 (flagellin receptor) and CERK1 (chitin receptors) localize on the plasma membrane and initiate defense through:

i. Calcium influx
ii. ROS burst
iii. MAPK cascade activation
iv. Callose deposition and stomatal closure

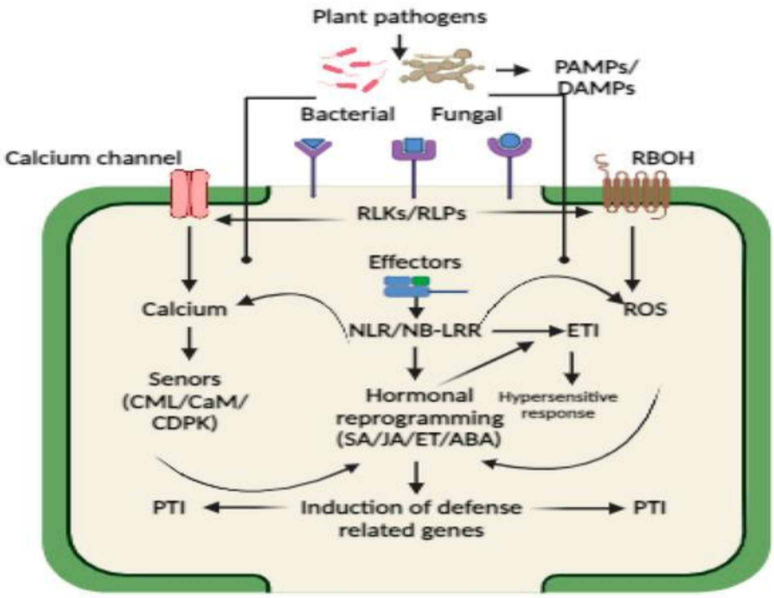

Fig.1: Schematic illustration showing the activation of two-tier plant immunity, namely PTI and ETI, in plants after pathogen, MAMPs/DAMPs, or effectors perception by PPRs and NLRs (Sajad Ali, *et al.,* 2024).

Key Components of PTI

Pattern Recognition Receptors (PRRs): Located on the plasma membrane of plant cells. Examples: FLS2 (Recognizes flagellin), CERK1 (Recognizes chitin)

Signal Transduction: Activation of PRRs leads to a cascade of intracellular signaling. Examples: MAPK cascades, Calcium influx, ROS (Reactive Oxygen Species) burst and Transcriptional reprogramming of defense genes.

Defense Responses: Defense responses are the biological reactions triggered to restrict damage, prevent or recover from infection, or protect against foreign invaders. Examples

- Cell wall reinforcement (callose deposition)
- Production of antimicrobial compounds
- Stomatal closure to prevent pathogen entry
- Activation of defense-related genes

Effector-Triggered Immunity (ETI)

Effector-Triggered Immunity (ETI) is the second layer of the plant immune system**,** activated when a plant detects specific pathogen effectors**.** ETI is often stronger and faster than Pattern-Triggered Immunity (PTI), and it usually results in localized cell death to prevent pathogen spread (Jones & Dangl, 2006)**.** ETI is mediated by intracellular NLR (nucleotide-binding leucine-rich repeat) receptors that recognize specific pathogen effectors.

Pathogen effector → Recognized by NLR → ETI activated

Key Components of ETI

1. **Effectors**:
    - Pathogen-secreted proteins delivered into the host cell to promote infection.
    - Examples: AvrPto**,** AvrRpt2 (from *Pseudomonas syringae*)
2. **NLR Receptors**:
    - Reside inside plant cells.
    - Recognize effectors either directly or by monitoring the modification of host proteins (the "guard" or "decoy" model).
    - Classes include:
        - TIR-NLRs (TNLs)
        - CC-NLRs (CNLs)
3. **Hypersensitive Response (HR)**:
    - Rapid, localized cell death at the infection site.
    - Restricts pathogen growth and spread.
4. **Systemic Acquired Resistance (SAR)**:
    - Long-lasting, whole-plant immunity following ETI.
    - Associated with salicylic acid (SA) signaling.

NLR Signaling Complexes

Nucleotide-binding leucine-rich repeat receptors (NLRs) are intracellular immune receptors in plants that detect pathogen-derived effector proteins and trigger a potent defense known as Effector-Triggered Immunity (ETI)**.** Once activated, NLRs form large signaling complexes that propagate defense signals, often culminating in the hypersensitive response (HR)**-** a programmed cell death to restrict pathogen spread (Wang *et al.,* 2019; Adachi *et al.,* 2019).

Plant NLRs have three primary domains**:**

1. **N-terminal domain**
    - *TIR* (Toll/Interleukin-1 receptor-like) in TNLs
    - *CC* (coiled-coil) in CNLs
    - *CC_R* (RPW8-like) in RNLs
2. **NB-ARC domain**
    - Central nucleotide-binding domain that regulates activation.
3. **LRR (Leucine-Rich Repeat) domain**
    - C-terminal domain involved in effector recognition and auto-regulation.

Systemic Defense Mechanisms

Systemic Acquired Resistance (SAR)

Plants are not passive organisms. After detecting a pathogen locally, they can activate defense responses throughout the entire plant**-** a phenomenon called systemic defense**.** These responses ensure enhanced resistance to future infections, even at uninfected sites. SAR provides long-lasting, broad-spectrum resistance triggered by localized infection. The mobile signal involves methyl salicylate, azelaic acid, pipecolic acid, and lipid transfer proteins (Maldonado *et al.*, 2002; Návarová *et al.*, 2012).

- **Key regulatory genes**: NPR1, TGA transcription factors, PR1.
- **Priming effect**: Plants "remember" prior exposure and respond more robustly to future threats.

Induced Systemic Resistance (ISR)

Induced Systemic Resistance (ISR) is a broad-spectrum, long-lasting defense mechanism in plants, activated by beneficial microbes particularly plant growth-promoting rhizobacteria (PGPR) without causing disease. Unlike pathogen-triggered immunity, ISR is initiated in the roots and confers resistance systemically throughout the plant. ISR is initiated by beneficial microbes like *Pseudomonas fluorescens* and *Trichoderma* spp. It primes the plant to respond faster to attack and is mainly regulated via JA and ET pathways.

- Pieterse *et al.* (2014) showed that ISR and SAR share downstream signalling components (like NPR1), but differ in hormone dependence.

Small RNAs in Antiviral Defense

Small RNAs (siRNAs) are crucial components of the RNA silencing machinery, acting as molecular sentinels that detect and neutralize viral infections in plants. These include:

- Small interfering RNAs (siRNAs)
- MicroRNAs (miRNAs)

Recent genome-wide studies (Zhang *et al.,* 2015) identified miRNAs targeting host defense regulators, suggesting a regulatory loop in immunity.

Hormonal Crosstalk in Immunity

- SA**:** Defense against biotrophs.
- JA & ET**:** Defense against necrotrophs and herbivory.
- ABA**:** Primarily involved in abiotic stress; modulates immune responses.
- Brassinosteroids (BRs)**:** Usually suppress immunity.

Crosstalk between these pathways allows context-specific responses but can lead to trade-offs (Derksen *et al.,* 2013).

Agricultural Implications

Breeding and Genetic Engineering

Modern breeding techniques and genetic engineering have revolutionized the ability to develop disease-resistant crops by improving and manipulating plant immune responses. These tools aim to either enhance innate immunity (like PTI and ETI) or introduce novel resistance genes from wild relatives or unrelated species.

- *Xa21* in rice and *Rpi-blb2* in potato confer resistance to major pathogens.
- Marker-assisted breeding and transgenic approaches have accelerated R gene deployment.
- Genome editing (e.g., CRISPR/Cas9) allows precise alterations. For instance, editing *MLO* gene in wheat confers powdery mildew resistance (Wang *et al.,* 2014).

Bio-control and Microbial Inoculants

Bio-control agents and microbial inoculants are beneficial microorganisms that enhance plant immunity and protect against pathogens. They induce plant defense mechanisms, outcompete pathogens, and improve soil health-offering a sustainable alternative to chemical pesticides in agriculture. Plant Growth-Promoting Rhizobacteria (PGPRs) like *Bacillus subtilis* trigger ISR and produce antifungal metabolites (Kloepper *et al.,* 2004; Pieterse *et al.,* 2014).

Synthetic Biology and Nano biotech

Emerging technologies like synthetic biology and nano-biotechnology are revolutionizing how we understand and manipulate plant immune responses. These fields offer precision tools to engineer disease-resistant crops**,** deliver immune-activating molecules, and monitor plant-pathogen interactions at nanoscale resolution.

- Engineered signaling circuits can modulate immunity.
- Nano formulations of immune inducers are being explored for targeted delivery (Chen *et al.,* 2022).

Current Challenges and Future Prospects

- **Pathogen evolution**: Continuous adaptation necessitates rotating or stacking R genes.
- **Durability of resistance**: Resistance pyramiding and multi-layered defenses can help.
- **Integrating immunity with growth/yield**: Avoiding fitness penalties.
- **Socio-economic barriers**: Access to technology, regulatory issues, and public perception.

Conclusion

Understanding plant immune responses offers profound implications for sustainable agriculture, especially as global food systems face challenges from climate change, evolving pathogens, and the need to reduce chemical pesticide usage. The layered immunity system in plants, consisting of PTI, ETI, systemic acquired resistance (SAR), and induced systemic resistance (ISR), not only provides immediate defense but also allows long-term protection through immune memory-like mechanisms (Spoel & Dong, 2012; Shah & Zeier, 2013).

Recent advancements in plant genomics and transcriptomics have revealed the complexity and plasticity of immune signaling networks. For instance, high-throughput sequencing and CRISPR/Cas9-based genome editing are accelerating the identification and functional validation of resistance (R) genes (Zhang *et al.*, 2020; Chen *et al.*, 2021). Such tools are transforming our ability to breed or engineer crops with durable resistance to a wide spectrum of pathogens.

In conclusion, leveraging knowledge of plant immune responses through genetic engineering, precision breeding, and ecological approaches can pave the way for a new era of crop protection that is environmentally friendly and economically viable. The future of agriculture lies in aligning biological defense systems with innovation and sustainability.

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ISSN : 2583-0910
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Article ID : 05/XI/27/1125

PALUDICULTURE: THE AGRICULTURE OF SWAMPS AND MARSHES

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Abstract

The world's most carbon-rich soils are peatlands but drainage made these habitats more cultivable which may have caused peat subsidence and the emission of greenhouse gases into the atmosphere, both of which contribute to the depletion of carbon stocks. Therefore, climate-smart agriculture, which maintains high water levels and minimal carbon emissions, must be used in peatland agriculture in the future. It promotes the buildup of organic matter in the peat, production of biomass from rewetted peatlands, and offers the ecosystem services associated with natural peatlands is known as paludiculture. However, agricultural crops are not suited to such damp circumstances and because wet peat soils have a low load-bearing capacity, making them inaccessible to machines and are less appropriate for agriculture. This objective is to evaluate the impact and possible advantages of peatland restoration in mitigating climate change.

Keywords: Peatlands, Carbon stocks, Greenhouse gas emissions, Ecosytems, Paludiculture

Introduction

Peatland soils are the most carbon-rich soils in the world, storing ca. 600 Gt of carbon. However, recent human activity and observed climate change have transformed these ecosystems from long-term carbon sinks into carbon sources, thus altering global carbon cycling.

Farming is a cornerstone of our civilization, but traditional agriculture often comes with a heavy environmental price tag. For centuries, farmers have drained peatlands those rich, waterlogged lands we know as bogs and marshes to make way for crops and livestock. This practice, however, releases massive amounts of carbon into the atmosphere, contributing significantly to climate change. A new approach called paludiculture, or "wet farming," offers a powerful solution by turning drained peatlands back into productive, carbon-storing wetlands.

Characteristics of Peatland

What is Paludiculture?
Paludiculture gets its name from the Latin word palus, meaning "swamp," and it's a revolutionary reversal of traditional farming. Instead of draining the land, paludiculture requires rewetting peatlands and keeping the water table permanently high. This prevents the peat from decomposing and releasing its stored carbon.

On this wet landscape, farmers cultivate plants that naturally thrive in marshy conditions. These aren't the typical crops you see in a field, but they are incredibly useful. Paludiculture crops can include:

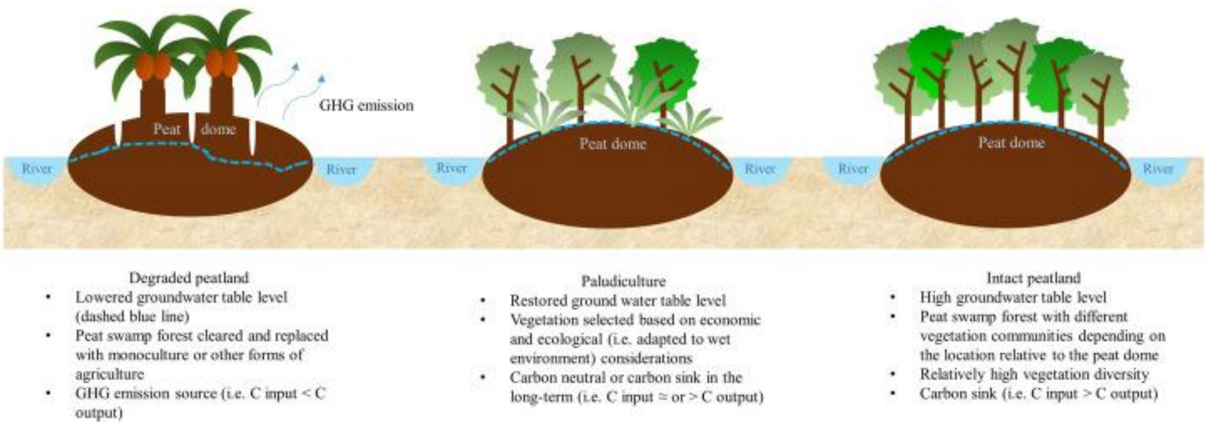
Cattails: The familiar "sausage-on-a-stick" plants are harvested for their strong, fibrous material, which can be used for building insulation.

Reeds: These versatile grasses are used for thatching roofs and can be turned into sustainable building materials and even biofuels.

Sphagnum moss: This moisture-retaining moss is a sustainable alternative to peat for gardeners, reducing the need to mine natural bogs.

Medicinal and food plants: Certain wetland plants, like some berries and herbs, are also being explored as commercially viable crops.

By using this approach, the peat stays intact, the ecosystem is restored, and the harvested plant material provides a new source of income.



Advantages

- ✓ **Fights climate change:** The most significant benefit is the reduction of greenhouse gas emissions. By keeping peatlands wet, paludiculture locks carbon into the soil, acting as a natural carbon sink.
- ✓ **Restores biodiversity:** Rewetting peatlands restores a natural habitat for a wide array of wetland species, including birds and insects, which were driven away by drainage.
- ✓ **Improves water quality:** Wetlands act as natural filters, and paludiculture practices can help reduce nutrient runoff from surrounding farms, protecting rivers and lakes from pollution.
- ✓ **Creates new economies:** Paludiculture opens up new markets for biomaterials, biofuels, and specialized crops, providing sustainable economic opportunities for rural communities.
- ✓ **Mitigates flooding:** Peatlands can absorb large amounts of water, helping to regulate water levels and reduce flood risk in surrounding areas.

Disadvantages

- ✓ **Market uncertainty:** Because paludiculture is a relatively new concept in modern farming, the markets for its products (like cattail insulation or reed biomass) are still developing and may be uncertain.
- ✓ **Infrastructure challenges:** Specialized equipment may be needed for harvesting wet-grown crops, and farmers may face new challenges in managing saturated land.
- ✓ **Policy and funding gaps:** In many places, government policies and financial incentives still favour traditional farming. This makes it difficult for early adopters of paludiculture to get the support they need.
- ✓ **Requires a mindset shift:** Farmers and landowners need to adopt a fundamentally different mindset. Instead of seeing wetlands as a problem to be solved by drainage, they must see them as an asset to be managed.

Conclusion

Paludiculture represents a significant paradigm shift in agriculture. It acknowledges that not all land is meant to be dry and that by working with nature, we can produce valuable resources while simultaneously addressing some of our most pressing environmental problems. While challenges remain in scaling up and establishing stable markets, the promise of a regenerative form of agriculture that actively benefits the planet is too important to ignore. As the world seeks innovative solutions to climate change, paludiculture offers a compelling vision for a greener, wetter, and ultimately healthier future.

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ISSN : 2583-0910
Agri-India TODAY
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Article ID : 05/XI/28/1125

PHYLLOPLANE YEAST FOR FOLIAR DISEASE SUPPRESSION

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Abstract

Phylloplane is a habitat for diverse microflora. Phylloplane yeasts are a major group among them and they could play a role in suppression of many foliar diseases. Many yeasts are having antagonistic action against various phytopathogens which make them good choice for foliar disease suppression. The brewers yeast ''*Sacharomyces cerviseae* '', ''*Pseudozyma*'' strains, a basidiomycetes yeast can be named as some among them. Phylloplane yeasts can improve plant growth (*Aureobasidium pullulans,Candida tropicalis,Rhodotorula mucilaginosa* etc) and yield as many of them produce plant growth promoting substances.

Keywords: Phylloplane yeast, Disease suppression, Rice, Corn, Pepper, Geranium

Introduction

Phylloplane is the region on the leaf surface. It is different from phyllosphere which include all the arial plant parts namely stem, leaf, flowers, buds, fruits etc. In short, Phylloplane is a part of phyllosphere. The community of microorganism inhabiting phylloplane constitute the phylloplane microflora. Almost all types of microorganisms, bacteria, fungi including yeasts, algae etc can thrive on th leaf surface. Most of the time, there exist a mutualistic relationship between these microbes and the plants. The microbiota make use of the plant exudates and in return provide them with certain phytohormones which play a role in plant growth, and fight harmful disease-causing agents.

The phylloplane is being exposed to various climatic fluctuations. It can be favourable to the microbes or could be stressful to them. Presence of nutrient, aminoacids, sugars and other plant metabolites, high moisture content and humidity on the leaf surface, a moderate temperature range of 20-30°C, moderate light intensity, leaf surface characters such as grooves, hairs, wax coatings provide favourable conditions to phylloplane microbiota.

Phylloplane microbes need to have certain properties for surviving in th microclimate of the leaf surface. Pigmented mycelia, spore production, cleistothecia formation against wind damage are some of the morphological adaptations of the fungus. Physiologically, as they produce certain enzymes such as cellulases, proteases and pectinases, many of them can avail nutrients for their survival from plant's complex organic compounds. In return the phylloplane microbes can significantly improve the crop yields, remove contaminants, and impart resistance to diseases, and produce novel compounds.

They achieve all this by undertaking

1. Biological nitrogen fixation – a process by which atmospheric nitrogen is converted into plant available form by microorganisms. There are free living N_2 microorganism (*Azotobacter, Clostridium,* Pseudomonas etc.) and symbiotic N_2 fixing microorganisms (*Rhizobium, Frankia, Cyanobacteria* etc.).
2. Antibiotic production – Antibiotics are the substances produced by the microbes that

defend pathogens. Substances such as phenolic compounds, proteases, chitinases, volatile organic compounds produced by phylloplane yeast inhibit growth of phytopathogens on leaf surface.

3. Iron chelation – Siderophores are low molecular- weight produced by microbes compounds having high affinity towards ferric iron. They scavenge iron from the environment.Plant growth regulation -Gibbereelic acid, IAA, cytokinins are growth promoters which induces cell division and elongation)
4. Improved mineral availability – By way of nitrogen fixation, mineral solubilisation,organic acid production.
5. Enhanced host resistance

Phylloplane Yeast

Yeast are major groups among the microbes that colonise on the leaf surface and that of fruits. Many yeast produces toxins and volatile compounds and they compete for availing the nutrients and survive in acidic environments. Majority of them belongs to the fungal families Ascomycota and Basdiomycota. Eg: *Saccharomyces cerevisiae* – they have antagonistic action to the growth of wood rot fungus and black spot of citrus. *Pichia membranifaciens* – produces a toxin which cause inhibition to the growth of *Botrytis cinerea. Torlaspora indica* DMKU-RP31 & *Wickerhamomyces anomalus* DMKU-RP25 have been found to suppress the rice sheath blight cauing fungus in green house conditions.

Phylloplane yeast & Suppression of sheath blight disease of Rice

From the phylum Ascomycota 15 yeast species and 2 species from the phylum Basidiomycota have been isolated from rice phylloplane and the majority from Basidiomycota. 14 strains of yeast have been tested to inhibit the rice pathogenic fungi *Pyricularia oryzae* (rice blast), *Helminthosporium oryzae* (brown spot of rice), *Rhizoctonia solani* (sheath blight of rice), *Fusarium moniliforme* (foot rot of rice) and *Curvularia lunata* (black kernel disease). *Torulaspora indica* DMKU-RP31, *T.indica* DMKU-RP35 and *Wickerhamomyces anomalus* DMKU-RP25 are the potential yeasts that inhibited all the mentioned pathogens. On conducting experiments, it is found that no basidiomycetes fungi showed any inhibition to the pathogens. *Torulaspora indica* and *Wickerhamomyces anomalus* inhibited all five rice pathogenic fungi. Antagonistic yeasts produced antifungal volatile organic compounds (VOCs), and enzymes β-glucanase, and chitinase. Yeasts competed with the harmful pathogens for nutrients and space.Some yeasts solubilized phosphate and zinc oxide. Two *W. anomalus* strains produced siderophores, the iron binding molecules. Most of antagonistic yeasts formed biofilms which are microbial communities made of fungal cells and extracelluar polymeric substances. Foliar application of yeast consortium with 25% reduced application of chemical fertilizers resulted in increased yield of rice.

Phylloplane Yeast *Pseudozyma churashimaensis* against bacterial and viral diseases in pepper

The RGJ1 strain of *Pseudozyma churashimaensis* on foliar application over pepper seedlings before and after transplanting was found to casue suppression against *Xanthomonas axonopodis pv.vesicatoria.* They induced systemic resistance in pepper plants. Foliar spray of RGJ1 starin was found to reduce symptoms caused by Pepper mottle virus (PepMoV), Pepper mild mottle virus (PMMoV), Broad bean wilt virus (BBWV) and cucumber mosaic virus (CMV). RGJ1 sprayed plant also showed significant increment in the fruit fresh weight and number of fruits. It was found that treatment with RGJ1 strain induced expression of the plant systemic resistance marker genes CaPR4 and CaPR5 and did not directly antagonize the pathogen in vitro. induced systemic resistance against the bacterial canker pathogen *Clavibacter michiganensis* on tomato, the powdery mildew fungus *Podosphaera xanthii* on cucumber, and the gray mold pathogen *Botrytis cinerea* on *Arabidopsis thaliana* was achieved through the leaf application of *Pseudozyma aphidis*

Phylloplane yeast for foliar disease suppression in corn

Most yeasts present on the phylloplane of corn plants belonged to the phylum *Basidiomycota*, as identified through a culture-dependent technique involving the plating of leaf washings. This outcome was consistent with results obtained from culture-independent analyses. The predominance of basidiomycetous yeasts on corn leaves mirrors findings from studies on other plant species. The species *Hannaella sinensis* occurred in greatest number. Most of the identified yeast have industrial and biotechnological applications.

Yeasts for Improved Control of *Botrytis cinerea* on Geranium Seedlings with Combinations of Fungicides

In geranium seedlings, treatment of phylloplane yeast *Rhodotorula glutinis* PM4 along with fungicides such as azoxystrobin, trifloxystrobin or vinclozolin have shown reduced lesion development caused by Botrytis cinerea by increasing the yeast's biocontrol efficacy. This treatment was found beneficial than application of phylloplane yeast or fungicide alone. When this yeast strain was used in combination with Mancozeb, biocontrol efficacy of the yeast remained un-alteared. On the contrary, thiophanate-methyl negatively affected the yeast efficacy.

Conclusion

Phylloplane microflora are the microbes colonizes on the leaf surface. They can be used as a biocontrol agent against diseases. By way of depending on these organisms, the usage of chemical fungicides can be cut short which reduces environmental pollution. Conventionally systemic fungicides likes carbendazim, propiconazole, hexaconazole etc and contact fungicides like mancozeb is being used. With a frequent application of these harmful chemicals, the pathogens develop resistance towards them. The issue of fungicide resistance can also be addressed by using these phylloplane microbes as a bio-control agent . From the studies conducted, *Torulaspora indica* DMKU-RP31, *T.indica* DMKU-RP35 and *Wickerhamomyces anomalus* DMKU-RP25 are found to be effective against *Pyricularia oryzae* (rice blast), *Helminthosporium oryzae* (brown spot of rice), *Rhizoctonia solani* (sheath blight of rice), *Fusarium moniliforme* (foot rot of rice) and *Curvularia lunata* (black kernel disease). RGJ1 strain of *Pseudozyma churashimaensis* induced systemic resistance in pepper plants and casue suppression **a**gainst *Xanthomonas axonopodis pv.vesicatoria.*A fungicide- yeast combination suppressed disease symptoms caused by *Botrytis cinerea* in geranium seedlings. Besides their usefulness in disease suppression,they are also found to be producing industrially important compounds.

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ISSN : 2583-0910
Agri-India TODAY
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monthly newsletter

Article ID : 05/XI/29/1125

PURPLE-COLOURED FRUITS: NATURE'S IMMUNITY BOOSTERS

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Introduction

Fruits with purple, bluish, or reddish pigmentation are not only visually attractive but also nutritionally rich. Their distinct colour is primarily due to the presence of anthocyanins, a subgroup of flavonoids known for their antioxidant, anti-inflammatory, and immunomodulatory properties (Khoo *et al.,* 2017). These compounds play a significant role in protecting the human body from oxidative stress, improving cardiovascular health, and enhancing immune response.

Why Purple Fruits Are Special

The deep pigmentation in purple fruits arises from anthocyanins and polyphenols, which act as natural antioxidants. Studies have shown that anthocyanins help in scavenging free radicals, reducing cellular damage, and regulating immune signalling pathways (Wallace & Giusti, 2015). Regular intake of these fruits has been associated with reduced risk of infections, better vascular function, and improved memory and cognitive health.

Nutritional and Immunity-Enhancing Role of Purple Fruits

Blueberries (*Vaccinium corymbosum*): Rich in Vitamin C, Vitamin K, manganese, and anthocyanins.

Immunity Role: Vitamin C stimulates white blood cell activity, while anthocyanins reduce oxidative stress and enhance immune defence. Studies suggest that blueberries may lower the incidence of respiratory infections (Ashique *et al.,* 2024).

Black Grapes (*Vitis vinifera*): Contain resveratrol, Vitamin C, potassium, and flavonoids.
Immunity Role: Resveratrol exhibits antiviral and anti-inflammatory activity, while Vitamin C enhances antibody production (Patil Pandurang *et al.,* 2020).

Jamun or Indian Blackberry (*Syzygium cumini*): Provides Vitamin C, iron, calcium, and polyphenolic compounds.

Immunity Role: Iron supports haemoglobin synthesis and blood health, while Vitamin C strengthens resistance against seasonal illnesses. Extracts of jamun have also demonstrated antimicrobial properties (Haque *et al.,* 2017).

Plums (*Prunus domestica*): Contain Vitamin A, Vitamin C, potassium, and polyphenols.

Immunity Role: Vitamin A helps maintain epithelial and mucosal barriers—the body's first line of defence—while polyphenols provide anti-inflammatory protection.

Purple Dragon Fruit (*Hylocereus costaricensis*): Source of Vitamin C, betalains, magnesium, and dietary fibre.

Immunity Role: Betalains act as anti-inflammatory pigments, while Vitamin C enhances natural killer (NK) cell activity (Esquivel, 2016).

Mulberries (*Morus alba, Morus nigra*): Rich in Vitamin C, Vitamin E, iron, potassium, and anthocyanins.

Immunity Role: A combination of Vitamin C and iron boosts haemoglobin levels, supports red blood cell production, and enhances immune efficiency (Butt *et al.,* 2008).

Mechanisms of Immunity Enhancement

Vitamin C: Stimulates production and function of immune cells, particularly lymphocytes and phagocytes.

Anthocyanins & Polyphenols: Reduce inflammation by modulating cytokine pathways and scavenging free radicals.

Iron & Folate: Essential for red blood cell synthesis, indirectly strengthening immunity.

Dietary Fibre: Improves gut microbiota, which is closely linked with immune regulation.

Conclusion

Purple-coloured fruits such as blueberries, black grapes, jamun, plums, dragon fruit, and mulberries represent a powerful combination of nutrients and phytochemicals that support human immunity and overall health. Their regular consumption not only reduces the risk of infections but also contributes to long-term well-being by improving cardiovascular, cognitive, and metabolic health. Encouraging the inclusion of these fruits in daily diets, whether fresh, in juices, or as part of functional foods, can be a natural strategy for boosting immunity.

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ISSN : 2583-0910
Agri-India TODAY
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Article ID : 05/XI/30/1125

THE THRESHOLD OF CAUSALITY: REGRESSION DISCONTINUITY DESIGN IN MODERN SOCIAL SCIENCE POLICY EVALUATION

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Introduction: Establishing the Quasi-Experimental Foundation

The Challenge of Causal Inference in Observational Data

A fundamental challenge in social science research and policy evaluation is determining the true causal effect of an intervention when randomisation is infeasible. This difficulty arises primarily from selection bias, where subjects who receive treatment (the treated group) differ systematically from those who do not (the control group) based on unobserved characteristics. For instance, in evaluating the effect of a merit-based scholarship, comparing students who received the award to those who did not would be biased, as high-performing students who receive the award are already predisposed to positive academic outcomes.

The Regression Discontinuity Design (RDD) offers a powerful solution by functioning as a quasi-experimental method that approximates the internal validity of a Randomised Controlled Trial (RCT) within observational settings. RDD is applicable in situations where the eligibility for an intervention is determined solely by whether an individual's score on a continuous metric exceeds a predefined cutoff value, or threshold. This methodology enables researchers to generate valid causal estimates under assumptions that are considered relatively weak compared to those of other non-experimental designs.

Historical Context and Rise to Prominence

The origins of RDD date back over half a century to the seminal work of Donald L. Thistlethwaite and Donald T. Campbell (1960). Their initial analysis examined the impact of merit awards on future academic outcomes, leveraging the fact that award allocation was based entirely on observed test scores. The key conceptual breakthrough was realising that individuals whose scores fell just below the Cutoff (and thus did not receive the award) served as excellent comparison units to those who scored just above the Cutoff (and received the award).

Despite its conceptual elegance, RDD remained largely underutilised in economics and related fields for several decades. Its widespread adoption began accelerating significantly only in the late 1990s, driven by critical methodological advancements. Early RDD applications often relied on global regression modelling, attempting to fit a single polynomial curve across the entire data range. This approach proved highly susceptible to functional form misspecification, which could potentially introduce severe bias. The modern surge in RDD credibility coincided with the formalisation of non-parametric estimation techniques, notably by Hahn, Todd, and van der Klaauw (2001), and thorough reviews by scholars such as Imbens and Lemieux (2008) and Lee and Lemieux (2010). These developments provided the robust, local econometric framework necessary to justify RDD's ability to estimate treatment effects accurately, thereby addressing earlier methodological scepticism. This formalisation ensured RDD's acceptance as a mainstream causal inference tool, allowing it to estimate program effects across a diverse range of economic, political, and clinical contexts.

Core Components of the RDD Framework

Three indispensable components define the RDD framework:

The Running Variable (Xi)

This is the continuous variable, also referred to as the assignment variable or forcing variable, that dictates treatment eligibility. Examples include standardised test scores, age, income level, or the margin of victory in an election.

The Cutoff (c)

The Cutoff is the specific, known threshold value of the running variable at which the probability of receiving the intervention changes discontinuously.

The Mechanism of Local Randomisation

The fundamental idea is that in a small neighbourhood immediately surrounding the cutoff c, individuals are practically identical in all respects other than their treatment status. Since their treatment assignment is determined only by tiny, effectively random variations in Xi that push them just above or just below c, the treatment allocation near the threshold is considered "as good as randomised". This local quasi-randomisation is what allows the RDD to yield strong internal validity.

Theoretical Foundations and Typologies: Sharp vs. Fuzzy Designs

The Core Identifying Assumption: Continuity of Potential Outcomes

The validity of any RDD hinges upon a critical premise known as the **continuity assumption** (also referred to as the exchangeability assumption).[11] This assumption states that, absent the treatment, the average outcome for individuals just above the Cutoff would be a continuous (smooth) function of the running variable X across the threshold c.

Formally, RDD requires the conditional expectation of potential outcomes—E (Y | U=0) (the outcome if untreated) and E (Y | U=1) (the outcome if treated)—to be continuous across c. Within the potential outcome's framework, the causal effect, τ, is identified as the jump in the outcome regression function at c:

$$\tau = x \to c + limE - x \to c - limE$$

If this assumption holds, then any observed discontinuous jump in the outcome variable Y at the Cutoff must be causally attributed solely to the intervention. Moreover, the methodological design of RDD, when appropriately implemented, allows researchers to empirically test the assumption of local randomisation by checking for the continuity of observable baseline covariates at the threshold. This provides RDD with a significant advantage over methods like traditional instrumental variables (IV) analysis, where the analogous identification assumption is typically untestable. The ability to test the distribution of observed factors near the Cutoff contributes greatly to RDD's reputation for internal validity.

Sharp Regression Discontinuity (SRDD)

Sharp RDD (SRDD) applies when the assignment rule determines treatment status deterministically. Crossing the cutoff guarantees treatment (or non-treatment). In an SRDD, the probability of receiving the intervention jumps abruptly and perfectly from zero to one at the cutoff c.

Simple Practical Example: Merit-Based Scholarships (SRDD)

Consider a university awarding a scholarship to all applicants whose standardised test score (X) is 1500 or higher (c). In a sharp design, every student with X≥1500 receives the scholarship, and every student with X<1500 does not.[5] The treatment effect is estimated directly by measuring the jump in the outcome (e.g., college graduation rate) at X=1500.

Fuzzy Regression Discontinuity (FRDD)

Fuzzy RDD (FRDD) is necessary when the treatment assignment is probabilistic, meaning that the cutoff rule strongly affects the likelihood of receiving treatment, but compliance is imperfect. In FRDD, the probability of therapy exhibits a sharp, discontinuous jump at c. Still, the jump height is less than one, meaning that some individuals just above c might not receive treatment, and some just below might receive it (due to non-compliance or crossovers).

Estimation Strategy: Instrumental Variables

Because treatment receipt is no longer deterministic, FRDD relies on a local Instrumental Variables (IV) approach, akin to a local two-stage least squares (2SLS) procedure. The assignment rule itself (being above or below c) serves as the instrumental variable.

1. **First Stage:** Estimate the jump in the probability of actually receiving treatment at the cutoff c.
2. **Second Stage:** Estimate the jump in the outcome variable Y at c.

The FRDD causal estimate is calculated as the ratio of the discontinuity in the outcome variable to the discontinuity in the probability of treatment. This methodology allows researchers to derive meaningful Local Average Treatment Effects (LATE) even in real-world scenarios where adherence to the assignment rule is not absolute.

Simple Practical Example: Clinical Guidelines (FRDD)

In healthcare, clinical guidelines often specify treatment thresholds. For instance, a guideline might recommend initiating pharmacotherapy for patients whose diastolic blood pressure (X) is 140 mmHg or higher (c). A patient with a blood pressure reading of 140 mmHg has a significantly higher probability of receiving treatment than one with a reading of 139 mmHg; however, treatment is not guaranteed due to physician discretion, patient refusal, or other factors (i.e., compliance is not perfect). The FRDD uses the discontinuous eligibility rule as an instrument for the actual treatment receipt.

RDD Typologies Comparison

Feature	Sharp Regression Discontinuity (SRDD)	Fuzzy Regression Discontinuity (FRDD)
Treatment Assignment	Deterministic (All assigned units receive treatment)	Probabilistic (Non-compliance is permitted)
Probability Jump (Δp)	Perfect jump (Δp=1)	Discontinuous jump (0<Δp<1)
Identification Method	Local Polynomial Regression (LPR)	Instrumental Variables (IV) via LPR
Estimated Effect	Local Average Treatment Effect (LATE)	Local Average Treatment Effect (LATE)

and Inference in RDD: The Local Approach

The Necessity of Local Regression

Effective RDD estimation requires robust methods that account for potential non-linearity in the outcome-running variable relationship away from the Cutoff. A common but flawed practice is using a single, high-order polynomial regression across the entire support of the data (Global OLS). This method is highly problematic because the overall shape of the fitted curve can be unduly influenced by data points far away from the Cutoff, leading to significant bias near the threshold. Since RDD identification hinges entirely on the behaviour of observations infinitesimally close to the Cutoff (c), using global models risks sacrificing the validity of the estimate for the sake of fitting the entire data set.

The Standard: Local Polynomial Regression (LPR)

To overcome the challenges of global modeling, the accepted methodology involves Local Polynomial Regression (LPR). LPR estimates the causal effect by restricting the analysis to a specific, narrow window (bandwidth h) around the cutoff c. Within this window, the outcome is regressed on the running variable, fitting a simple polynomial function (usually linear or quadratic) separately on the left and right sides of c.

Local Linear Regression (LLR) Preference

Local Linear Regression (LLR), where the polynomial order p is set to 1, has become the conventional standard in RDD. While using higher-order local polynomials might sometimes outperform LLR by reducing the asymptotic Mean Squared Error (MSE), LLR is generally preferred because it exhibits superior bias properties when estimating the regression function at the boundary. LLR effectively minimises the specification bias that arises from local non-linearities, confirming the estimate's fidelity to the data immediately adjacent to the threshold. Although exploring higher polynomial orders can provide valuable sensitivity checks, researchers generally prioritise the robustness and simplicity of the linear specification (p=1), which minimises dependence on arbitrary functional form assumptions, especially in settings where the number of observations very close to the Cutoff is limited.

The Critical Role of Bandwidth Selection (h)

The selection of the estimation window, or bandwidth (h), is perhaps the most crucial implementation decision in RDD. This choice represents a critical **trade-off between bias and variance**.

- A *narrow* bandwidth restricts the estimation to observations closest to c, maximising the assumption of local randomisation and minimising bias, but simultaneously increasing variance (making the estimate less precise).
- A *wide* bandwidth increases the number of observations, reducing variance, but increases the risk of including non-comparable observations far from c, thereby introducing bias from non-linear trends.

Current best practice strongly advocates for the use of data-driven, optimal bandwidth selection methods, often implemented through computational procedures such as those found in the *rdrobust* statistical packages. These methods calculate *h* by optimising the trade-off between bias and precision based on the local curvature and density of the data. Furthermore, analysts are required to perform robustness checks by testing the primary estimate across various bandwidths—such as narrower, wider, and optimal choices—to ensure that the causal finding is not merely an artefact of a specific window choice.

Validity Checks and Methodological Robustness

The credibility of RDD estimates rests on the non-manipulation of the running variable and the strict continuity of all confounding factors. Rigorous specification checks are mandatory for any published RDD study.

The Primary Threat: Strategic Manipulation (Sorting)

Suppose individuals, institutions, or other agents are aware of the cutoff c and possess the ability to precisely control their position relative to c (e.g., through extra studying, delayed enrolment, or misreporting income). In that case, they may strategically "sort" into or out of the treatment group. If the treatment is desirable, this sorting leads to an unnatural clustering of observations just above c (known as bunching). If the treatment is undesirable, observations may cluster just below c. Such strategic manipulation violates the core assumption of local randomisation, as the individuals near the Cutoff are no longer comparable, rendering the RDD invalid.

Formal Density Test: The McCrary Method

The most influential diagnostic tool for detecting such sorting is the McCrary Density Test, developed by Justin McCrary (2008). This test explicitly checks for a discontinuous jump in the probability density function of the running variable X at the cutoff c.

A finding of a significant discontinuity in the density suggests that agents successfully manipulated the running variable, creating a systematic imbalance in the population at c. Conversely, if the density is continuous across the threshold, it strengthens the argument that assignment is quasi-random in the immediate neighbourhood of c.

It is important to acknowledge, however, that the traditional McCrary test, which tests the null hypothesis of zero discontinuity, has inherent limitations. Failing to reject the null (finding statistical insignificance) does not confirm the absence of manipulation; it only confirms a lack of statistically significant evidence *for* manipulation. Sophisticated manipulation may still be present, albeit on a small but practically meaningful scale. Furthermore, the test is sensitive to methodological choices such as bin size and bandwidth selection, and it cannot detect situations where equal numbers of individuals sort in opposite directions across the threshold (balanced manipulation).

For highly credible policy work, researchers are increasingly encouraged to augment the standard McCrary test with **equivalence testing**. This approach statistically bounds the potential jump in density, allowing the researcher to assert with statistical certainty that any manipulation is below a level considered functionally negligible.

Falsification and Robustness Tests

Beyond testing for manipulation, RDD requires several falsification tests to confirm that the observed discontinuity is genuinely caused by the intervention and not by an unrelated jump in confounding factors.

- **Continuity of Predetermined Covariates (Balance Checks):** Covariates—baseline characteristics that pre-date treatment and should not be influenced by the assignment rule—must be continuous across c. If observable covariates show a discontinuous jump at c, it raises serious doubts, suggesting that an unobserved confounder is also jumping at that point, thereby violating the fundamental continuity assumption.[5]

- **Placebo Cutoffs and Pseudo-Outcomes:** RDD estimates should only be non-zero at the true policy threshold c. Researchers should estimate the treatment effect at arbitrary, non-existent "placebo" cutoffs (c~□=c). If the impact is significant at a placebo cutoff, the RDD design is highly suspect. Similarly, testing the RDD effect on a predetermined outcome variable (a pseudo-outcome) that is theoretically unaffected by the treatment should yield an estimate close to zero.
- **Sensitivity to Specification:** The final causal estimate must be robust to changes in the specification. Results should be consistent when varying the bandwidth h and the polynomial order p.[10] Fragile estimates that change dramatically with minor specification adjustments suggest the findings are unreliable.

Table 2: RDD Validity Check Diagnostics

Check Type	Goal	Methodology/Test	Interpretation of Failure
Running Variable Manipulation	Test for strategic sorting around c	McCrary Density Test	Violation of local randomisation; self-selection bias
Balance of Covariates	Test for smoothness of predetermined variables	Test for discontinuity in observable covariates at c	Suggests confounding variables jump at c, violating the continuity assumption
Sensitivity Analysis	Test the robustness of the causal estimate	Varying bandwidth (h) and polynomial order (p)	The forecast is fragile or dependent on functional form specification

Practical Applications in Social Science Policy Evaluation

RDD is widely applied across the social sciences, providing credible evaluations for numerous policies tied to explicit thresholds.

Education Policy: The Impact of Academic Eligibility

The evaluation of merit-based scholarships remains the foundational application of RDD. To determine the causal effect of receiving financial aid (the treatment) on subsequent outcomes (e.g., degree completion or future earnings), RDD compares students whose test scores or GPA fell just above the required minimum cutoff (c) with those whose scores fell just below. Early studies by Angrist and Lavy (1999) and van der Klaauw (2002) used RDD to evaluate the effects of class size and financial aid, respectively, further establishing its role in education research.

Social Welfare and Economics: Evaluating Anti-Poverty Programs

RDD is highly effective for evaluating large-scale social programs where administrative criteria govern eligibility. For example, the Head Start program, which offers comprehensive services to children from low-income families, presents clear RDD opportunities. Ludwig and Miller (2007) utilised RDD to assess whether Head Start improves children's life chances, exploiting the fact that program eligibility was often tied to county-level poverty rankings or specific income thresholds. Since income thresholds define eligibility but do not guarantee enrollment, these studies frequently utilise the FRDD framework, treating the eligibility rule as the instrument for actual program participation.

A critical consideration in policy evaluation is addressing the potential for institutional sorting—where the policy rule itself is selected to achieve a specific outcome. Suppose the administrative body responsible for the program strategically sets the cutoff c based on prior knowledge to include or exclude particular groups. In that case, a Robust RDD application requires researchers to confirm that the Cutoff was exogenously imposed and not subject to this institutional endogeneity.

Political Science: The Causal Effect of Winning an Election

RDD has become a standard approach in political science for estimating the effect of holding office. The running variable (X) is the margin of victory, and the Cutoff (c) is the zero margin (50% vote share). In extremely close elections, tiny, uncontrollable factors—such as minor counting errors or highly localised turnout variations—determine the outcome. RDD assumes that candidates just above and just below the zero margin are virtually identical in underlying quality and district characteristics, meaning the outcome (winning) is quasi-randomly determined. This allows RDD to estimate the causal effect of winning the election (treatment) on subsequent policy decisions or re-election rates (outcome).

Public Health and Clinical Research

In public health, RDD is utilised to study the impact of legal age limits (e.g., minimum drinking age) or clinical guidelines. For instance, researchers may use age as the running variable, exploiting the discontinuity created when individuals cross the age threshold required to purchase alcohol or health insurance legally. Similarly, in medical studies, RDD can evaluate the effect of initiating a treatment based on a specific biological marker, such as using a CD4 count threshold to determine eligibility for antiretroviral therapy (ART) in HIV patients.

Interpretation, Limitations, and Conclusion

Interpreting the Local Average Treatment Effect (LATE)

A critical nuance in interpreting RDD findings is understanding that the estimated causal effect is the Local Average Treatment Effect (LATE). The LATE is the causal impact of the treatment, identified precisely for the specific subpopulation of units whose running variable value is exactly at the cutoff c.

While this focus on the marginal unit limits the generalizability of the finding, the LATE is often highly relevant for policy decision-making. For example, determining the effect of a scholarship on the marginal student who just barely qualified provides direct evidence on the efficacy of the current eligibility threshold, which is typically the margin of greatest interest to policymakers.

The Trade-Off: Internal Validity vs. External Validity

RDD's key strength is its high internal validity, which stems from rigorously exploiting the local quasi-randomisation near the Cutoff. Empirical comparisons between RDD estimates and those from high-quality RCTs have confirmed RDD's ability to generate unbiased local causal effects.

However, this strength is simultaneously RDD's principal limitation: external validity (generalizability) is inherently constrained. The estimated effect cannot be reliably extrapolated to individuals whose running variable values are far from the Cutoff.[3] Attempting to generalise RDD estimates away from the threshold necessitates making strong assumptions about the functional form of the relationship, which directly sacrifices the design's inherent advantage in internal validity. This localisation constraint also necessitates that RDD studies often require large sample sizes to ensure sufficient observations remain within the narrow optimal bandwidth, a prerequisite for adequate statistical power.

Conclusion: RDD as a Gold Standard for Specific Causal Questions

The regression discontinuity design occupies a privileged space in the hierarchy of causal inference methods. Where transparent, continuous thresholds define policies or interventions, RDD offers a powerful, transparent, and defensible methodology for evaluating causal effects. By adhering to rigorous standards—including non-parametric estimation, optimal bandwidth selection, and meticulous validity checks (especially the McCrary density test and covariate continuity checks)—researchers can produce highly credible causal evidence.[4] While its findings are localised to the margin of the intervention, the RDD approach provides robust insights that are crucial for refining social science policy and program implementation.

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ISSN : 2583-0910
Agri-India TODAY
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Peer reviewed monthly newsletter

Article ID : 05/XI/31/1125

THE GADGET GRAVEYARD: WHY YOUR NEXT UPGRADE IS A GLOBAL PROBLEM

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Abstract

E-waste is the world's fastest growing waste stream, primarily driven by rapid technological change and socio-economic development. Globally, 53.6 million tones were generated in 2019, projected to rise to 82 million tonnes by 2030. This surge represents a critical challenge to sustainable development due to the hazardous chemical components within the waste. Improper management of e-waste, particularly in vulnerable developing countries that lack inventory data, sufficient policy, and advanced processing technology, leads to the release of toxins. This poses severe environmental and human health risks. Of particular concern are the impacts on water sources. Informal and rudimentary e-waste recycling and disposal methods such as acid leaching, burning, and indiscriminate dumping cause heavy metals (like lead, mercury, and cadmium) and other pollutants to leach into the soil and subsequently contaminate groundwater and surface water systems. This direct pathway of chemical release threatens local aquatic ecosystems and compromises the safety of water resources essential for human consumption, aquaculture, and agriculture. Effective global strategies are urgently required to prevent e-waste from becoming a widespread, long-term contaminant of the world's environment.

Keywords: E-waste, water contamination, **Endocrine Disruptors,** Incineration, Acid leaching.

Introduction

Electronic waste (E-waste) has emerged as the fastest-growing solid waste stream globally, posing an imminent and complex threat to environmental sustainability and public health. This alarming trend is fundamentally driven by rapid socio-economic development and relentless technological advancement, leading to shorter product lifecycles and outdated electronic equipment. The world has a serious electronic trash problem. We are creating "e-waste" like (old phones, computers, and TVs) five times faster than we are recycling it. In 2022 alone, we generated a record of 62 million tons of this waste, which is enough to fill 1.5 million trucks that could circle the entire planet. The biggest issue is that we fail to properly recycle almost 80% of it, which is not only dangerous and polluting but also wastes a huge amount of money. This problem is only getting bigger and is expected to get much worse by 2030.

Understanding E-Waste and its Scale

- E-waste is defined as any used electronic equipment or device that has reached the end of its useful life, a wide array of products including:
- Consumer Electronics: Smartphones, laptops, tablets, televisions, and gaming consoles.
- Home Appliances: Refrigerators, washing machines, microwaves, and air conditioners.
- Industrial Equipment: Machinery used in manufacturing.
- Telecommunication Devices: Phones, modems, and routers.

Composition of E-waste

Category	Components / Examples	Environmental Significance
Metals	Precious metals (Gold, Silver, Platinum); Base metals (Copper, Aluminum); Hazardous metals (Lead, Mercury)	Hazardous metals pose significant environmental and health risks when improperly disposed.
Plastics	Various types used in casings and components.	Can release toxins upon burning or improper degradation in landfills.
Glass	Found in screens and display devices.	Components of older Cathode Ray Tube (CRT) glass often contain lead.
Batteries	Contain toxic substances such as Cadmium and Lithium.	Highly toxic and prone to leaching hazardous materials into the environment.

The Global E-Waste Scenario

The global e-waste scenario has evolved dramatically in response to a deepening crisis. The UN's 2024 "Global E-waste Monitor" revealed that generation (62 million tones in 2022) is outpacing recycling fivefold, with the 22.3% recycling rate projected to fall by 2030. This urgency, compounded by a 2021 WHO report linking informal recycling by 18 million children to severe health damage, has triggered a strong policy backlash. Internationally, the Basel Convention's 2022 amendments (effective 2025) now require prior consent for all e-waste shipments, while a 2024 EU law will ban exports to non-OECD (nations that are not members of the Organization for Economic Co-operation and Development) countries by 2027. Concurrently, major nations have tightened domestic laws, such as China's 2018 "National Sword" import ban and India's 2022 Extended Producer Responsibility (EPR) rules, which hold manufacturers directly responsible for end-of-life product management.

E-waste production in India

India is grappling with a massive and rapidly growing electronic waste (e-waste) challenge, now ranking as the world's third-largest producer, surpassed only by China and the United States. The sheer volume of this waste stream is accelerating, with official government data showing a significant jump from 1.01 million tonnes in 2019-20 to approximately 1.75 million tonnes in 2023-24. However, the core of the problem is not just the quantity, but the recycling method. It's estimated that over 90% of India's e-waste is still processed by the unregulated informal sector, which often employs hazardous and environmentally damaging practices. To address this, the government has translated its "Garbage to Wealth" philosophy into a specific policy, the E-Waste (Management) Rules, 2022, which went into effect on April 1, 2023, to enforce stricter, safer, and more accountable e-waste management.

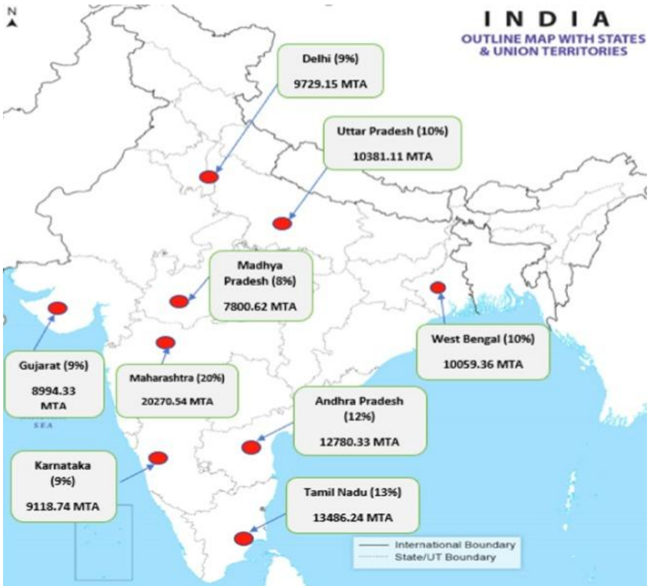

Fig.1 shows the state wise production of E-waste across the popular cities of India.

Impact of E-Waste on Water Sources

E-waste poses an intense and insidious threat to global water security, as toxic components inevitably seep into the freshwater supply. The environmental devastation is particularly acute where e-waste is managed through unregulated, informal processes.

Fig.2 Improperly discarded e-waste

Hazardous Leaching and Water Contamination

Improper disposal methods, such as dumping in landfills or rudimentary, high-heat recycling, facilitate the uncontrolled release of harmful substances. Once these devices are exposed to weather and soil, the contamination pathway to water sources is clear and direct:

Heavy Metal Poisoning: E-waste is a cocktail of highly toxic heavy metals, including lead, mercury, and cadmium, originating from components like circuit boards and batteries. When this waste is abandoned, these metals leach into the surrounding soil and ultimately contaminate groundwater. This polluted water, if used for drinking, cooking, or agriculture, presents catastrophic health risks to humans, potentially causing organ damage and cancer.

Endocrine Disruptors: The threat extends beyond metals to potent organic pollutants, such as brominated flame retardants (BFRs), which are used in plastics and casings. These chemicals leach into water systems and are known to disrupt the endocrine (hormone) systems of both humans and wildlife, potentially affecting development and reproduction across ecosystems.

A. Landfilling

Landfilling is a common disposal method where e-waste is simply mixed with diverse types of municipal garbage and buried. This approach is not a true recycling solution and is chosen primarily to meet minimal compliance requirements, not to be environmentally friendly. The method is problematic because electronic waste is not inert. It takes a very long time to break down, and as it does, it leaches toxic heavy metals like cadmium and mercury into the soil and groundwater. Furthermore, the gases produced by the landfill, if burned, can release these hazardous substances into the atmosphere, posing significant long-term environmental risks.

B. Incineration

The incineration process reduces the volume of e-waste by burning it, sometimes using techniques like pyrolysis (heating without oxygen) or gasification (heating with low oxygen). While this reduces the physical mass of the waste, it is an extremely hazardous practice, particularly in informal settings. When the plastic components of electronics, such as motherboards and PVC-coated wires are burned, they release a cocktail of highly toxic gases, including dioxins, furans, carbon monoxide, and heavy metal oxides. This smoke and the remaining ash are dangerously contaminated with lead, arsenic, mercury, and other poisons, posing a direct and severe threat to human health and the surrounding environment.

C. Acid bath leaching

This is a chemical method used specifically for resource recovery, aiming to extract valuable metals from e-waste. The process involves soaking circuit boards in a bath of strong acid, such as sulfuric acid, for 10 to 15 hours. This dissolves metals like copper, which can then be recovered from the solution. Other acids are used to extract lead, silver, and gold. While effective at recovering materials, this method is incredibly dangerous. It involves handling highly corrosive acids and produces a significant amount of toxic liquid sludge, which, if not treated, causes severe soil and water pollution when dumped.

Biological procedure of E-waste

Biological techniques represent an emerging innovation for recycling electronic waste, particularly for recovering valuable metals like gold and copper. This field, known as bio-metallurgy, utilizes microbes such as *Acidithiobacillus ferroxidase* and *Acidithiobacillus thiooxidans*. In a process called bioleaching, these bacteria produce chemical oxidants that dissolve the metals from the e-waste, transforming them into soluble salts into a liquid solution. This method is gaining traction as a promising and environmentally aware approach to handling complex electronic waste.

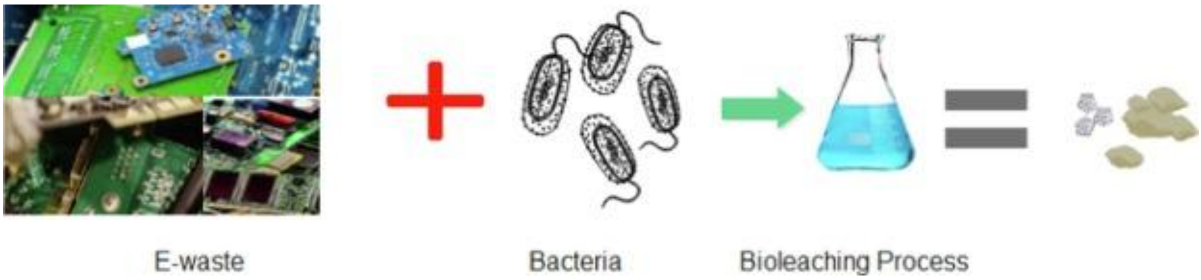

Fig. 3 Biological method for E-waste disposal.

Conclusion

The improper disposal of electronic waste presents a grave and escalating threat to the health of our planet's water sources and the survival of aquatic life. The toxic heavy metals and hazardous chemicals leaching from discarded electronics relentlessly poison groundwater, rivers, and oceans. This contamination has devastating and far-reaching consequences for aquatic ecosystems, leading to biodiversity loss, genetic damage in marine animals, and the accumulation of toxins throughout the food web, ultimately impacting human health.

However, through a combination of reducing consumption, reusing and repairing electronics, and most critically, recycling through certified and safe channels, we can effectively divert this toxic stream from our environment. Strong government policies, corporate accountability through Extended Producer Responsibility (EPR), and increased public awareness are the cornerstones of this effort. Ultimately, safeguarding our water from the perils of e-waste is a shared responsibility that is crucial for preserving aquatic biodiversity and ensuring a healthy, sustainable future for all.

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ISSN : 2583-0910
Agri-India TODAY
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Peer reviewed monthly newsletter

Article ID : 05/XI/32/1125

THE RISE OF SPECIALTY & UNDER-UTILIZED CROPS: MILLETS, MEDICINAL PLANTS, PULSES & SUPERFOODS

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Introduction

In India's fields, a quiet revolution is gathering steam. Farmers are rediscovering crops like hardy millets, nutrient-rich pulses, medicinal herbs, and indigenous "super foods" that thrive where hybrids fail. What began as small-scale sustainable farming initiatives has expanded into a national and global movement driven by health consciousness, export potential, and policy vision.

The high-yield crops of rice, wheat, and sugarcane dominated Indian agriculture for decades, filling granaries while depleting soils and water supplies. Specialty and underutilized crops that combine resistance and high value are now again in the forefront as climatic stress increases, markets change, and consumers seek out healthier options.

The global and national context

Globally, consumers are embracing plant-based diets and functional foods that are rich in antioxidants, fiber, and micronutrients. Previously dominated by Mexican chia seeds and South American quinoa, India's own pulses, millets, and therapeutic herbs are increasingly becoming superfoods.

A data point to open the story

According to The Economic Times, India plans to increase the area planted to pulses to 31 million hectares by 2030–31 in an attempt to become self-sufficient and less dependent on imports. India took the lead in marketing its traditional grains globally during the UN's International Year of Millets (2023), which led to a growth in millets and value-added commodities exports since 2022. The demand for these resilient crops is exceeding supply, which presents a chance for farmers who are ready to diversify, from global nutraceutical corporations to health conscious urban consumers.

Millets: The smart grains of the future

Millets, once dismissed as “poor man’s food,” are now recognised as “smart foods” good for people, farmers, and the planet.

Importance of millets:

- **Climate resilience:** They require 70–80% less water than rice and grow in poor soils.
- **Nutrition:** Rich in iron, calcium, and dietary fibre, helping combat hidden hunger.
- **Economics:** Input costs are low, and government procurement under the National Food Security Mission (NFSM-Nutri Cereals) is rising.

The market surge

Metro areas saw a huge increase in demand for ragi, jowar, and bajra goods following the UN's statement. Energy bars, biscuits, noodles, and millet flakes are currently sold by contemporary companies. With the support of APEDA (Agricultural and Processed Food Products Export Development Authority), exporters have discovered markets for organic millets in the Gulf and Europe.

Pulses: Powering protein security

Pulses have always been India's protein backbone. Yet for years, domestic production lagged behind demand, forcing costly imports. Now, policy and innovation are closing that gap.

The statistics and policy:

- India's pulse production has crossed 27 million tonnes and is targeted to reach 32 million tonnes by 2030.
- The government's National Food Security Mission-Pulses and Price Support Scheme (PSS) ensure minimum support prices and procurement.
- Research centres like ICAR-IIPR (Indian Institute of Pulses Research), Kanpur, are developing short-duration, drought-tolerant varieties of chickpea and pigeon pea.

The opportunity

Global plant-protein demand is growing rapidly, driven by vegan and health-focused diets. India can supply processed lentils, gram flour, and protein isolates to this market. For farmers, pulses also fix nitrogen in the soil, cutting fertilizer costs for subsequent crops an ecological and economic bonus.

Medicinal and aromatic plants for farming wellness

As herbal remedies, Ayurveda, and natural cosmetics gain popularity, medicinal and aromatic plants (MAPs) have become one of the fastest-growing segments in agri-exports.

Demand drivers

The global herbal market is expanding at over 8–10 % annually. India, home to 7,000 plant species used in traditional medicine, is well-placed to supply raw materials sustainably.

Government and institutional support

- The National Medicinal Plants Board (NMPB) promotes cultivation through subsidies and training.
- ICAR institutes and state horticulture departments provide guidance on species like ashwagandha, tulsi, lemongrass, and vetiver.
- The AYUSH Mission links farmers with pharmaceutical and essential-oil industries.

Superfoods and niche crops: New markets, New mind sets

Beyond millets and pulses, a host of indigenous crops are finding premium niches:

- Moringa (drumstick): leaves rich in iron and protein, exported as powder and capsules.
- Amaranth: gluten-free grain gaining attention as a quinoa alternative.
- Black rice and red rice: high-antioxidant varieties fetching premium prices in wellness markets.
- Jackfruit: processed into flour, chips, or vegan meat alternatives.

Startups and Farmer Producer Organizations (FPOs) are packaging these crops into branded, ready-to-cook products. The startup ecosystem, supported by the RKVY-RAFTAAR program, helps young entrepreneurs link farmers to modern supply chains.

Economic and environmental benefits for farmers

Diversifying into specialty crops is not just trendy it's smart economics:

- Better margins: These crops often earn 20–40% higher net returns per hectare compared to traditional cereals.
- Lower input costs: Millets and pulses need fewer fertilizers and pesticides.
- Resilience: Deep-rooted systems withstand erratic rainfall, providing stability under climate stress.
- Soil health: Crop rotations with pulses and millets restore organic carbon and microbial life.

Policy & institutional framework supporting the shift

Several government initiatives are converging to promote specialty and under-utilized crops:

- National Year of Millets (2023): Led to inclusion of millets in the public distribution system and midday meals.
- NMSA & NFSM: Provide incentives for pulses and nutri-cereals cultivation.
- Paramparagat Krishi Vikas Yojana (PKVY): Encourages organic certification for niche crops.
- Mission for Integrated Development of Horticulture (MIDH): Supports aromatic and medicinal plant cultivation.
- APEDA & FSSAI: Facilitate export certification, branding, and market access.

Challenges on the horizon

Despite enthusiasm, scaling up remains complex:

- Market linkages: Smallholders struggle to access processing units and premium buyers.
- Seed availability: Quality seed systems for minor crops are still limited.
- Awareness: Many farmers remain unaware of potential returns or cultivation techniques.
- Post-harvest management: Lack of dryers, storage, and grading reduces quality.

Addressing these will require cluster-based models, public-private partnerships, and digital platforms that connect producers with consumers transparently.

The global opportunity from India’s farms to the world’s plates

India's biodiversity gives it an inherent advantage in the superfood era. Millets, Moringa, Amaranth and Pulses have the potential to be export success stories, representing sustainable Agriculture on a global scale. African and Asian countries are already looking to India for expertise in climate-resilient crops. With proper branding, geographical indications (GIs), and traceability, India may offer its indigenous crops as luxury wellness goods rather than simply necessities.

Conclusion:

The growth of specialized and underutilized crops is more than a commercial trend; it represents a return to equilibrium. These crops bring together health and soil, biodiversity and business, and tradition and technology. As the globe seeks climate-resilient crops and natural nutrition, Indian farmers offer the earth what it most needs: diversity, expertise, and adaptation. By investing in millets, pulses, medicinal herbs, and superfoods, India can sustainably feed its people and economy. The fields of the future may not be entirely green; some may be gold with millets, red with amaranth, and purple with black rice, representing a farming revolution based on resilience and opportunity.

ISSN : 2583-0910
Agri-India TODAY
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Peer reviewed
monthly newsletter

Article ID : 05/XI/33/1125

THE RISING THREAT OF WILD BOAR TO AGRICULTURE

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Introduction

The wild boar (*Sus scrofa* Linnaeus), commonly referred to as the wild pig in its native range, is among the most widely distributed large mammals, found across every continent except Antarctica (Barrios-Garcia and Ballari, 2012). It comes under the family Suidae. Wild pigs, also known as feral hogs, Eurasian boars, or feral swine, are invasive animals that pose a serious danger to rural lives and agricultural productivity across the world. Wild boar's eating, rooting, trampling and wallowing behaviors harm crops, ruin fields and lower agricultural output. In addition to liking fruit and vegetable crops they essentially like rice, peanuts, oats, wheat, maize, sugar cane and sorghum. They eat seeds, nuts and seedlings and destroy land, it can also hinder forest regeneration by preventing the emergence of new trees and delaying the growth of existing trees. Wild boars may survive in a diversified environment, including semi-deserts, wetlands, forests and even high-altitude mountains (d'Huart, 1991).

Habitat of Wild Boar

The wild boar is a highly adaptable animal. It inhabits dense forests, scrublands, riverbanks, hilly regions, as well as agricultural fields. It thrives particularly in areas where water, grass and food are easily available. During crop maturity periods, it prefers to raid fields at night in search of food.

Agricultural Damage by Wild Boar

Wild boar has become a serious problem for farmers. It uproots crops, feeds on roots and also causes severe damage to standing crops. Their eating habits can interfere with plant regeneration and lead to ecological imbalances because of their extensive population in some locations. Wild boars cause great misery to the local community by destroying their crops (Pandey *et al*., 2019; Pandav *et al*., 2021), which has a detrimental impact on the villager's economics and standard of living (Chauhan *et al*., 2009). According to Liu *et al*. (2019), wild boars negatively affect water resources by reducing plant populations, diminishing biodiversity, increasing the risk of soil erosion, and altering soil characteristics. Their rooting behavior disturbs the soil and removes plant cover, thereby accelerating erosion. Over time, these activities can degrade soil quality, reduce future crop yields, and cause damage to surrounding ecosystems. Livestock can get a variety of diseases from wild boars. They can spread to domestic pigs (Boklund *et al*., 2008), cattle (Boadella *et al*., 2012) and other wild animals (Vicente *et al*., 2007). They also act as carriers of many illnesses and infections (Nair & Jayson, 2016). For developing an effective management strategy against wild boar, it is essential to understand their origin, distribution, habitat preferences, feeding behavior and reproductive patterns. Wild boars are declared wild under Schedule III and is protected, but their hunting does not attract high penalties or severe punishments.

Combined Methods for Controlling Wild Boar

Wild boar management can involve techniques such as small-scale exclusion, trapping and shouting. In India, wild boars are protected under Schedule III of the Wildlife Protection Act, 1972, which prohibits lethal control methods, as any action causing the animal's death is punishable by law. Under these circumstances, the adoption of strategic and integrated management practices becomes crucial. Such approaches not only help to minimize crop damage caused by wild boars but also reduce conflicts between farmers and wildlife within agricultural landscapes.

1. Physical Barriers

The behavioral tendencies of wild boars can be exploited to design effective physical barriers that help protect crops from their intrusion.

Wire Fencing

One common method is erecting a three-row barbed wire fence, with the first row positioned 12 inches above the ground. This arrangement creates an effective barrier against both stray animals and wild boars attempting to enter cultivated fields.

- Install barbed wire fence on farm periphery with posting cement poles at 10' (3.05 m) interval and tie 7 parallel rows of barbed wire one above other and 2 rows diagonally crossing each other at centre between two adjoining poles to restrict boar (*Sus scrofa*) entering into crop field. Tie parallel rows of barbed wires, starting from 6" (15.24 cm) above ground, lower 4 rows 8" (20.32 cm) apart and upper 3 rows 12" (30.48 cm) apart. By replacing lower 3 rows of barbed wire with chain linked net pushing 6" (15.24 cm) inside ground can increase the effectiveness.
- An alternative method is fencing with razor blades fixed on iron wires at regular intervals around the field boundary in circular loops. This setup inflicts serious injury on wild boars attempting to breach the barrier, thereby discouraging entry into crop fields.
- A chain link mesh fence about 3 feet high can be installed around the field, keeping it at least 1 foot away from the cropped area to prevent wild boar entry.

Plastic Fencing

Polypropylene fencing is a relatively low-cost option that is easy to install and repair compared to other types of barriers. It is widely accepted under various regulations and is generally effective as a short-term solution (lasting up to 10 years). However, its effectiveness is limited in regions with high populations of wild animals.

Solar Fencing

Solar-powered fencing is a modern and highly efficient method of protecting agricultural land. Functioning like an electric fence, it operates on solar energy and delivers a brief but strong shock when touched by animals or humans. While non-lethal, the shock serves as a powerful deterrent, ensuring protection without causing fatalities. In addition to safeguarding crops, solar fencing is environmentally friendly as it utilizes renewable energy.

Trenching

Trenching is another method to restrict wild boar movement. Farmers can dig trenches around cultivated fields approximately 8 feet deep, 3.25 feet wide at the base and 7 feet wide at the top. When wild boars attempt to cross, they are likely to fall into the trench, making it easier for forest department officials to capture and safely remove them.

2. Bio-fencing

Bio-fencings is the lines of trees or shrubs planted around the field boundaries that provide protection to crop against wild animals or cattle. It also acts as windbreaks, enrich the soil, bee forage, shading to crop and control the dust. These are less expensive and more useful than the wooden, barbed wire or stone masonry fencing. It is ecofriendly in nature giving additional income to the farmer through their produce. Various species have been tested to discover their suitability for use as bio-fencing plants *eg*. thorny species have been widely used.

- The most promising method for reducing wild boar damage near ground nuts was to plant four rows of safflower as a border crop. Wild boars will first be unable to find the crop, or if they do, the thorns of safflower injure them as they attempt to enter, particularly in groundnuts.
- To assist defend against wild boar, plant four to five rows of castor crops closely spaced around the maize field. The strong odor of castor effectively masks the odor of the maize field, making it impossible for wild boars to recognize the maize crop without using their sense of smell. In addition to oil seeds and pulses, castor may be utilized as a border crop.
- The prickly character of xerophytes and thorny plants, such as Cacti sp., *Euphorbia caducifolia*, *Emeriifolia*, *Opuntia elatior*, *Odillenii*, *Ziziphus mauritiana* and *Caesalpini acriatata*, helps guard the crop from wild boars.

3. Local methods

- Spraying a solution made from local pig dung in a one-foot-wide strip around the field at weekly intervals can mislead wild boars into believing they are entering another animal's territory, discouraging them from moving further to avoid territorial clashes.
- Placing human hair along wild boar movement paths irritates their nostrils when inhaled, causing respiratory discomfort and distress calls. This confusion not only diverts their movement but also prevents other wild boars from entering the crop area.
- Hanging colorful old sarees around the field creates an illusion of human activity, which makes wild boars hesitant to approach or invade the crops.

- Burning dried dung cakes mixed with pig dung produces a smell that mimics the presence of local pigs, tricking wild boars into avoiding the area.
- Community-based use of trained dogs effectively drives away wild boars approaching fields, providing a reliable and sustainable protection method.
- Collective actions like bursting firecrackers, beating drums or tins, lighting bonfires and shouting help to scare wild boars away from crop fields.

- **The rotating hand torch:** Farmers have developed another method of scaring wild animals away from fields by creating the illusion of human presence. In this method, a torch is tied with a string and hanged inside an empty oil tin that has been cut open on four sides. The tin is supported by three wooden sticks arranged in a tripod at a certain height in the crop field. When the wind blows, the torch rotates in all directions, scaring the animals and keeping them away from the field.

4. Bioacoustics

The bio-acoustic method relies on playing predator sounds, distress calls and alarm calls of the target species or closely related animals. These sounds are broadcast in the field using an electronic system equipped with sound drives. The Wild boar Repeller is a modern, advanced device that plays different sounds at set intervals to deter wild boars from entering crop fields.

The system includes one or two loudspeakers, an electric control unit with cable, battery terminal clips for power connection and a mounting plate. It operates at a fixed volume of 110 dB, effectively covering 4–5 acres in areas with an ambient noise of 42 dB and up to 19 acres at 37 dB ambient noise levels. This makes it highly suitable for farmers seeking crop protection. In addition, the newly developed Duet Sonic Technology enables the Ultra-Duet Pest Repeller to emit ultrasonic waves through two synchronized sound systems. This dual-sound mechanism enhances its efficiency in driving away wild boars and other stray animals, making it useful for safeguarding houses, gardens and agricultural fields.

5. Chemical Methods for Wild Boar Management

Although chemical control of wild boars may appear to be a simple practice, it cannot be widely adopted since wild boars are protected under **Schedule III of the Wildlife Protection Act, 1972**. Nevertheless, a few approaches have been explored that comply with legal restrictions and aim to reduce crop damage.

- **Use of insecticide odour barriers**: Granular insecticides mixed with sand are placed in perforated polythene bags and hung at a height of 60–100 cm, spaced about 3 m apart around the crop. The slow release of odor by wind currents confuses wild boars by masking the natural smell of the crop, thereby deterring their entry.
- **Egg solution spray**: Since wild boars largely depend on crop odor for identification, spraying a solution of eggs (20 ml per liter of water) on border rows or on moist soil around the crop helps mask the natural scent. This treatment reduces wild boar damage and should be repeated at 10-day intervals in cases of heavy infestation.
- **Kerosene-soaked niwar strips**: Three rows of niwar strips soaked in kerosene for about two hours are arranged around the field at one-foot spacing using wooden poles. The strong kerosene odor overpowers the crop smell, preventing wild boars from recognizing the field. This method is generally effective for 10–15 days.
- **Sulphur and pig oil ropes**: Three rows of coconut ropes soaked in a mixture of sulphur and pig oil are placed around the crop at one-foot spacing. The strong odor generated serves as a repellent, discouraging wild boars from entering. Re-application at 10-day intervals ensures effectiveness.
- **Phenyl solution:** The obnoxious smell from the spray of phenyl solution around the crops fields keeps blue bulls away from the crops fields for more than 10 days after application. This method is commonly used by the farmers (Babbar *et al*., 2022).

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ISSN : 2583-0910
Agri-India TODAY
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Article ID : 05/XI/34/1125

AQUAMIMICRY: A REVOLUTIONARY CONCEPT FOR SHRIMP FARMING

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Introduction

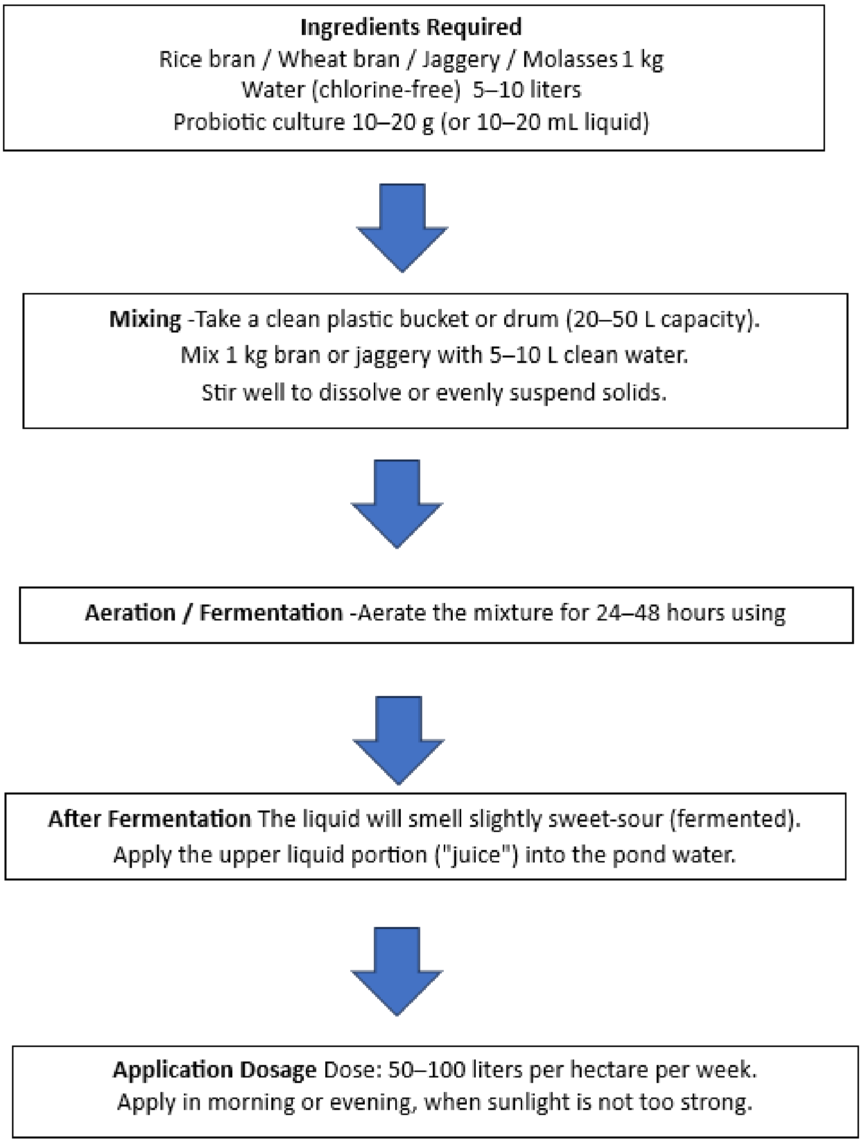
Aquamimicry is one of the innovative and sustainable technologies in the shrimp farming sector that stimulates natural conditions by applying natural prebiotics, e.g., fermented carbohydrates, to develop living food, especially "Copepod," for the postlarval before stocking (Khanjani *et al*., 2022; Santos *et al*., 2022). Fermented carbohydrate sources, such as fermented rice bran, are the most effective feed additives because of their effective roles as pre- and probiotics (Yang *et al*., 2021). The fermentation process enhances and improves the water solubility, palatability, nutritional digestibility, and immunological function of the feed (Abdel-Tawwab *et al*., 2022). The aquamimicry technique, which uses fermented rice bran, performs two essential functions. First, it forms bioflocs to maintain good water quality by creating heterotrophic microbial community formation and stabilization (Emerenciano *et al*., 2017). These microorganisms help to improve the water quality of a system by removing inorganic nitrogen from wastewater by uptaking nitrogen compounds, generating in situ microbial protein (Emerenciano *et al*., 2017). Second, it supports pond zooplankton and provides supplemental nutrition to shrimp (Khanjani *et al*., 2023). In addition to the post-larvae actively feeding on live feeds, it is believed that the larger and benthic shrimp consume zooplankton eggs when they sink to the pond bottom (Romano *et al*., 2018).

Natural foods contain a variety of essential components such as proteins, lipids, carbohydrates, amino acids, vitamins, minerals, and fatty acids. Consequently, they are often referred to as "living capsules of nutrition" (New, 1998). Moreover, the carbon source provides a balanced carbon:nitrogen (C:N) ratio to heterotrophic microorganisms for growth and function; thus, harmful nitrogenous compounds such as ammonia are transformed into microbial proteins (Avnimelech, 2009). Therefore, fermented carbohydrates and probiotics used in aqua mimicry systems could significantly minimize the cost of feed in shrimp farming (Ekasari *et al*., 2014). In addition, aquamimicry technology provides a disease-free culture environment and emphasizes the natural remediation of ecosystems by encouraging the natural cycling of minerals and the production of natural food organisms (Romano and Kumar, 2017). This technique significantly reduces water exchange and high-stocking-intensive cultures (Nisar *et al*., 2022). It provides low-cost, sustainable aquaculture production and high-quality outputs by reusing organic nutrients (Romano *et al*., 2018).

Pond preparation

Fill the pond to 80-100 cm depth with a filter bag (200-300 µm), add probiotics (Bacillus sp.), and chain-drag for seven days. If lined ponds are used, heavy ropes should be used to prevent the liner from tearing. Gentle dragging is used to improve soil mixing with the probiotics and to reduce the formation of biofilms, which could be hazardous to shrimp. To eliminate any small fish or eggs, teased cake (20 ppm) is combined with fermented rice bran or wheat bran (without the husk) at 50-100 ppm. More additions lead to more copepod blooms, which should appear within two weeks. Meanwhile, adequate aeration is important for optimal mixing, reducing teeseed cake levels, and mixing the nutrients and probiotics in the pond.

Carbon source preparation and use



Different steps of natural food production during pond preparation of the aquamimicry treatment ponds.

Days	Materials Applied/acre	Purposes
1st - 5th	Bleaching powder (6 ppm)	Disinfection of water
6th - 8th	6 kg LFRB	Production of natural food
9th	4 L water probiotics (super PS)	Control the growth of harmful bacteria

Days	Materials Applied/acre	Purposes
10th	5 kg of LFRB	Support the plankton production
11th	6 L of soil probiotics (Superbiotic)	Control the growth of harmful bacteria
13th	7 kg of minerals	Production of natural food
14th	5 kg of LFRB	For the copepods production
15th	4 L water probiotic	Control the growth of harmful bacteria

Live Food Importance

Aquamimicry technology utilizes natural organisms, particularly copepods, as a feed source for shrimp in a process known as copefloc technology (Deepak *et al*., 2020). In this strategy, copepods become the dominant species, replacing other zooplankton species and demonstrating system maturity (Chakravarty *et al*., 2018). Copepods are more nutritious than rotifers and Artemia, especially in terms of LC-PUFA (e.g., eicosapentaenoic, docosahexaenoic, and arachidonic acids), which are essential for growth and development (Satoh *et al*., 2009). Additionally, copepods are rich in carotenoids, free amino acids (such as taurine), peptides, vitamins, and minerals (including selenium, iodine, copper, and manganese).

The challenges ahead and future perspective

New technologies are used in aquaculture, and the challenges associated with them become evident as time goes on. Aquamimicry system faces some challenges as well, including

- It is difficult to use this technology in indoor environments.
- New diseases and pathogens could occur.
- The sediment pond is relatively large (soil preparation after crop cycles) in this system.

Shrimp farming is regarded as an essential economic activity, and the application of innovative technologies for production is critical. The aquamimicry technique promotes sustainable aquaculture by increasing production without significantly increasing the use of natural resources (water and land). It is also environmentally friendly and seeks a cost-benefit ratio to support economic and social sustainability (Santhanam *et al.,* 2020). The use of fermented bran with probiotics in the aquamimicry system has proven successful in shrimp farming by improving water quality and growth performance. Naturally fed shrimp in aquamimicry systems may be highly immunocompetent and resistant. Shrimp raised in this manner are organic and contain no hazardous chemicals or antibiotics.

Advantages of Aquamimicry in Shrimp Culture

- Stability Enhancement: The system offers a more stable culture environment than conventional systems.
- Improvement in Shrimp Health: The presence of bacterial secondary metabolites such as lipopolysaccharides and peptidoglycans in probiotics can enhance farmed shrimp's immunocompetence, resulting in healthier individuals.
- Feed Conversion Ratio Improvement: The abundance of zooplankton, especially copepods, improves feed conversion ratios.
- Disease Prevention: Providing a more natural and welfare-focused environment reduces the likelihood of disease outbreaks in shrimp aquaculture.
- Applicability to Large and Semi-Intensive Systems: Aquamimicry can be utilized in large-scale and semi-intensive cultivation systems, leading to reduced feed consumption and water exchange rates.

- Improvement in Nutrition: The presence of live foods in the culture media improves the overall nutrition of farmed shrimp.
- Stress Alleviation and Biosecurity: The limited water exchange rate alleviates stress conditions in farmed shrimp and enhances biosecurity.
- Reduction in Pathogen Propagation: Aquamimicry creates unfavorable conditions for the propagation of harmful bacterial pathogens and reduces the formation of black soil.
- Rise in Production Yield and Profitability: Implementing will help to increase shrimp production yield, reduce expenditures, and enhance profitability. The reduced dependency on commercial feeds decreases biological oxygen demand and the need for intense aeration, leading to higher energy consumption efficiency.

Conclusion

Aquamimicry is the combination of aquatic biology and technology to mimic the characteristics of natural aquatic habitats in order to raise healthy shrimp. The aquamimicry method reduces water exchange, maintaining biosecurity, and uses probiotics and FRB-derived oligosaccharides as symbiotics to promote immunological responses in shrimp, resulting in organic marine shrimp without the need for medicines. While hurdles still exist, more research and application are required to overcome these obstacles and support the gradual growth of this sustainable aquaculture approach.

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ISSN : 2583-0910
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Article ID : 05/XI/35/1125

AN OVERVIEW OF SUGARCANE CULTIVATION, VALUE CHAIN AND MANAGEMENT STRATEGIES FOR RED ROT DISEASE

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Abstract
Sugarcane (*Saccharum spp.*) is a major cash crop and a vital source of sugar, jaggery, ethanol, and other by-products that support rural livelihoods and industrial growth. Its extensive value chain—from cultivation to processing—adds significant economic value and contributes to national income. However, red rot, caused by *Colletotrichum falcatum*, remains one of the most destructive diseases of sugarcane, leading to severe yield and quality losses. The disease spreads through infected setts, crop residues and water, posing major challenges to sustainable production. Effective management involves adopting resistant varieties, maintaining field sanitation, and employing biological control strategies using *Trichoderma* and other beneficial microbes. Integrated disease management and eco-friendly approaches are essential to ensure the sustainability and profitability of sugarcane cultivation.

Keywords: Sugarcane; Value chain; Red rot; *Colletotrichum falcatum*; Biological control, Disease management; Sustainability

Introduction

Sugarcane (*Saccharum spp*.) is a perennial plant that has been shaped by human influence, evolving from a wild grass into a vital source of food, animal feed, and bioenergy. It was specifically selected for its exceptional ability to store large amounts of sucrose in its stalks. As sugarcane belongs to Gramineae family, stems are cylindrical and having fibrous root system. It is a rapidly growing tropical species because of its high photosynthetic efficiency as a C4 grass. However, it has significant nutrient needs as a long-duration crop (Paul *et al.,* 2005). The availability of nutrients in the soil diminishes due to monoculture practices and intensive farming (Shukla et al. 2016). Sugarcane is a rich source of carbohydrates and is used worldwide in multiple forms. It serves as food for humans, fodder for animals, and as a fertilizer in crop production. In terms of food, it yields products like sucrose, fructose, syrups, and jaggery. The fibrous part of sugarcane provides valuable cellulosic material. Its green leaves and top portions are commonly used as fodder. Residual and waste materials are utilized as fuel, while chemical by-products such as alcohol, bagasse, and press mud are significant industrial outputs.

Economic Importance and Production

According to the figures published by Directorate of sugarcane development (2023-24), Government of India, in India leading sugarcane producing states are Uttar Pradesh, Maharashtra, and Karnataka, with nationwide production of 446.43 million tons in 56.48 lakh ha area and productivity of 79.03T/ha in 2023-24 which has contributed around 19% of global sugar production and becoming the 2nd largest producer of the world. Sugarcane is primarily used to produces sugar, khandsari, and jaggery, which are its main products and serve as essential sources of sweeteners widely used in households and various food processing industries. There is a significant market demand for sugarcane stalks (used for chewing, raw juice, and religious purposes) and cane juice (used for making jaggery, brown sugar, and vinegar). These products, whether in raw or processed form, provide excellent entrepreneurial opportunities for rural communities, particularly in regions where sugarcane is extensively cultivated (Singh P and Singh J 2020). In India, many industries utilize agricultural produce as raw material and in doing so, they generate various types of waste. Among these, the sugarcane industry is a prominent example, producing substantial amounts of by-products such as bagasse, molasses, vinasse, press mud and bioethanol.

Sugarcane By-products

Sugarcane bagasse- Sugarcane bagasse is generated as a by-product during the milling and juice extraction stages of sugarcane processing, with the residual fiber constituting approximately 35% of the total weight of the processed cane (Rocha *et al.,* 2014). It is estimated that processing one ton of sugarcane yields around 280 kilograms of dry bagasse (Saelee *et al*., 2015). It is a lignocellulosic by-product left after juice extraction in the sugar industry, mainly composed of 40–50% cellulose, 20–30% hemicellulose, 20–25% lignin, and 1.5–3% ash which contribute to its high energy content. Brazil and India rank as the top global producers of sugarcane, with Brazil alone harvesting over 560 million tons during the 2012-13 season, which led to the production of approximately 185 million tons of bagasse (Varma *et al.,* 2016).

Sugarcane Molasse- It is a sugar rich liquid by product of sugarcane processing that was earlier used as sweetener in various food processing industries. In a metabolic study conducted in rats, molasses reduces peak and overall glucose responses, while enhancing insulin, amylin, and gastric inhibitory polypeptide levels (St-Pierre *et al.,* 2014). A human trial demonstrated that molasses attenuated plasma glucose and insulin responses to a carbohydrate load as contains compounds having properties to influence glycaemic index (GI), carbohydrate metabolism and also compounds like minerals, phenolic compounds and organic acids. (Wright *et al*., 2014). Molasses can be used for increasing silage quality of fodder (Ramzan *et al*., 2022), bio-asphalt preparation (Mehta and Saboo 2024), energy production by ethanol fermentation (Kabeyi and Olanrewaju 2022) and in various methods.

Press mud- Sugarcane press mud emerges as the earthy residue left behind after the sweet juice of sugarcane is filtered. In the clarification stage, the golden liquid gracefully rises to the surface, ready for transformation into sugar, while the heavier mud settles quietly at the bottom. As rich in organic matter used as manure that helps in improving the soil health, maintaining sustainable agriculture and decreasing the proliferation of soil borne pathogens (Patel and Gill 2023).

Bioethanol- Sugarcane is a highly productive crop with excellent potential for cost-effective bioethanol production (Rudorff et al. 2010). Through the organosolv process involving dilute acid hydrolysis, lignin and hemicellulose in sugarcane bagasse are solubilized to yield bioethanol (Dias et al. 2009). The surplus bagasse undergoes a three-step hydrolysis process that includes hemicellulose pre-hydrolysis, organosolv delignification, and cellulose hydrolysis (Bamidele et al. 2018). As per the Press Information Bureau (PIB), Government of India, the initial target of achieving 20% ethanol blending by 2030 was advanced to 2025 by the Cabinet Committee on

Economic Affairs (CCEA) in 2020. This initiative has increased ethanol blending in petrol from 1.53% in Ethanol Supply Year (ESY) 2013–14 to 15% in 2024, resulting in substantial economic and environmental benefits, including saving ₹1,06,072 crore in foreign exchange, replacing 181 lakh metric tons of crude oil, and reducing CO_2 emissions by 544 lakh metric tons.

Red Rot Disease in Sugarcane

Red rot, also known as "sugarcane cancer," is a severe disease that significantly affect sugarcane stubble and yield in many countries and causes economic losses. Red rot of sugarcane was recorded more than 100 years before in Java, India, Argentina, USA and other countries and it is one of the most devastating diseases of sugarcane (Viswanathan and Samiyappan 2008). In India, red rot was first reported in Madras presidency (state of Tamil Nadu) and progressively infiltrated to mostly every sugarcane producing state (Barber 1901). Since the cultivated sugarcane (*Saccharum officinarum*) has failed across the countries, systematic inter-specific hybridization between *S. officinarum* and the wild species *S. spontaneum* referred as 'nobilization' was done to develop resistant varieties and the disease was managed in most of the countries. In India, a severe red rot outbreak in the Godavari delta caused major damage to sugarcane crops, created an urge for resistant varieties and incurred a need for establishment of the Sugarcane Breeding Institute (SBI) at Coimbatore in 1912. As the first institute globally to develop sugarcane varieties for subtropical regions, it played a key role in advancing India's sugar industry (Duttamajumder 2008). Under Dr. C. A. Barber and T. S. Venkatraman efforts for hybridization work at Coimbatore produced the first interspecific hybrid, 'Co 205,' released in 1918 for Punjab. The successful use of wild species for traits like red rot resistance and stress tolerance revolutionized sugarcane breeding and influenced programs worldwide (Viswanathan 2010). Severe red rot outbreaks in Peninsular India during the 1990s led to 30–50% yield losses in sugarcane varieties such as Co 6304, CoC 671, CoC 85061, CoC 86062, CoC 92061, and CoSi 86071 (Alexander and Viswanathan 2002).

Symptoms, Impact and Spread of Disease

The typical symptoms of the disease are yellowing of leaves followed by drying, sometimes in susceptible crop, reddish lesions on the leaves that extend along the entire length of leaf vein; in the stalk, the pith turns red, interspersed with occasional white spots and the presence of a slightly acidic odor in the affected tissues due to sucrose fermentation (Sharma et al. 2017; Singh et al. 2017). During the early infection chlorosis and dropping of leaves, poor growth of plant is observed in susceptible varieties. In severe infection, when stem is split longitudinally, it is found that pith discoloration to reddening extended in vascular tissues and the vascular bundle is filled with dark brown mycelial growth of the fungus leads to hollowness and drying of the cane.

Red rot infection drastically reduces cane yield due to increased invertase activity and disrupted carbohydrate metabolism, resulting in sucrose degradation and accumulation of reducing sugars. Studies on variety CoC 671 showed 25–75% lower sucrose content, reduced brix, purity, and commercial cane sugar (CCS) compared to healthy canes (Satyavir *et al.,* 2002). This infection is a severe fungal disease that causes extensive damage to sugarcane once established, particularly during the monsoon season when the pathogen encounters favorable environmental conditions (Kumar *et al.,* 2018). In most sugarcane-growing regions of India, the planting of *eksali* (one-year) sugarcane is carried out from December to February. With the onset of the monsoon in July–August, the cane elongation phase begins, which coincides with conditions conducive for the development and spread of red rot. The simultaneous occurrence of rapid vegetative growth and high humidity creates an ideal environment for disease proliferation, often resulting in severe yield losses and deterioration in cane quality.

A field study in Bihar revealed that the variety CoS 8436, despite being high-yielding, suffered major losses due to red rot, with yield reductions of 30,664 q and 147,084 q in 2016–17 and 2017–18, respectively. Productivity declined to 86 q/ha and 456 q/ha during those years compared with healthy seasons (Kumar *et al.,* 2018). The decrease in yield was primarily due to the crop's vigorous growth during the monsoon coinciding with fungal infection.

The disease is primerily sett-borne, spreads through multiple pathways such as infected crop residues, setts (seed pieces), water, and even aerial transmission via leaf lesions and dew (Costa *et al.,* 2021). Hence, sustainable management of red rot requires an integrated strategy combining cultural, physical, chemical, biological, and varietal approaches.

Management Strategies

1. Cultural and Agronomic Practices

Cultural practices play a pivotal role in preventing the establishment and spread of red rot. Using disease-free, healthy setts from uninfected fields is essential, as the disease is primarily sett-borne. Crop rotation with non-host crops such as legumes or cereals for one or two seasons helps in reducing inoculum load. Good field sanitation through the removal and burning of infected stubbles and trash, coupled with efficient drainage to avoid water stagnation, prevents the buildup of the pathogen (Viswanathan and Samiyappan, 2008; TNAU Agritech Portal, 2023). Avoiding successive ratooning of infected crops and maintaining soil health through organic amendments and balanced fertilization also help minimize disease pressure.

2. Physical and Heat Treatments

Hot-water treatment of seed setts is an effective physical control method. Immersion of setts at 50–52 °C for 30 minutes or exposure to hot moist air at 54 °C for 2–3 hours eliminates internal mycelium of *C. falcatum* without affecting germination (Duttamajumder, 2008; Singh *et al.,* 2017). Such treatments are recommended for seed multiplication programs and for nursery establishment in endemic areas.

3. Chemical Control

Fungicidal treatments of seed setts remain an important preventive measure. Dipping setts in 0.1% carbendazim or benomyl solution for 10 minutes before planting has been reported to reduce infection rates substantially (Komarek *et al.,* 2010; TNAU Agritech Portal, 2023). Field application of systemic fungicides is less effective because the pathogen colonizes internal tissues. Hence, chemical use should be limited and integrated with other eco-friendly management options to prevent residue accumulation and resistance development.

4. Resistant Varieties

Breeding and adoption of red rot-resistant varieties are the most sustainable management approaches. Systematic hybridization between *Saccharum officinarum* and *S. spontaneum* initiated at the Sugarcane Breeding Institute, Coimbatore, led to the release of several resistant varieties such as Co 205, Co 86032, Co 0238, and CoSe 01434 (Alexander and Viswanathan, 2002; Viswanathan, 2010). However, due to the pathogen's high genetic variability, resistance often breaks down within a few years, necessitating continuous surveillance and breeding for durable resistance (Viswanathan, 2021).

5. Biological Control and Eco-friendly Approaches

Biological control offers a safe, sustainable alternative to chemical fungicides. Beneficial rhizosphere microorganisms such as *Trichoderma harzianum*, *T. viride*, and *Pseudomonas fluorescens* effectively suppress *C. falcatum* through mechanisms including antibiosis, mycoparasitism, competition for nutrients, and induced systemic resistance (Mendes *et al.,* 2013; Berendsen *et al.,* 2012). *Trichoderma* isolates have shown 60–80% inhibition of *C. falcatum* growth *in vitro* (Joshi and Misra, 2013; Dennis and Webster, 1971). Field applications of *Trichoderma*-fortified compost or sett treatment with *P. fluorescens* suspensions significantly lower red rot incidence (Viswanathan and Samiyappan, 2008). Plant-derived antifungal extracts such as neem (*Azadirachta indica*), turmeric (*Curcuma longa*), and eucalyptus (*Eucalyptus globulus*) also exhibit inhibitory effects on the pathogen (Tariq *et al.,* 2020). Combining biocontrol agents with organic amendments enhances soil microbial activity and plant defense responses, thereby improving disease suppression and crop vigor (Patel *et al.,* 2019).

Conclusion

In managing red rot of sugarcane, an integrated approach is indispensable. Preventive cultural practices such as the use of disease-free setts, crop rotation with non-host crops, and strict field sanitation form the first line of defense. Physical methods like hot-water treatment of planting material help reduce pathogen load, while chemical treatments, particularly sett pretreatment with systemic fungicides such as carbendazim, provide supplementary control though their standalone efficacy remains limited due to the deep-seated nature of the pathogen. Varietal resistance continues to be a cornerstone of management. However, the evolving pathogen population necessitates continuous breeding and rotation of resistant cultivars. Biological control agents, particularly *Trichoderma* spp. and *Pseudomonas fluorescens* along with plant-based extracts, offer promising, eco-friendly complements to conventional methods. Integrating these strategies within an IDM framework has been shown to reduce disease incidence and enhance productivity. Nevertheless, challenges such as pathogen variability, inconsistent field performance of biocontrols, and the need for wider farmer awareness underscore the importance of ongoing research, diagnostics, and extension efforts.

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ISSN : 2583-0910
Agri-India TODAY
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Peer reviewed monthly newsletter

Article ID : 05/XI/36/1125

WASTE TO BLOOM: TRANSFORMING KITCHEN WASTE INTO ECO-FRIENDLY LIQUID FERTILIZERS

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Abstract

Each day, millions of households discard nutrient-rich kitchen scraps such as fruit peels, vegetable trimmings, tea leaves, and coffee grounds, that could be turned into valuable fertilizers. Transforming this waste into eco-friendly liquid fertilizers is an innovative and sustainable approach to reducing household waste, enhancing soil health, and cutting dependence on chemical inputs. This article explains, in simple terms, how kitchen waste can be converted into organic liquid fertilizers, what benefits they offer, their limitations, and how they differ from synthetic fertilizers. With a few mindful practices, waste can literally turn into bloom- a true step toward circular living.

Introduction

Waste management and soil health are two pressing environmental concerns today. Kitchen waste, which forms about 50-50 per cent of household solid waste, often ends up in landfills, releasing methane and adding to pollution. Yet, this "waste" is not waste at all, it is a treasure trove of organic nutrients that can be recycled back into nature. Liquid fertilizers made from kitchen waste represent a practical, low-cost, and eco-friendly solution for home gardeners, urban households, and even small-scale farmers. Compared to traditional solid compost, liquid fertilizers are easier to apply, quicker in action, and can be absorbed by plants through both soil and leaves. They not only nourish plants but also improve the microbial life in soil, creating a healthier ecosystem (Bonanomi *et al.,* 2025).

This approach reflects the essence of a circular economy, where every form of waste is reused, recycled, and brought back into the production cycle. Instead of discarding kitchen scraps, converting them into liquid fertilizers ensures that nutrients return to the soil, completing nature's loop. It bridges the vital link between waste management and sustainable agriculture by transforming what was once considered waste into a resource that nourishes life. Such small household actions, when adopted collectively, can significantly reduce landfill pressure, minimize pollution, and promote a greener, more self-sustaining future- proving that sustainability truly begins at home.

(Source-www.asiafarming.com/eco-friendly-gardening-how-to-make-liquid-fertilizer-from-kitchen-waste**)**

From Scraps to Solutions- How It's Made?

The process of converting kitchen waste into liquid fertilizer is simple, flexible, and requires minimal equipment. In essence, organic materials are broken down by beneficial microbes in the presence (or absence) of oxygen, producing a nutrient-rich liquid that can be diluted and used to feed plants.

There are several general approaches to making such fertilizers:

- **Compost-based extracts**, where mature compost or decomposed organic matter is soaked in water to release soluble nutrients.
- **Fermented liquids**, made by fermenting kitchen scraps with beneficial microorganisms such as lactic acid bacteria or "Effective Microorganisms", producing a nutrient-dense and microbially active solution (Lew *et al.,* 2021).
- **Soak or enzymatic methods**, where vegetable and fruit wastes are soaked or decomposed naturally to yield mild nutrient teas suitable for home plants (Khanyile *et al.,* 2024).

The preparation time can range from a few days (for fermentation) to a couple of weeks (for natural soaking). The resulting liquid is usually diluted before use. This fertilizer can be applied directly to soil, added to compost pits to accelerate decomposition, or used as a foliar spray. Unlike synthetic fertilizers that supply only chemical nutrients, organic liquid fertilizers made from kitchen waste deliver a balanced mix of macronutrients, micronutrients, enzymes, and beneficial microorganisms, enriching both plants and soil.

Benefits - Turning Waste into Worth

The advantages of liquid fertilizers derived from kitchen waste go far beyond plant nutrition.

1. **Sustainable waste management:** It drastically reduces the volume of organic waste going to landfills, cutting methane emissions and lowering waste collection costs. A single household can recycle over 100 kilograms of organic waste annually just by composting and liquid extraction.
2. **Soil enrichment:** These fertilizers add organic carbon and beneficial microbes to the soil, improving its structure, water retention, and biological activity (Bonanomi *et al.,* 2025). Over time, soils treated with organic liquids become softer, richer, and more resilient to stress.
3. **Plant health and productivity:** The presence of natural growth hormones, humic substances, and microbial metabolites promotes stronger root systems and greener foliage. Studies have shown that liquid fertilizers derived from compost and fermented waste enhance yield and reduce plant stress under nutrient-limited conditions (Khanyile *et al.,* 2024).
4. **Eco-friendly and economical:** Since they are prepared from household waste, their cost is almost negligible. They are free from harmful residues, making them safer for people, pets, and pollinators.
5. **Fast nutrient availability:** Liquid fertilizers act faster than solid compost because nutrients are readily soluble and easily absorbed by plants.

How They Differ from Synthetic Fertilizers?

Synthetic fertilizers provide quick, measurable nutrient doses but often lack organic matter and can degrade soil health with continuous use. Liquid fertilizers made from kitchen waste are biologically active as they nurture the soil microbiome and improve long-term fertility. They work holistically rather than chemically: enriching soil texture, supporting beneficial microbes, and providing balanced nutrition without environmental harm.

While synthetic fertilizers are "plant feeders," organic liquids are "soil healers." This distinction is key to sustainable farming and gardening (Chalker-Scott, 2008). However, it's important to note that organic liquids are slower in action and nutrient content may vary based on waste composition and fermentation method. Thus, they complement rather than completely replace other nutrient sources.

Conclusions- A Step Toward Greener Living

The concept of converting kitchen waste into eco-friendly liquid fertilizers is a simple yet transformative approach to sustainable agriculture and waste management. It combines environmental responsibility with practicality, turning everyday organic waste into a valuable resource. While small in scale, such initiatives collectively have a profound impact on soil health, waste reduction, and environmental awareness. Future urban ecosystems must embrace such closed-loop systems where every peel, scrap, and shell finds a purpose. Transforming kitchen waste into liquid fertilizer is not merely an environmental act; it's a lifestyle shift toward conscious living. It empowers individuals to contribute to sustainability in a tangible way. Schools, community gardens, and households can adopt this practice to reduce waste generation and foster environmental responsibility. When kitchen waste feeds plants instead of landfills, the cycle of life completes itself beautifully — *from waste to bloom.*

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ISSN : 2583-0910
Agri-India TODAY
visit us at www.agriindiatoday.in

Peer reviewed
monthly newsletter

Article ID : 05/XI/37/1125

PEARL CULTURE PROCESS AND RECENT TECHNOLOGIES

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Introduction

Pearl culture or pearl farming refers to the cultivation of pearls within oysters, mussels, and clams in a controlled environment conditions Natural pearls, which form by chance when an irritant penetrates into a mollusc's shell whereas cultured pearls are created by intentionally inserting a tiny irritant, usually a bead nucleus or tissue of another molluscs, into the mantle tissue of a molluscs. Later the molluscs secrete layers of calcium carbonate and protein called nacre around this irritant, which slowly builds up the formation of the pearl. Worldwide pearls have also been valued throughout history for their beauty, rarity, and symbolism and worn as jewellery and for decorative arts for thousands of years. The pioneer attempts at pearl farming were in the early days of China under the Song Dynasty, but the modern cultured pearl farming started successfully in the early 20th century in Japan by Kokichi Mikimoto successfully commercializing round cultured pearls. Nowadays, more than 95% of pearl sales are cultured pearls, providing a cost-effective, sustainable alternative to natural pearls. Pearl culture development in India started in the year 1970s, with pearl oysters of the genus Pinctada being the primary species cultured on Indian shores. Good-quality pearls can be acquired through diversified techniques like rack, raft, and long-line farming in optimal salinity environments

CULTURE PROCESS OF PEARL OYSTER

They are five stages in pearl culture.

1. Pearl farm construction

a. Selection of farm site: This will decide the mode of pearls produced, and the survival rate of oysters. While choosing the site some of the things to be observed are:

- Natural elements such as mountains and reefs are required to guard the farm from winds, currents, storms, etc.
- Constant uniformity of temperature
- Nature of sea bed, i.e., rocky or sandy.
- Gentle currents are required for the oyster survival as they provide food and oxygen.

b. Construction of pearl farm: The entire pearl farm system is on series of floating wooden rafts. Ten sets of wooden rafts are utilized. Each raft contains two to five pieces of wood making the entire length to 20 ft. The raft is covered with wire mesh baskets, each containing 10 oysters.

c. Well-planned work schedule: An average work schedule plays a very crucial part in pearl culture. The time for fetching and seeding the oysters should be timed and strictly followed.

2. Collecting oysters

After pearl farm construction, the divers proceed to the sea bottom, to gather the oysters. Divers are dragged by huge lugger boats along the direction of the tidal flow. Oysters are usually found on a flat rock bottom and are generally covered with marine life and a thin layer of silt. Hence, it is frequently very hard for the divers to identify them. The gathered shells, are washed, graded, and put into baskets for storage until they are shipped to the pearl farm.

3. Seeding

Two-three years old healthy oysters are chosen for surgical implantation referred to as seeding. It is a very sensitive operation and involves two steps:

a) Preparation of the graft
b) Fixing the graft

a. Preparation of the graft: A donor oyster is killed to get mantle. The host oyster requires mantle to accept the nucleus. The mantle is found on the outside part of the oyster and Mantle secretes the nacre that produces pearl. The oysters are starved for a few days to reduce the rate of metabolism of the oyster before a graft is removed from the mantle. This serves to reduce the threat of core rejection and easily open the oyster.

b. Fixing the graft: Special pliers and wedges are used to open the oyster and a scalpel slit is then cut in the soft tissue close to the reproductive organ and a living mantle graft is placed inside the slit. Inserting the core: A nucleus is inserted into the scalpel slit, and the oyster returned to the water. The inserted core irritates the oyster, and it responds by layering the core with thin layers of nacre, mother of pearl. After a while, the oysters are harvested, and x-rayed to determine if the implants have been accepted. Oysters that refused the implant are returned to the water and operated again. The oysters that have accepted the implant are moved to the pearl farm. The planter has to be highly careful not to hurt the small pea-crab that lives unharmed inside every healthy oyster. It is assumed that the crab helps the oyster by cleaning it and by also sharing the refuse which the oyster sucks.

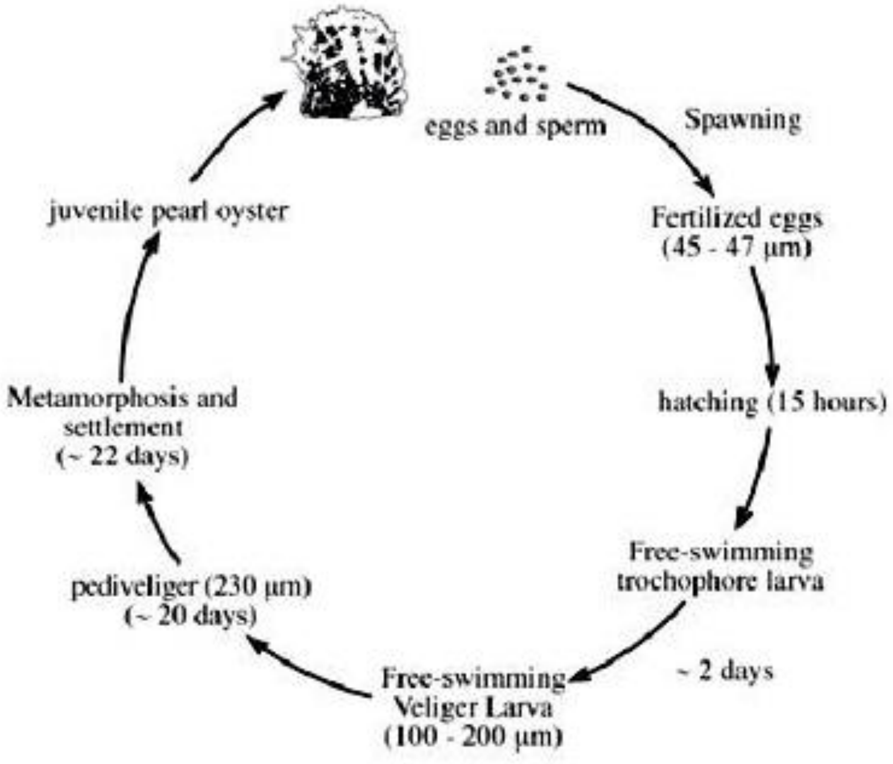
4. Caring the oyster

The collected shells and moved to the pearl farm are put in baskets or panels that are harnessed on long lines linked to the floating rafts. The rafts are released down into the ocean with the oyster safely inside the basket, where they stay until they get operated on for further seeding. The oyster may produce more than a single pearl in its lifetime. Seaweed cleaning of the shells on a regular basis leads to improved pearls plus easy handling. The cleaning is conducted by a machine that employs water jets and brushes to brush away any seaweed. The oysters require very careful handling so as to be productive when opened.

5. Harvesting

After 2-3 years, the oysters are harvested. It is very important to conduct a trial harvest so as to establish if the pearls have an adequate coating or not. When it is inadequate, that means that a further six months to a year of culturing is required. The scalpel used to split the oysters and also cuts the pearl bags in order to extract the pearls. Collected pearls have to be dried thoroughly after harvesting to avoid loss of luster.

Life Cycle of Pearl Oyster



Pearl culture rearing methods:

Raft culture

Raft oyster culture is one of the appropriate farming methods in protected bays. A raft unit of size 6 x 5m, made up of logs of teak, lashed with coir rope and buoyed with 4 buoys of capacity 200 1 is found to be appropriate for Indian conditions. This raft has the capacity to accommodate up to 100 culture cages. Raft culture may be used when the water depth is 5m and above.

Rack culture

When the water depth is below 5 m, the rack system may be adopted. Under this teak poles are planted into the sea bottom at distances of 1m and horizontal poles are tied with coir ropes over the seawater level. Culture cages are hung into the water from the horizontal poles. The rack may be extended according to the requirement.

Onshore tank culture

Huge concrete tanks built on the shore with the holding capacity between 75 and 150 tons of seawater may also be utilized for rearing the oysters. The desired depth of the water is 3 m to obtain the normal development in oysters. In this system, it is required to feed the oysters/juveniles with cultures of phytoplankters. Other systems such as long-line culture and on bottom culture can also be adopted depending upon the condition of the sea, sea bottom etc.

Natural vs culture pearls

Natural pearls	culture pearls
Natural pearls occur in nature with no human hand.	Cultured pearls are produced under human manipulation
They are created when an irritant, like a	They are produced Pearl farmers intentionally

Natural pearls	culture pearls
fragment of coral or sand, inadvertently finds its way into a mollusk and causes it to react to the irritant by secreting layers of nacre around it over many years.	place an irritant, commonly a bead nucleus, into the mollusk to trigger the secretion of nacre under controlled conditions.
This renders natural pearls extremely scarce and usually more asymmetrical in shape with thicker nacre deposits as they form naturally and slowly.	This permits greater control in terms of shape, size, and quality. Cultured pearls are generally more symmetrical, frequently round or oval, and are cultivated in much higher numbers, thus more accessible and affordable.

Difference between fresh water and marine water pearls

Feature	Freshwater Pearls	Saltwater Pearls
Origin	Mussels in rivers, lakes, ponds (mainly China)	Oysters in ocean bays, lagoons, seas (Japan, Tahiti, Australia, Indonesia)
Cultivation Method	Mantle tissue inserted; multiple pearls per mussel	Bead nucleus + mantle tissue; usually one pearl per oyster
Shape	Often irregular, baroque, wide variety of shapes	Generally rounder, more uniform in shape
Nacre Thickness	Thick nacre layer	Thinner nacre layer
Luster	Softer, dewy luster	Brighter, sharper, mirror-like or satin-like luster
Size	Generally smaller	Generally larger
Production Time	Shorter cultivation period	Longer cultivation period (10 months to 4 years)
Color	Wide range, often chemically treated (dyed, bleached)	Natural colors, less commonly treated
Availability	More abundant, widely available	Rarer, considered luxury gems
Value	More affordable	Higher value due to rarity and luster

RECENT TECHNOLOGIES IN PEARL CULTURE

Conventional pearl culture used to involve inserting a nucleus into an oyster, which secretes nacre to create a pearl around it. Nowadays, all this has been perfected through a series of technological innovations:

1. **Enhanced Nucleus Quality**: Better quality, carefully manufactured nuclei enable oysters to produce pearls that are brighter and of better quality.
2. **Water Quality Monitoring:** Ongoing monitoring systems are currently implemented to ascertain that water quality is within its optimal levels for pearl oyster growth. This is crucial for fostering the ideal conditions for tahiti pearl cultivation.
3. **Genetic Selection**: The application of selective breeding to improve such desirable traits in oysters has been a game-changer, leading to a more reliable pearl quality and quantity.
4. **Gene Editing and Manipulation:** Scientists have started investigating gene editing technologies to help in the cultivation of pearls. By pinpointing genes associated with producing lustrous nacre, scientists can potentially optimize the factors that result in quality black Tahitian pearls.

5. **CRISPR Technology:** This gene-editing technique enables farmers to edit the genetic material of oysters, enhancing their capacity to form pearls quickly.
6. **Biomimicry:** Drawing inspiration from the way oysters produce nacre naturally, advances in synthetic materials try to mimic the processes, with the possibility of artificial pearls that could compare to the beauty of natural pearls.
7. **Automation and Smart Farming:** The use of automation in pearling farming is quickly changing farm operations. From the monitoring of water quality to optimizing the process of harvesting, technology is optimizing the productivity of pearl farming:
8. **Automated Monitoring Systems:** The latest technologies enable real-time monitoring of several aspects that influence the health and growth of pearl oysters:
9. **Environmental Sensors**: Sensors that are immersed in the water all the time monitor parameters like temperature, salinity, and pollution levels constantly, and that information is used by farmers to ensure optimal conditions.
10. **Drones and Aerial Imaging**: Using drones with cameras enables farmers to monitor the extensive waters covered with oyster beds. That improves management efficiency and enables quick problem identification.

PROBLEM AND THEIR SOLUTION IN PEARL OYSTER CULTURE

Predation: Predation causes losses in pearl culture, specifically for oyster spat and juveniles. The main predators are sponges of the family Clionaidae, gastropods Cymatium (Family: Ranellidae), and Crustacea that damage the oysters culture.

Solution: some ways to deal with the problem. Firstly, spat can be removed from collectors at a shorter period 3-4 months instead of 6 months, when mean size is 15mm and reared in panel nets.

Using protective mesh covers with small openings help in improving survival rate by preventing predators. For juvenile the ear hanging and 24 pocket juvenile panel nets are suitable to promote growth and reduce mortality.

Biofouling: Biofouling is caused by organisms like barnacles and polychaete worm attach to oyster shells and culture equipment due to this reduction in oyster growth &deforms their shells, and increases in maintenance cost.

Solution: regular cleaning is the most common way to control the biofouling. Cleaning every 6to 8 weeks is generally effective and safe for oyster culture. The rate of fouling increases as the oyster age because natural formed protective shell layer gradually wears off. Biofouling can be reduced by using antifouling coatings or paints.

Diseases: Diseases out breaks causes a Major affect on productivity.

For Example: Pinctada Maxima population had suffered with high mortality due to algal bloom *Trichodesmium erythraeum*. Due to this oyster show swelling of digestive glands, sloughing of epithelial cells and increase in number of brown cells and granulocytes which indicates inflammation. This is caused due to certain algae like paralytic shell fish toxin, saxitoxin and there can't be prevented. In *Pinctada* fucata reddening of abductor muscle is a common problem caused due to infection. This can be prevented by lowering temperature of water less than 19 °C which suppresses pathogenic activity.

Genetic Improvement and Conservation Problem: Low diversity of genes and susceptibility to disease limit cultured pearl quality and productivity. Over time, inbreeding and accidental breeding can result in slowed growth and less survival and threaten sustainability.

Solution: Selective breeding and cryopreservation present efficient means to enhance and maintain pearl oyster stocks. Selecting parent oysters with favourable characteristics including increased growth rate and improved shell colour enables better pearl quality. Preservation of sperm through cryopreservation retains genetic lines and keeps high-quality gametes in reserve for future breeding. Sperm from *P. fucata* can be conserved using methanol-based solutions and controlled cooling apparatus. For *P. margaritifera*, slow freezing with sugar and dimethylsulfoxide based solutions maintains sperm viability. The sperm may be reactivated as needed for fertilization. In addition, selective breeding for white-shelled oysters has succeeded in reducing the output of sub-standard yellow pearls. Genetic monitoring ensures diversity stability and does not incur long-term genetic erosion.

Conclusion

Pearl culture is a shining combination of ancient handicraft and current aquaculture science, turning nature's miracle into an eco-friendly enterprise. Technological innovation in pearl culture such as genetic selection automated monitoring water quality control Pearl culture is now an eco-friendly, commercial sustainable industry today. Pearl culture in India is specifically cultured on the *Pinctada fucata*. Different government schemes have been implemented under the scheme of Pradhan Mantri Matsya Sampada for the promotion of farmers' rural livelihoods and sustainable utilization of marine resources. By way of the equilibrium between conservation and innovation in pearl culture, pearl culture not only keeps global jewellery markets but also represents nature-and-human harmony, having a promising future for sustainable aquaculture.

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