

ISSN: 3048-989X

Innovative Agriculture

A Monthly Magazine for
Agriculture and Allied Sciences

January 2026



www.innovativeagriculture.in



INNOVATIVE AGRICULTURE

www.innovativeagriculture.in



INNOVATIVE AGRICULTURE

A MONTHLY MAGAZINE

ISSN No.: 3048 – 989X

Frequency: Monthly

Month: January 2026

Volume: 02, Issue 03

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Influence of Climate Variability on Fisheries and Aquaculture Sustainability



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1. Introduction

The aquatic food industry globally is a very important sector of human livelihood and well-being. In 2020, fisheries and aquaculture recorded an all-time high production of 214 million tonnes with aquatic foods supplying about 17 percent of the global animal protein intake. However, the basic production system is faced with unprecedented stressors. Although the scientific literature focuses on long-term climate change, the climate variability, or the variation concerning the mean climatic conditions within relatively shorter periods (months to years), presents the greatest threat to operational sustainability.

The variability of climate includes both natural oscillations like the El Nino-Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO), and the rising occurrence and severity of extreme weather events due to the anthropogenic forcing. Such variations destroy the fine balance of aquatic systems. In the case of capture fisheries, variability changes the stock distribution and productivity, whereas in aquaculture, it introduces risks (uncontrollable) associated with water quality, disease epidemics, and damage to physical infrastructures.

2. Mechanisms of Impact on Wild Capture Fisheries

The capture fisheries have inherent dependency on natural ecosystem productivity and make these fisheries very vulnerable to changes in the environment. These systems are affected by climate variability either directly by physical drivers or indirectly by biological cascades.

2.1 Thermal Stress and Distributional Shifts

The ecological master factor that controls the physiology of fish is temperature. The majority of the aquatic species are poikilothermic (cold-blooded), which means that their metabolism, growth and reproduction are determined by the ambient water temperatures. Climatic variability often defies temperatures beyond favourable thermal limits. Mass mortality events can occur during acute marine heatwaves and especially in sessile life (like coral reefs, which are key fish habitats) and kelp forests. On a bigger scale, the process of warming and variability pushes the stocks of fish to the poles in search of colder water, thus tropicalizing the temperate waters, and leading to a massive loss of biodiversity and fishing capability to the tropical areas that are also home to some of the most fisheries-dependent communities.

2.2 Ocean Acidification and Deoxygenation

Although acidification is a long-term process caused by the uptake of CO₂, its impact is enhanced by local fluctuations, including upwelling. The higher acidity will decline the supply of carbonate ions that are necessary in the process of calcifying organisms such as shellfish, planktonic pteropods, and corals, and this would destabilize the base of the marine food web. At the same time, warmer water contains lower levels of dissolved oxygen; when combined with higher levels of nutrient runoff (as precipitation varies, causing eutrophication), this enlarges hypoxic regions. The crabs and flatfish are the most vulnerable to these low-oxygen events (benthic fisheries).

2.3 Disruption of Biological Synchrony

The reproduction of the fish is usually synchronized with the phytoplankton blooms to give the highest survival of the larvae. These events can be decoupled due to climate variability, especially changes in the timing of the seasons (phenology). Should water temperatures become warmer than normal, there can be a phytoplankton

bloom and decline before the hatching of fish larvae, causing a recruitment failure and consequently a collapse in the biomass of adult stocks in future years.

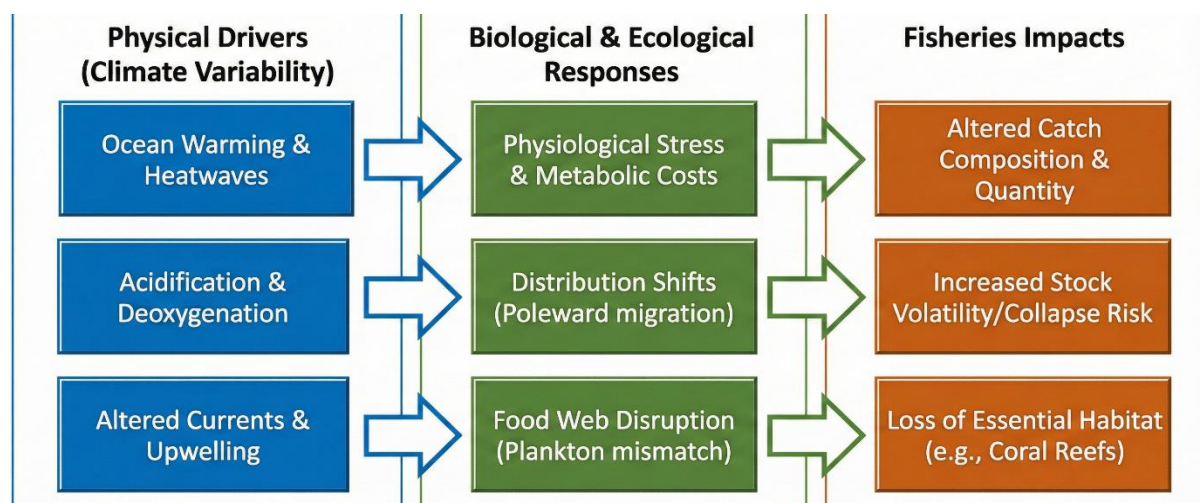


Figure 1. Conceptual Pathways of Climate Variability impacting Marine Capture Fisheries

3. Vulnerability in the Aquaculture Sector

Aquaculture, unlike capture fisheries, allows a certain level of control over the environment. However, this regulation is often not enough in the face of extreme variability, and high-density farming may increase stress response.

3.1 Inland Aquaculture

Inland systems (ponds, raceways) are reliant on predictable hydrological cycles. Climate variability increases droughts, which reduce water availability, and increases water resource competition with agriculture. On the contrary, severe rainfall leads to flooding that may destroy infrastructure, allow the proliferation of non-native farmed species into the wild, and bring runoff containing pathogens to culture systems. The volatility of temperature in shallow ponds may be very quick, and pressure on fish and immunity; this thermal pressure is a major initiator of disease outbreaks, including Tilapia Lake Virus or bacterial infections in shrimp farming.

3.2 Coastal and Marine Aquaculture (Mariculture)

There are different stressors on the coastal systems (cages, pens, mollusk rafts). Physical threats to infrastructure include the rise in sea levels and storm surges. Heightened variability in rainfall changes the salinity gradients at the coast; sudden low salinity can result because of flooding runoff, and this can be fatal to osmoconformers like oysters and clams. Furthermore, nutrient pulses or red films are favoured by warmer waters and nutrient pulses. HABs release toxins that accumulate in shellfish, making them unsafe to consume and resulting in significant financial losses due to closures and recalls.

Table 1. Comparative Vulnerability of Aquaculture Systems to Climate Variability Stressors

Aquaculture System	Primary Key Climate Stressors	Major Impacts	Adaptation Examples
Inland Pond Culture (e.g., Carp, Tilapia)	Drought/Water scarcity; Extreme temperatures; Flooding runoff.	Reduced water quality (DO drops); Disease outbreaks due to thermal stress; Infrastructure damage.	Water recycling systems (RAS); Deeper ponds for thermal refuge; Flood-resistant dykes.
Coastal Cage Farming (e.g., Salmon, Seabass)	Storm surges/Wave action; Harmful Algal Blooms (HABs); Increasing Sea temperatures.	Physical destruction of cages; Mass mortality from toxins or hypoxia; Increased parasite loads (e.g., sea lice).	Submersible cages to avoid surface storms; Real-time monitoring for HABs; Selective breeding for thermal tolerance.
Shellfish Aquaculture (e.g., Oysters, Mussels)	Ocean acidification; Salinity fluctuations (heavy rain); Extreme heat during tidal exposure.	Weaker shells and reduced larval survival; Mortality due to osmotic shock; "Burn" during low tide heatwaves.	Moving farms to deeper/more stable waters; Hatchery buffering against acidity; Shifting to more resilient species.

4. Socio-Economic Implications and Vulnerability

The biophysical effects of climate variability are directly converted to socio-economic shocks. Vulnerability of a community is not only dependent on the exposure of the society to climatic risks but also on sensitivity and adaptability.

4.1 Food Security and Nutritional Risks

Fish contain vital micronutrients (omega-3 fatty acids, vitamins D and B, calcium, iodine) that are in most cases, lacking in staple-based diets, especially in developing countries. The high variability in supply and increase in prices because of scarcity impacts low-income people more than the rest, who rely on fish as a food source. The tropicalization of catch means that the food resources are shifted out of the most food-insecure areas of the world.

4.2 Livelihood Instability and Migration

The greatest workforce in the sector is made up of small-scale artisanal fishermen. They are simply not as capital-endowed, technologically advanced, or have large ships that can chase the changing stocks or battle harsh storms. The incomes drop suddenly when the traditional fishing grounds fail to be reliable because of variability (e.g. an unpredictable ENSO event inhibiting upwelling). This economic instability may cause the movement of people out of the coastlines to cities, generating new social demands. In aquaculture, just one extreme phenomenon, like a flood, outbreak of a disease, can destroy the whole season's investment and leave the farmers in a cycle of debt.

5. Adaptation Strategies and Mitigation Measures

The fisheries and aquaculture business-as-usual models are not sustainable anymore. Increasing resilience requires preventive measures of adaptation that include policy, technology and management.

5.1 Ecosystem-Based Adaptation (EbA)

In the case of capture fisheries, management should now go past the single-species maximum sustainable yield (MSY) models to the Ecosystem Approach to Fisheries Management (EAFM). EAFM recognizes the complexity of the ecosystem and climatic impact and contains:

- a) **Dynamic Catch Limits:** Updating quotas on a short-term basis based on current environmental factors instead of past averages.
- b) **Marine Protected Areas (MPAs):** setting up of networks of MPAs that include climate refugia that is projected to be comparatively sustainable, thus allowing stock regenerations.
- c) **Habitat Restoration:** conservation of mangroves, seagrass and coral reefs, which act as nurseries and natural storm barriers.

5.2 Technological Innovations in Aquaculture

Aquaculture should lose its reliance on highly uncertain natural resources.

- a) **Selective Breeding:** Genetic improvement programmes are hastening the process of obtaining strains with higher resilience to high temperatures, hypoxia, and disease-specific conditions.
- b) **Recirculating Aquaculture Systems (RAS):** Moving production to the indoor environment significantly reduces exposure to meteorological extremes and water shortage, although energy consumption remains a major impediment.
- c) **Alternative Feeds:** Reduction of reliance on wild-caught fishmeal and fish oil, which are prone to climatic variability, by creating feed formulations based on algae, insects and microbial proteins.

5.3 Policy and Financial Mechanisms

Governments have to play the transition role that involves investing in climatic information services that can provide early warning of extreme weather conditions and harmful algal blooms to fishers and aquaculture farmers. Index-based weather insurance can provide farmers with quick compensation according to preset weather measures, e.g. amount of precipitation and therefore avoid the time-consuming process of claims and provide fast recovery.

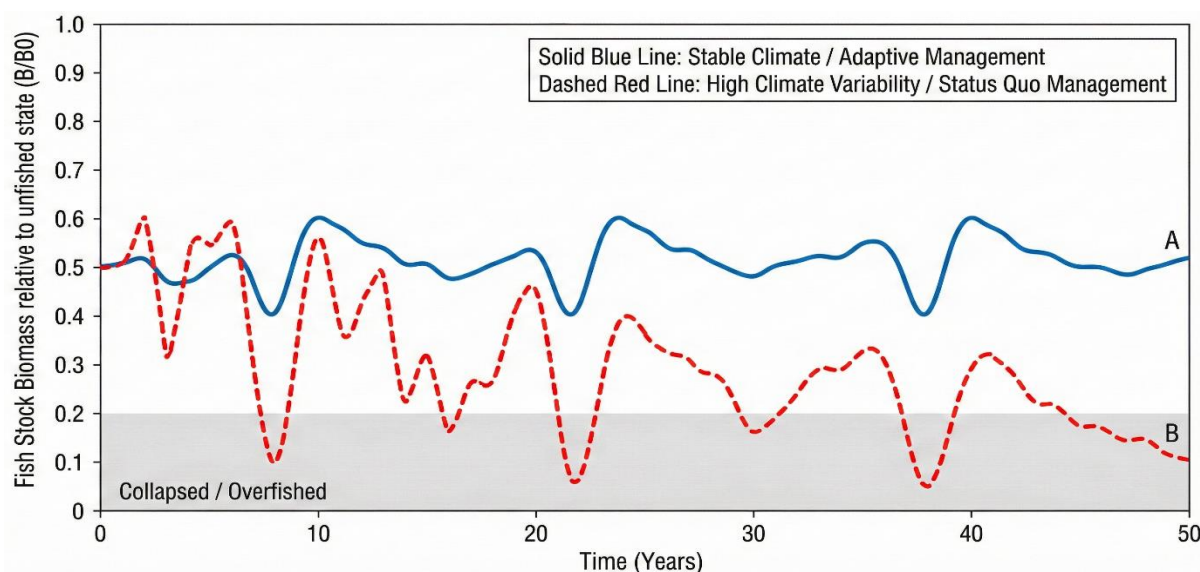


Figure 2. Projected Fish Stock Biomass under Stable vs. High Climate Variability Scenarios

6. Conclusion

Climate variability is a multiplier of threatening factors in the fisheries and aquaculture sectors, which further exacerbates already existing pressures on the areas due to overfishing, pollution, and habitat loss. The effects are not only hypothetical future conditions but are being witnessed globally, and are presenting themselves as changed stock distributions, increased rates of aquatic disease outbreaks, and broken supply chains.

To achieve the sustainability of blue food systems, there is a need to move swiftly to risk-based planning frameworks and not reactive ones in response to a crisis. The success will depend on the incorporation of climate science in fisheries governance frameworks, investment in resilient aquaculture technology, and enhancement of socio-economic safety nets among targeted vulnerable communities on the coastlines. Failure to adjust to this growing volatility puts at risk not only the economic sustainability of the industry, but also food security all over the world.

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Integrated Multi-Trophic Aquaculture as a Sustainable Production Approach



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1. Introduction

It is estimated that the world will have to increase food production by a significant margin by 2050 to feed a growing population, according to projections by the Food and Agriculture Organization (FAO). With the wild-capturing fisheries coming to a stall, aquaculture has emerged as the second fastest-growing part of animal-protein production in the world. However, the existing model of industrial aquaculture, which is intensive monoculture of high-trophic-level species (salmon or shrimp), faces the inherent limitation to sustainability.

These linear production systems are highly reliant on the exogenous inputs as feed, but also generate large amounts of effluents of uneaten feed, faecal matter and metabolic excretions. The consequential organic and inorganic enrichment in open-water net pen enclosures can trigger eutrophication, localized hypoxia, benthic, and hyper-nutritification of the surrounding coastal ecosystems. Moreover, monoculture practices make operations susceptible to disease outbreaks and market volatility intrinsically.

Consequently, ecosystem-based management is a conditioned change. Integrated Multi-Trophic Aquaculture (IMTA) provides a way of achieving this transition by offering an integrated framework. In contrast to polyculture, which can simply co-culture different species at one trophic level, IMTA actively takes advantage of trophic interactions. It involves the co-culture of species so that the excreta of one organism is collected and reused to provide inputs to other organisms: fertilizer, feed, or bioenergy. This paper will discuss how IMTA can emulate natural ecosystem processes to bring into being balanced, cleaner and more productive aquaculture systems.

2. Theoretical Framework

The ethos behind IMTA has its roots in the principles of industrial ecology and the circular economy; it further assumes that waste is not a pollutant, but instead a wasted resource. In a natural aquatic ecosystem, there is no waste; energy and nutrients constantly recycle within trophic networks. IMTA attempts to imitate a scaled-down version of such a network in a controlled production space.

An effective IMTA system requires the choice of biological materials, which play various ecological functions across different trophic levels. These are usually defined as follows:

- I. **Fed Aquaculture (Trophic Level 3-4):** The main crop, either fish species (e.g., salmon, bream, seabass) or shrimp, which relies on exogenous feed (pellets) to grow, and which serves as the major source of nutrients into the system.
- II. **Inorganic Extractive Aquaculture (Trophic Level 1):** Organisms that get their nutrients dissolved in inorganic nitrogen (DIN) and inorganic phosphorus (DIP) excreted by the fed species, mainly macroalgae (e.g. *kelp*, *Gracilaria*, or *Ulva*).
- III. **Organic Extractive Aquaculture (Trophic Level 2):** Prey species that feed on particulate organic matter (POM), such as uneaten feed and faecal detritus. This subdivision is even further subdivided by particle size and spatial orientations:
 - a) *Suspension Feeders:* Mollusks (filter-feeding, e.g., mussels, oysters, scallops) that consume fine particulates suspended in the columnar water body.
 - b) *Deposit Feeders:* Benthic (e.g., sea cucumbers, polychaetes, sea urchins) feeders that prey on the heavier, settleable organic solids that accumulate in the seabed underneath the farm.

An IMTA system is effective when the proportionality between these components is balanced hence ensuring that the extractive species has adequate biomass to complete the bioremediation of the effluents that are produced by the fed component.

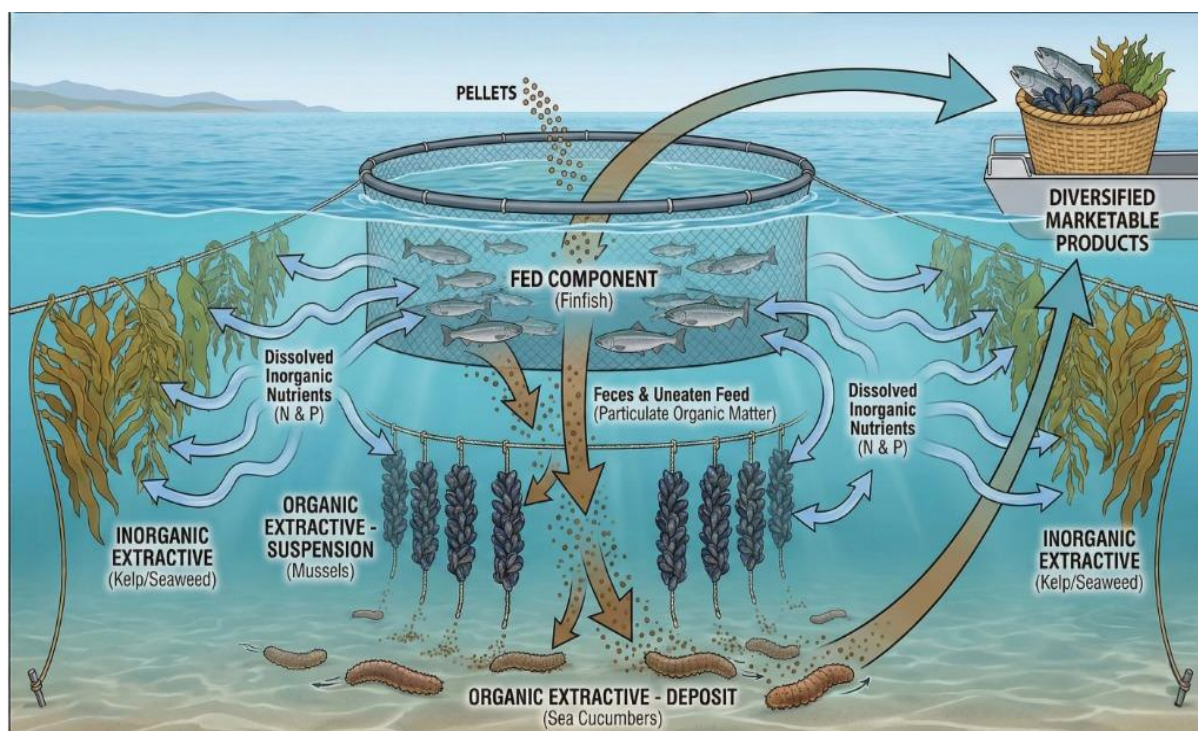


Figure 3. Conceptual Diagram of Nutrient Flows in IMTA

3. Environmental and Ecological Dividends

The shift from monoculture to IMTA creates a biomitigative effect, where the environmental footprint of the primary fed species is substantially reduced.

3.1 Nutrient Remediation and Eutrophication Control

The most important ecological advantage of IMTA is the valorisation of nutrient effluence. Fish farming results in high nitrogenous (ammonium and urea) and phosphorus release into the water column; in areas of low flushing, this release causes the growth of algal blooms and subsequent depletion of oxygen.

IMTA systems are biological nutrient scrubbers by including large amounts of macroalgal biomass. Empirical studies have indicated that kelp that is cultivated near salmon farms grows faster as well as having higher nitrogen levels, which can directly be traced to the nutrients that are released by the farms. Similarly, filter-feeding species like mussels intercept solid waste before sedimentation and hence reduce the benthic organic load that causes sediment anoxia and hydrogen sulphide release.

3.2 Carbon Sequestration and Halo Effects

Seaweed farming under the IMTA systems will aid in the sequestration of carbon. Though some part of the carbon volume is emitted during harvesting and consumption, a part of the algal biomass scales off and sinks to the deep ocean, hence providing potential long-term sequestration. In addition, locally, seaweeds may increase pH, which may relax the negative impact of ocean acidification on calcifying organisms, such as shellfish.

The halo effect is a common aspect of IMTA installations with augmented local biodiversity. The three-dimensional structure provided by mussel ropes and kelp lines creates habitat, nurseries, and shelters to various populations of wild fish and invertebrates, thus increasing the ecological importance of the aquacultural site beyond mere production rates.

Table 2. Environmental and Operational Comparison: Monoculture vs. IMTA

Feature	Intensive Monoculture (Fed Species)	Integrated Multi-Trophic Aquaculture (IMTA)
Trophic Structure	Single trophic level (linear).	Multiple, interacting trophic levels (circular).
Nutrient Output	High release of dissolved N/P and particulate organic matter into the environment.	A significant portion of N/P and particulates is captured and converted into secondary biomass.
Benthic Impact	High risk of localized benthic sedimentation and anoxia below cages.	Reduced benthic loading due to interception by suspension and deposit feeders.
Disease Risk	High density of a single species favours rapid pathogen transmission.	Increased distance between host species; potential for natural bio-filters (e.g., mussels filtering certain pathogens).
Biodiversity	Often reduces local biodiversity through habitat simplification.	Increases structural complexity, attracting wild species (artificial reef effect).
System Resilience	Low. Highly susceptible to market crashes or species-specific biological failures.	High. Diversification buffers against biological and economic shocks.

4. Economic and Socioeconomic Dimensions

Despite the ecological virtues of IMTA being somewhat convincing, its widespread adoption in the business aquaculture industry requires empirical economic soundness. IMTA provides one of the paradigms of economic resilience based on diversification.

4.1 Product Diversification and Risk Management

Farmers who practice monoculture are price-takers and vulnerable to price volatility, which appears in the single-commodity market. An economic crisis in the prices of salmon or an epidemic of a disease that will only affect finfish will destroy a monoculture business.

IMTA provides an aquaculture portfolio strategy. The farmer can diversify against vicissitudes in the market by growing three or more products in distinct products, such as fish, shellfish, and seaweed. In case a crop fails or fetches lower prices in the market, the subsistence revenues from other products will be able to keep the business afloat. It is also a characteristic of the extractive species to have dissimilar growth phenology and harvest periods, thus having the benefit of stable cash flow throughout the year compared to the boom-and-bust periods of some finfish operations.

4.2 Premium Pricing and Social License

The consumer population has moved towards a greater focus on sustainably sourced seafood. The IMTA products naturally have a story of environmental custodianship, which can be used to charge a premium price in the niche markets. Goods that have an eco-label certification of integrated practices can fetch a superior market price.

In addition, aquaculture is also faced on a regular basis with opposition on the part of coastal inhabitants who fear pollution, aesthetic effects and the greater concept of social licence to operate. Through the visible solution to the waste management problem that can be biological, IMTA can ease the attitude of people and foster greater acceptance of the aquaculture projects in the coastal areas by society.

5. Challenges and Future Directions

Although IMTA has an obvious theoretical base and empirically proven advantages, it has not achieved large-scale commercial mainstreaming. It has several bottlenecks that reduce its scalability.

5.1 Regulatory Frameworks:

The majority of modern aquaculture regulations are geared towards monocultures, where single-species businesses are licensed and have a low capacity to support the complex multi-species authorization of integrated multi-trophic aquaculture (IMTA). As an example, biosecurity regulations often do not allow close proximity of shellfish and finfish in a similar environment based on fears of transmitting infections, despite the empirical evidence that shellfish can also act as bio-filter in some circumstances.

5.2 Operational Complexity:

The administration of the IMTA system is many times more complex than that of a monoculture activity. It also requires a thorough understanding of the biology, physiology, and husbandry conditions of taxonomically diverse

populations, including vertebrate fish, mollusks, and macroalgae. The attainment of optimal ratios of biomass to encourage optimal nutrient uptake and ensure that resources are not wasted in competition for space or dissolved oxygen requires advanced modelling technology and adaptive management strategies, site-specific.

5.3 Market Development:

Even though the primary feed species of most IMTA businesses have a well-established market, the downstream markets of the co-produced entities, especially some species of seaweed and deposit feeders, like sea cucumbers, remain underdeveloped in Western economies. The development of value-added supply chains of these co-products is therefore necessary in order to make them economically viable.

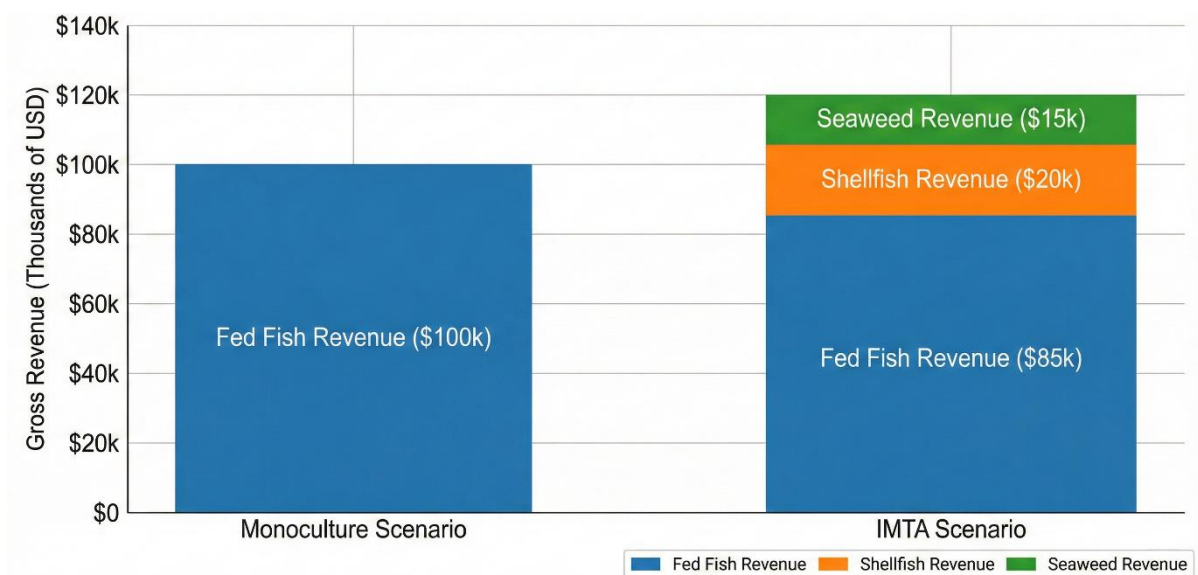


Figure 4. Gross Revenue Comparison. The following graph illustrates a hypothetical revenue comparison, demonstrating how the additive value of lower-trophic species in IMTA can match or exceed monoculture despite potentially lower densities of the primary fed species.

The Path Forward:

The optimal use of species assemblies that are congruent with particular geographic and oceanographic contexts is an area of research that needs to be focused on by future research. It is essential that engineered systems are developed, e.g. submersible cages or integrated infrastructures that cut down labour costs linked to multi-species management. Additionally, policy changes which encourage the introduction of credits based on nutrient-trading, where the large-scale farmers will be rewarded with money to eliminate nitrogen and phosphorus in the coastal waters through the development of sea-weed and the shellfish can be used to provide the necessary financial incentive to adopt large-scale IMTA.

6. Conclusion

The concept of Integrated Multi-Trophic Aquaculture is a requisite evolutionary stage to aquaculture, shifting it away from an extractive and linear paradigm to a regenerative and circular bio-economy. IMTA turns environmental liabilities into economic resources by pursuing the harmony between operations and ecological principles and by taking advantage of the natural trophic processes. Although certain technical and regulatory issues continue to bedevil the industry, the need to produce greater volumes of food with smaller ecological footprints has placed IMTA not only as an alternative but also as a precondition towards the sustainable future of marine agriculture. To realise this potential, there should be a concerted effort that cuts across the scientific field, industry players, and policy-makers to realise the full potential of the three-dimensional aquaculture systems.

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ITKs (Indigenous Technological Knowledge) USED IN AQUACULTURE



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INTRODUCTION

Over the past ten years, the sector of food production with the fastest growth has been aquaculture. For many years, Asia has been the dominant region for producing aquaculture, with China being the largest producer globally. Currently, more than 90% of all aquacultures is produced in Asia. It's interesting to note that more than 70% of the world's aquaculture production is provided by small-scale farmers, who also make up the bulk of the industry's small-scale inventions and adaptations. Due to the development of sustainable and environmentally friendly aquaculture methods in many nations across the world because of the adaption of indigenous technologies, farmers have been able to expand aquaculture production during the past decade. Indigenous technological knowledge (ITK) in aquaculture has been produced by farmers based on their own experiences and is primarily related to farm inputs. Farmers use their local knowledge as the basis for their innovation. This significantly altered the way fertilizers were used and created some novel right-hand rules for disease detection and treatment without the use of expensive antibiotics and chemotherapeutics, which are primarily helpful for underprivileged fish farmers.

DIFFERENT TECHNIQUES OF ITKS KAKABAN

A kakaban is square or rectangular shaped frame of bamboo. Its size varies from place to place but generally 1 x 0.6 m sized is common. The aquatic weeds like hydrilla, water hyacinth etc. are fixed in kakaban. The fibers of coconut are also used in kakaban. This structure is commonly used for common carp breeding. The eggs of common carp are adhesive type hence attach with the fiber or aquatic weeds.

DEGUMMING EGGS

Use of tannin in a solution of 15 g tannin/10 l water. However, tannin is toxic to fish eggs, and chronic use can have a variety of detrimental effects. An alternative method is the use of a urea-sodium chloride solution, but this approach is also not effective and there is potential for contamination farmers also apply milk powder at the time of egg fertilization. At the time of fertilization, eggs are sticky and the cell wall is thin. Milk powder dissolves the fat-soluble sticky substance as in the case of *Cyprinus carpio* and *pangasius*. "Ala mati" is a term used to describe red or laterite soil. It is used in the stripping process of artificial fertilization to remove the stickiness of fish eggs.

USAGE OF HARITAKI & KHAYER

Farmers in west Bengal were reported to use proper doses of the plant extracts from *ascasia catchu* and *terminalia chebula* in hatching pool, to make the eggshell hard. Higher hatching rates are facilitated by this, which is known to aid in shell hardening and prevent the premature release of hatchlings.

TRANSPORT AND ACCLIMATIZATION OF FISH

Vendors of fish seed in the district of karbi-anglong, assam, transported their product in aluminum hundis. For each 10 liters of water in these hundies, 50 ml of the local rice beer is added. According to vendor, adding rice beer to hundies during transportation improves fry survival since rice beer may function as a mild anesthetic. During transport of fish seeds alamati is mixed with the water to prevent them from blister formation in the direct sun light, which is termed as 'sun-cancer'. It also reduces the stress of the fish by affecting the visualization.

REMOVAL OF PREDATORY AND WEED FISHES

Farmers used mahua which contains saponin (4-6%), derris root powder which contain rotenone (5%), tea seed cake which contains rotenone (5.2 -7.2%) for eradication of predatory and weed fishes. Mahua cake subsequently becomes the manure for the pond.

CONTROL OF ALGAL BLOOMS

The problem of algal bloom generation in fish culture ponds is caused by a trend of high nutrient mass or heavy metal load. The growth and health of fish are also affected by this problem. Farmers used floating aquatic plants, such as water hyacinth (*Eichhornia crassipes*) to solve the problem using traditional techniques. In order to absorb nutrients and heavy metals from the pond water with algal bloom, they used this invasive plant carefully. Additionally, it helps in protecting the dykes from regular erosion due to the waves. In addition to this ITK, farmers reported applying large amounts of cow urine to the issue of algal bloom growth in pond water. They covered the entire surface of the pond with 17 L of applied cattle urine per hectare.

PROVISION OF SHADE IN POND

Long and broad leaves of 'coconut' (*cocos nucifera*) or 'khajur' (*date palm*) are tied to with 2-3 bamboo poles. The poles are fixed at the pond bottom. This provides shelter for fishes to overcome hot summer.

USE OF NEEM SEED OIL

Farmers used Neem seed oil for controlling aquatic insects in nursery ponds. In Neem seed oil (NSO) active ingredient, azadirachtin, acts as an insects growth regulator (IGR) preventing exoskeleton development and impeding the moulting process.

RAW COW DUNG

Raw cow dung is utilized to boost zooplankton in the nursery pond, as the spawn or very early fry feed on them. It is also used to increase the phytoplankton density of any pond and increases the fish production. Cow dung is commonly used as a fertilizer for fishponds in India, but fish production is limited to 1 500-2 000 kg/ha. These yields can, however, be more than doubled if the dung is first fed to a biogas plant and the digested slurry then used instead of the raw dung. The slurry is high in nitrogen and phosphate and free of harmful gasses produced when cow dung decomposes in ponds.

TURBIDITY MANAGEMENT:

Many fish ponds encounter the problem of turbidity. for controlling persistent clay turbidity farmers in Assam farmers apply paddy straw. 4 When the hay rots, the farmers periodically remove them from the pond. The method of controlling clay particles is found to be effective.

CONTROL OF pH

Shrimp farmers use toddy (palm sap) to control pH. Goswami *et al.* have reported that by cutting banana pseudo stems into pieces and submerging them in pond water, farmers can use them to raise pH levels through their alkaline secretion. Farmers in West Bengal are said to use this method to minimize Argulus and protozoan diseases.

Some farmers in Mathurapur I and II utilize tamarind and moringa tree branches to reduce the pH of the water. They apply these branches @ 3-5 pieces of 30-35 cm and keep them for 3-4 days. When the yellowish color of water turns off then they remove those branches.

USE OF PIECES OF BANANA TRUNKS

Banana trunk pieces are floated in village fish ponds to preserve the alkalinity and provide additional food. The opening to the oxygen-filled pockets is located in the pores on the surface of the banana trunk, which ultimately contributes to raising the oxygen content. It is necessary to take precautions to get rid of the trunks before they deteriorate.

DISSOLVED OXYGEN DEFICIENCY:

Farmers control the depletion of dissolved oxygen using traditional techniques such as channelling fresh spring water, shaking the water with bamboo poles or banana pseudo stems (TNAU), spraying water from open containers, and making children to swim in ponds.

BROADCASTING ASH OVER POND

In this method, paddy straw or hay are burnt and the ashes are broadcasted over the pond. It is used for correcting the water pH. This is used as a prophylactic measure to keep out the disease. It is also a good fertilizer.

CHECKING WATER pH

Farmers used blotting paper and red Camellia to test the pH of their water in accordance with a traditional method (*Camellia japonica*). In order to turn red camellia violet-blue, they first rubbed it in blotting paper. The paper was then submerged in pond water after turning violet-blue. While no color change indicates a neutral nature of water, turning the paper red or turning it blue indicates an acidic or alkaline nature, respectively.

GARLIC AND FENUGREEK- AS A FISH ATTRACTANT

To make harvesting easier and as a fish attractant, some farmers use fenugreek and garlic seeds. 250g of roasted and ground fenugreek seed was added to the mixture of 1 kilogram of semi-dried garlic. Both substances were applied in a pond after mixing. After an hour, a group of fish is attracted to a body of water large enough to cover a one-hectare area. Additionally, this mixture is used in angling as bait or an attractant.

AKASHI FRUIT FOR FISH TRANQUILIZER

The perfect strategy for harvesting pond fish is to tranquilize or anaesthetize them. The fruit of the Akash plant is used by the local indigenous people of Jharkhand to tranquilize fish. This fruit is semi-grained and thrown on the water's surface after combined with water at a ratio of 1 kg per 100 liters. Fish are caught by hand picking or netting after a half-hour when they begin to float on the water's surface.

CRAB REDUCTION

Ripe palm fruit is sometimes used by fish farmers to reduce the number of crabs in ponds. Crabs assemble on ripe fruit to eat due to its aroma, which farmers can easily remove by hand or with a scooping. Empty earthen pots are sometimes used to remove crab from shrimp farms because the crab competes with the shrimp for food. These pots are placed at the bottom of the shrimp pond at a different location from where feed is typically put. The pots are removed from the pond, which is then filled with crabs, after 4-5 days.

FISH FEEDING

Placing feed in gunny bags

The common method of application of feed in pond is by broadcasting them over pond as powder or slurry form. But this method increases the chances of wastage of food as it suspended in the bottom. Thus, the organic load of the pond increased. Andhra Pradesh farmers have developed a simple feeding method called "the bag feeding technique" in this method the feed is kept in a gunny bag and suspended in the water to ensure the effective utilization of feed from the meshes of the bags. This increases the productivity and decreases the cost of production as feed (60% of total investment) wastage is checked.

Supplementing common salt with feed

Common salt is used in feed, which is another indigenous technique practiced by farmers in Andhra. Studies done on carp at the College of Fisheries in Mangalore have shown that NaCl could promote growth.

FISH HEALTH MANAGEMENT

Control of leaches

To control leaches the farmers of Assam throw peels of cucumber or leaves of bitter gourd made into paste form. These plants help in eradication of leaches.

Turmeric as an antibacterial agent in fish ponds

Both antibacterial and anticancer properties are present in turmeric. To treat the *Aeromonas hydrophila* infection, this is applied as pastes over the water. Turmeric's active component, curcumin, has been demonstrated to have a wide range of therapeutic effects. Useful for treating bacterial infections in wounds when used as an external antibiotic. Additionally, it functions well as an exterior antifungal and insecticidal agent.

Control of tadpoles and snails in ponds

Farmers employ banana leaf, coconut leaf, palm leaf, and bamboo baskets, which are placed in the pond for a period of 15 to 20 days, to manage the snail population that is hindering fish culture. These substances serve as a substratum for snails. The attached snails and those materials were then removed from ponds.

Farmers use the rachis of jackfruit in the pond to get rid of tadpoles. Rachis is pulled along through pond surface. tadpoles are attached with the rachis. Later tadpoles are removed from the water.

Control of epizootic ulcerative syndrome (EUS):

Fish farmers in Assam have used a paste made of turmeric powder and hay or bamboo ash to control EUS. Even some farmers use Neem plant branches in fish ponds. hatchery owners in West Bengal spraying the water of a 0.133 ha pond with a paste comprised of garlic (2 kg), salt (2 kg), CuSO₄ (20 g), and KMnO₄ (20 g) to control EUS.

A farmer of Sabroom, South Tripura District developed a mixture of 8 kg mustard oil cake, 4-liter kerosene and 1½ kg soil for a hectare pond against this disease with encouraging result. Some traditional farmers are applying branches of Neem into fish pond for help to control ulcers on the body of fishes.

Argulus (fish lice) control:

In rural fish ponds, farmers install a lot of bamboo sticks vertically and drive them into the bottom soil. Fishes rub their body against the bamboo sticks. This helps in removing many ecto -parasite mainly Argulus from their body.

Farmers submerge old gunny bags in pond water and remove them on a regular basis to dry and kill argulus eggs that have accumulated on them.

Control of white feces syndrome in shrimp

Farmers West Bengal used Thankuni (*Centella asiatica*) leaf Fresh thankuni leaf is mixed with the shrimp feed @30-40 leaves per kg feed to control white feces syndrome in shrimp.

CONCLUSION

ITK is a type of knowledge that is apparently environmentally friendly, economical, and very reliable from a point of application, without any negative side effects. Generation after generation, the traditional farmers have kept using ITKs as a part of their culture. The ITKs are usually supported by solid scientific evidence and have an environmentally sustainable approach, which is an urgent need of current era. To construct efficient hybrid management systems, it is also possible to combine indigenous technical expertise with management knowledge based on modern science. Such technologies should be examined in order to fully understand the scientific principle behind them. Once this is done, it will be easier to further refine and upgrade them by blending them with modern scientific knowledge.

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“Cover Crops: A Key to Healthy Soil and Sustainable Farming”



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ABSTRACT

Modern agriculture faces serious challenges such as declining soil fertility, soil erosion, increasing weed pressure, rising input costs, and climate change-related uncertainties. Continuous monocropping, excessive use of chemical fertilizers and leaving fields bare during off-seasons have significantly degraded soil health. Cover crops offer a practical, cost-effective, and environmentally friendly solution to these problems. Cover crops are grown primarily to protect and improve the soil rather than for direct economic yield. They enhance the physical, chemical and biological properties of soil by improving fertility, preventing erosion, conserving moisture, suppressing weeds, and supporting beneficial soil organisms. Different groups of cover crops legumes, grasses and crucifers serve specific functions such as nitrogen fixation, biomass production, soil structure improvement and pest and disease suppression. Additionally, cover crops play an important role in climate-smart agriculture by enhancing carbon sequestration, reducing greenhouse gas emissions and increasing soil resilience to climate extremes.

Introduction:

Agriculture plays a vital role in ensuring food, nutritional and developmental security for many countries across the world. In India, agriculture bears enormous pressure to sustain the food requirements of nearly 14 per cent of the global population while utilizing only 2.8 per cent of the world's total land area. As a predominantly nature-based sector, agricultural production is highly sensitive to climatic factors and ongoing climate change. Variations in temperature and rainfall patterns directly influence crop growth, yield and overall productivity, while also exerting significant impacts on soil health, which is the primary natural resource supporting agricultural systems.

Improper and unsustainable management practices often result in substantial losses of soil moisture and essential nutrients through runoff, erosion and leaching, leading to irreversible degradation of land resources. Such losses not only reduce soil fertility but also threaten the long-term sustainability of agricultural production systems. Therefore, effective management of the agricultural ecosystem is imperative to conserve natural resources and maintain sustainable productivity.

Cover crops constitute one of the key resource-conserving practices for improving soil, water and nutrient management in agricultural systems. By maintaining continuous soil cover, cover crops protect the soil surface from the impact of intense rainfall, enhance water infiltration and significantly reduce soil and nutrient losses through runoff. Their early and rapid establishment also helps in suppressing weed populations by competing for light, space and nutrients, thereby contributing to effective and sustainable weed management. Hence, the integration of cover crops into cropping systems represents an efficient and environmentally sustainable strategy for resource conservation and climatic adaptation.

What Are Cover Crops?

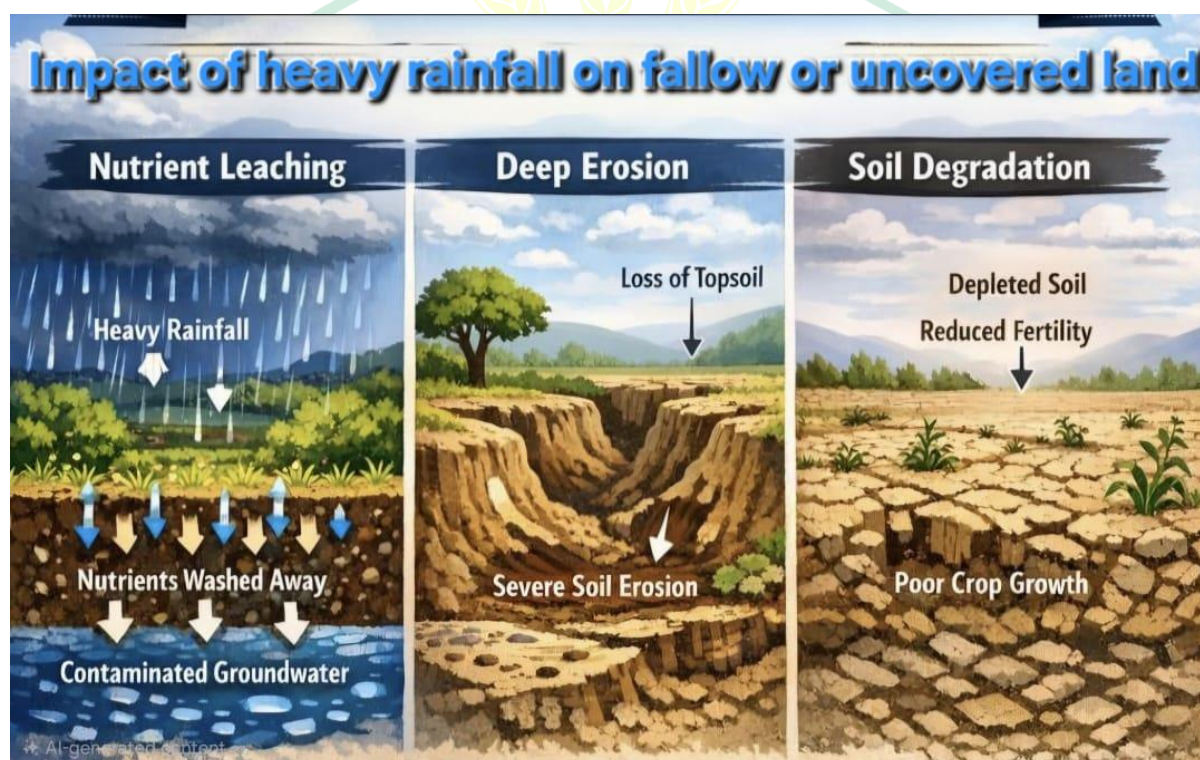
Cover crops are defined as crops grown primarily to provide soil cover rather than for direct economic yield and are mainly used to protect soil from erosion and nutrient losses through leaching and runoff. By maintaining continuous soil cover, cover crops reduce the impact of raindrops, minimize surface sealing and enhance water infiltration, thereby effectively controlling soil erosion and runoff losses. The protective mulch and canopy

formed by cover crops also conserve soil moisture by reducing evaporation and moderating soil temperature, which is particularly beneficial under rainfed conditions and during periods of moisture stress.

In addition, cover crops contribute significantly to the improvement of soil health by increasing soil organic matter content, enhancing soil aggregation and stimulating microbial activity, all of which play a vital role in nutrient cycling and soil fertility enhancement. The incorporation or surface retention of cover crop biomass provides readily available carbon substrates that promote biological activity and support long-term soil sustainability. Deep-rooted cover crop species further assist in alleviating soil compaction and breaking plough pans, thereby improving root penetration, soil porosity and water movement for subsequent crops.

Cover crops also play an important role in integrated weed management by competing with weeds for light, water and nutrients, as well as by providing a surface mulch that suppresses weed germination and emergence. Certain cover crop species additionally contribute to pest and disease suppression and enhance on-farm biodiversity by creating a favorable habitat for beneficial insects and soil organisms.

There is increasing evidence that the inclusion of cover crops enhances the resilience of agricultural systems to climate variability. Improved soil structure and higher organic matter content increase soil water-holding capacity under drought conditions, while continuous soil cover protects agricultural fields from erosion during high-intensity rainfall events. Thus, the integration of cover crops into cropping systems represents an effective and sustainable strategy for resource conservation, climate change adaptation and long-term agricultural productivity.



Characteristics of an Ideal Cover Crop

An ideal cover crop should possess certain characteristics that make it effective in improving soil health while fitting well into existing cropping systems. The main characteristics are as follows:

- **Fast Germination and Rapid Growth:** An ideal cover crop should establish quickly and grow vigorously to cover the soil surface in a short time. This ensures effective protection against soil erosion and weed infestation.
- **Good Ground Cover:** It should form a dense canopy that fully covers the soil, reducing moisture loss, preventing erosion, and suppressing weed growth.

- **High Biomass Production:** A good cover crop should produce sufficient green biomass, which on decomposition adds organic matter and nutrients to the soil.
- **Ability to Improve Soil Fertility:** Leguminous cover crops should be capable of fixing atmospheric nitrogen, while non-legumes should help recycle nutrients from deeper soil layers.
- **Well-Developed Root System:** The crop should have an extensive root system to improve soil structure, enhance aeration, increase water infiltration, and reduce soil compaction.
- **Adaptability to Local Climate and Soil:** An ideal cover crop must be well adapted to the local agro-climatic conditions and soil types, ensuring reliable growth with minimal inputs.
- **Weed Suppression Ability:** The cover crop should effectively compete with weeds for light, space and nutrients, reducing weed population naturally.
- **Ease of Management and Termination:** It should be easy to establish and terminate (by incorporation, mulching, or rolling) without affecting the succeeding crop.
- **Non-Host to Major Pests and Diseases:** The cover crop should not harbor pests or diseases that could affect the following main crop.
- **Compatibility with Cropping System:** It should fit well into existing crop rotations without competing for water or nutrients with the main crop.
- **Contribution to Soil Biological Activity:** An ideal cover crop should promote beneficial soil organisms, enhancing nutrient cycling and overall soil health.

Benefits of Cover Crops

1. Improvement of Soil Fertility

One of the most important benefits of cover crops is their contribution to soil fertility. Leguminous cover crops fix nitrogen from the air and convert it into plant-available forms. When the crop residues decompose, nutrients such as nitrogen, phosphorus and potassium are released into the soil for the next crop. Over time, continuous use of cover crops increases soil organic carbon, which is the foundation of soil fertility.

2. Prevention of Soil Erosion

Soil erosion is a silent threat to agricultural productivity. Heavy rainfall can wash away fertile topsoil, while strong winds can cause soil loss in dry areas. Cover crops protect the soil by forming a physical barrier that reduces the impact of rain and wind. Their root systems hold soil particles together, preventing runoff and soil loss.

3. Weed Suppression

Cover crops suppress weeds by competing for light, nutrients, and space. Dense cover crop canopies shade the soil surface, preventing weed seed germination. Some cover crops also release allelopathic substances that inhibit weed growth. This natural weed control reduces dependence on herbicides and lowers cultivation costs.

4. Improvement of Soil Structure

Cover crops improve soil structure by increasing aggregation and reducing compaction. Their roots create channels in the soil, improving aeration and water infiltration. This results in better root growth for the succeeding crop and improved drought tolerance.

5. Conservation of Soil Moisture

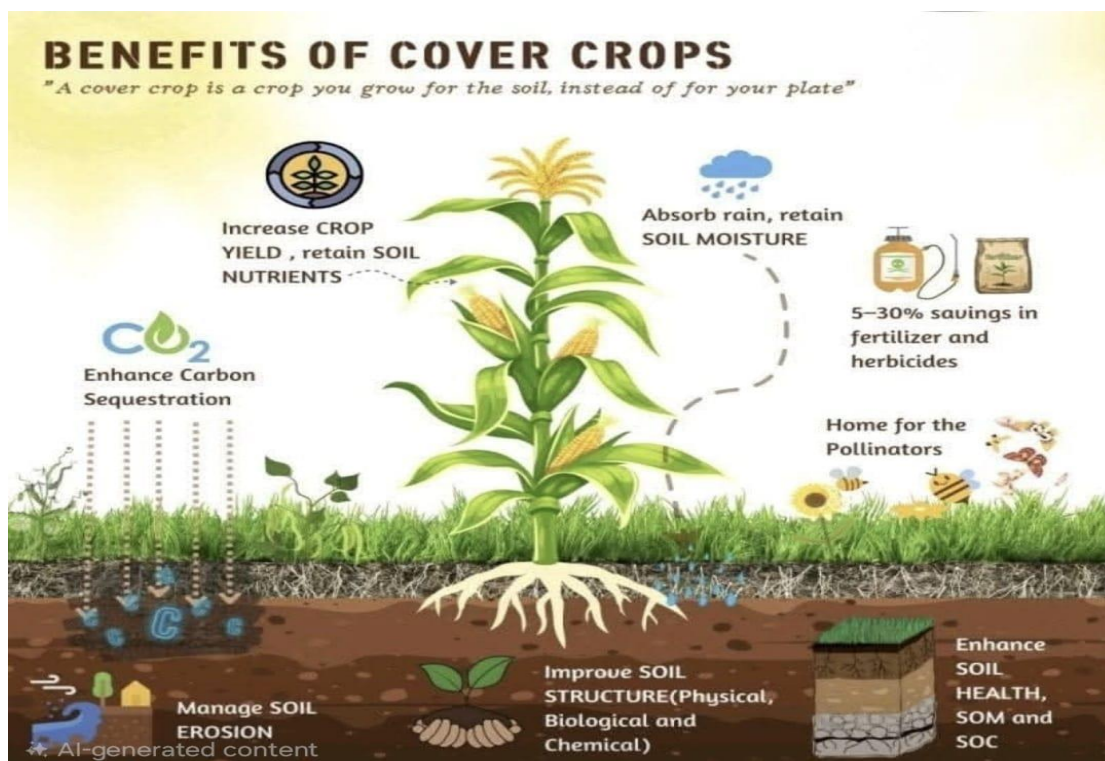
Bare soils lose moisture rapidly through evaporation. Cover crops reduce moisture loss by shading the soil surface and lowering soil temperature. Crop residues left as mulch further help conserve moisture, especially in rainfed and dryland areas.

6. Enhancement of Soil Biological Activity

Cover crops provide food and shelter for beneficial soil organisms such as earthworms, bacteria, fungi and actinomycetes. These organisms help in organic matter decomposition, nutrient mineralization and disease suppression. A biologically active soil is more resilient and productive.

7. Reduction of Pest and Disease Problems

Some cover crops interrupt pest life cycles by acting as trap crops or by reducing host availability. Certain species, such as mustard, release bio-fumigant compounds that suppress soil-borne pathogens and nematodes.



Types of Cover Crops

Cover crops are broadly classified based on their botanical group and function.

1. Leguminous Cover Crops

Legumes have the unique ability to fix atmospheric nitrogen through symbiotic bacteria present in their root nodules.

Examples: Sunhemp, Dhaincha, Cowpea, Greengram, Blackgram, Horsegram

Major benefits: Improve soil nitrogen status, Add organic matter, Improve soil fertility and crop growth

2. Grasses and Cereal Cover Crops

Grasses are fast-growing and produce large amounts of biomass.

Examples: Sorghum, Pearl millet, Oats, Rye, Maize

Major benefits: Excellent soil cover, Prevent soil erosion, Improve soil structure and Suppress weeds

3. Cruciferous and Other Cover Crops

These crops have deep taproots and bio-fumigation properties.

Examples: Mustard, Radish, Sesame

Major benefits: Break soil hardpan, Reduce soil-borne pests and diseases, Improve nutrient cycling

Cover Crops in Different Cropping Systems

Rainfed Agriculture

In rainfed areas, short-duration cover crops like cowpea or greengram can be grown during early monsoon or off-season to protect soil and improve fertility.

Irrigated Agriculture

In irrigated systems, cover crops can be grown between two intensive crops to restore soil health and reduce nutrient depletion.

Orchards and Plantations

Cover crops grown between tree rows reduce erosion, improve soil organic matter, and enhance water infiltration.

Management of Cover Crops

- Select cover crops based on climate, soil type and cropping system
- Sow immediately after harvest of the main crop

- Allow sufficient growth (30–60 days)
- Terminate by incorporation, mulching or rolling before planting the next crop
- Avoid water and nutrient competition with the main crop

Cover Crops and Climate-Smart Agriculture

Cover crops play a vital role in climate-smart agriculture. They help in carbon sequestration, reduce greenhouse gas emissions, and improve soil resilience to droughts and floods. By improving soil health, cover crops enhance long-term productivity and sustainability.

Conclusion

Cover crops are a low-cost, high-benefit practice that can transform soil health and farm productivity. They protect the soil, improve fertility, control weeds, conserve moisture and promote beneficial soil life. Though the benefits may not be immediately visible, long-term adoption of cover crops leads to healthier soils, reduced input costs and sustainable farming systems.

“Healthy soil is the foundation of agriculture, and cover crops are the green bridge to that future.”



Invisible Engineers: How Microbes Drive Heat, Carbon, and Soil Health



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Introduction:

Microorganisms are among the most powerful yet often overlooked drivers of life on Earth. Although these tiny organisms are invisible to the naked eye, microbial communities quietly regulate how organic matter breaks down, how nutrients are recycled, and how carbon moves through ecosystems. From compost piles to agricultural soils, microbes function as biological engines releasing heat, transforming waste into re-usable resources and sustaining plant productivity.

Understanding the role of microbes is essential for appreciating how natural systems maintain balance and efficiency. Whether decomposing organic residues or supporting plant growth, microbial activity plays an essential role in many processes that are central to sustainable agriculture and environmental management.

Microbial Metabolism: Turning Organic Matter into Energy

When microorganisms consume organic material, they do more than simply break it down - they release energy. Composting is a clear example of this process. As microbes metabolize carbon-rich compounds, heat is generated as a natural byproduct of respiration. The heat released during the decomposition process is not incidental, it is a direct reflection of microbial activity and efficiency.

The composting process undergoes distinct biological stages driven by microbial populations. In the early phase, mesophilic bacteria thrive at moderate temperatures, rapidly decomposing easily available organic compounds. As metabolic activity intensifies, temperatures also rise, creating conditions favourable for the thermophilic microorganisms. These heat-loving microbes tolerate high temperatures, sometimes approaching to 70 °C while degrading more complex organic materials.

This marks the thermophilic phase, which is critical as it not only accelerates decomposition, but it also contributes to pathogen suppression and organic matter stabilization. Fungi and actinomycetes become particularly important at this stage, breaking down cellulose, hemicellulose and other resistant compounds that bacteria alone cannot efficiently process.

Why Microbial Diversity Matters

No single microorganism can perform all the tasks required for organic matter decomposition. Instead, composting depends on diverse microbial communities for this task, each contributing specific metabolic capabilities. Although bacteria dominates the rapid breakdown of simple compounds, fungi specialize in degrading fibrous plant materials while actinomycetes bridge the gap by decomposing complex polymers.

Research shows that higher microbial diversity improves composting efficiency by shortening the early decomposition stages and help sustain longer periods of high biological activity. Diverse microbial communities enhance this systems resilience, ensuring that decomposition continues regardless of the external environmental conditions fluctuations.

As all the organic matter is consumed by the microbes, a stage where compost matures, microbial activity slows and shifts again. Mesophilic organisms return, focusing on lignin degradation and humus formation. This processes helps to stabilize organic matter and improve its long-term value for soil health.

Heat as a Biological Signature

Heat production during decomposition is more than a practical outcome of the natural process, it is a biological signal. Temperature profiles provide insight of microbial metabolism, activity levels and system health. Sustained high temperatures indicate robust microbial respiration, while declining temperature signals substrate depletion or environmental limitations.

However, temperature must remain within biological limits. Although thermophilic microbes tolerate elevated heat, excessively high temperatures can stop enzymatic function and thereby slow decomposition. Traditional composting principles suggest maintaining temperatures below 70 °C to preserve microbial efficiency and diversity.

By observing the rise and drop in temperature patterns, managers and researchers can infer microbial performance without directly measuring microbial populations, making heat a powerful indicator of biological function.

Microbial Respiration and Carbon Cycling

Another important result of microbial metabolism is the creation of carbon dioxide (CO₂). CO₂ is emitted into the environment when bacteria oxidize organic carbon. Microbial respiration is a mechanism that is essential to the cycling of carbon in soils and composting systems.

CO₂ emissions are frequently utilized as markers of breakdown rates and microbiological activity. In general, faster organic matter breakdown and more active microbial populations are reflected in higher respiration rates. Respiration dynamics are influenced by seasonal variations, substrate quality, and environmental factors, underscoring the sensitivity of microorganisms to their environment.

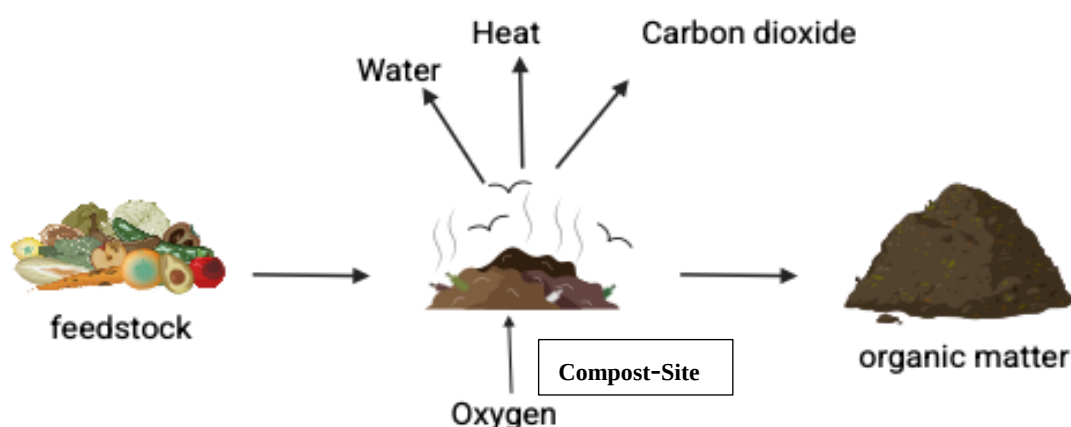
Additionally, microbial respiration has a wider ecological significance. The majority of CO₂ emissions in many ecosystems come from soil microorganisms, directly connecting biological activity to global carbon fluxes.

Environmental Controls on Microbial Performance

Environmental factors have a significant influence on microbial efficiency. The interplay of temperature, moisture, oxygen availability, and substrate quality determines the efficiency of microorganisms.

Oxygen diffusion can be restricted by too much moisture, which slows aerobic metabolism and lengthens the time it takes for breakdown. On the other hand, low moisture limits the movement of microorganisms and the activity of enzymes. Because aerobic microorganisms need oxygen to produce energy and break down organic matter, its availability is equally important.

Microbial behavior is also influenced by nutrient balance. Whether bacteria release nitrogen for plant use or temporarily immobilize it inside their biomass depends on the carbon to nitrogen ratio in organic materials. This equilibrium controls the availability of nutrients in soils and reflects the stoichiometric requirements of microbial populations.



Microbes as Architects of Soil Health

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Why Microbes Matter for Sustainable Agriculture

Microorganisms are at the nexus of soil fertility, waste management, and climate regulation. They are essential to sustainable systems because of their capacity to convert organic wastes into heat, carbon dioxide, and stable organic matter.

It is more accurate to think of bacteria as active engineers who shape energy flows, control nutrient cycles, and preserve ecological stability rather than as passive decomposers. With advantages ranging from soil health to climate mitigation, advances in our knowledge of microbial communities and their environmental needs present chances to better control biological processes.

Conclusion

Some of the most significant processes in agriculture and environmental systems are powered by microbes. They promote the breakdown of organic matter, produce heat, control carbon emissions, and maintain soil fertility through respiration, the synthesis of enzymes, and community interactions.

The emphasis is shifted from inputs and technologies to biology itself when the crucial role of microorganisms is acknowledged. It is conceivable to improve naturally occurring processes that are already incredibly effective by promoting microbial diversity and improving the environments in which microorganisms flourish. By doing this, agriculture can get closer to systems that complement biology rather than work against it.

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CONTRACT FARMING: DEFINITION, TYPES, PROS AND CONS



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Abstract:

Contract farming is an important approach to support farmers facing market price fluctuations and production risks that arises mainly due to globalization and changing consumer preferences. It links farmers directly with companies through assured prices, quality inputs and technical guidance, leading to better productivity and stable incomes. With transparent agreements and effective institutional support, contract farming can contribute significantly to sustainable agricultural and rural development.

Key words: Contract farming, Globalization, Vertical coordination, Sustainable agriculture and Rural development

Introduction:

Modern agriculture is continuously changing due to globalization, changing consumer preferences, market competition, technological advancements and the need for quality and safe food (Rehber, 2007). Due to these factors, farmers now-a-days facing uncertainties such as fluctuating market prices, lack of reliable buyers, limited access to advanced technologies, and rising production risks. Consequently, population shifts towards urban areas are increasingly witnessed in most regions (Eaton and Shepherd 2001). To overcome these challenges, stronger vertical coordination between farmers and agribusiness firms has become essential.

Contract farming helps in creating a stronger vertical coordination link between producers and buyers, ensuring a reliable supply chain, stable incomes, improved technology access and better market opportunities (Bellemare and Novak, 2017). Thus, contract farming is increasingly chosen as a preferred method of agricultural development in both developed and developing countries.

What is contract farming?

Contract farming is an agreement between a farmer and a company (or firm) where the farmer agrees to produce a specific crop under predetermined conditions and the company agrees to purchase it at a pre-decided price (Eaton and Shepherd, 2001).

The company (or firm) often provides seeds, fertilizers, credit, technical guidance and extension support, while the farmer agrees to supply the produce at the agreed price. Thus, contract farming acts as a form of vertical coordination linking farmers directly with processors, exporters, or retailers.

Types of contract: (Bijman, 2008)

1. Market specification contract:

- It is a pre-harvest agreement between producers and contractors on the conditions governing the sale of the crop.
- Besides time and location of sales, these conditions include the quality of the product, thus affecting a few of the production decisions of the farmer.
- The contractor reduces the producer's uncertainty of locating a market for the harvest.
- Under the market-specification contract, the farmer maintains most of the decision rights over his farming activities and thus his farm assets.
- Under this contract, the farmer bears most of the risk of his production activities.

2. Production-management contract:

- It gives more control to the contractor than the market specification contract, as the contractor will inspect production processes and specify input usage.
- Under this type of contract, producers must agree to follow precise production methods and input regimes.
- Under the production-management contract, the farmer has delegated a substantial part of his decision rights over cultivation and harvesting practices to the contractor (means the farmer no longer makes all the decisions on how to grow or harvest the crop.); he is willing to do so because the contractor takes on most of the market risks.

3. Resource-providing contract:

- Under the resource-providing contract, the contractor not only provides a market outlet for the product, but he also provides key inputs.
- Providing inputs is a way of providing in-kind credit, the cost of which is recovered upon product delivery.
- How much decision-rights and risk is transferred from the farmer to the contractor depends on the actual contract.
- Resource providing contracts can include production-management, thus shifting most decision-rights and risks to the contractor, but can also just focus on providing inputs and an output market and leaving most of the production decisions as well as a substantial part of the risk with the farmer.

Policy Support: (Shelke, 2020)

Agricultural marketing in India is controlled by state laws called the APMR Acts (Agricultural Produce Marketing Regulation Acts). To support contract farming, the Government has been encouraging States and Union Territories to update these laws. The updates include setting up a system to register contract farming companies, keep records of their agreements and create ways to solve disputes fairly. So far, 21 States (Andhra Pradesh, Arunachal Pradesh, Assam, Chhattisgarh, Goa, Gujarat, Haryana, Himachal Pradesh, Jharkhand, Karnataka, Maharashtra, Madhya Pradesh, Mizoram, Nagaland, Odisha, Punjab, Rajasthan, Sikkim, Telangana, Tripura and Uttarakhand) have changed their laws to allow contract farming, but only 13 of these States (Andhra Pradesh, Chhattisgarh, Goa, Gujarat, Haryana, Himachal Pradesh, Jharkhand, Karnataka, Maharashtra, Madhya Pradesh, Odisha, Rajasthan and Telangana) have created the detailed rules needed to make these changes work in practice.

Table-1: Contract farming for promoting production of high-value agricultural products (Chen and Chen, 2021)

Buyer ^a	Traditional product	HVA
Angkor Kasekam Roongroeng, Cambodia	rice	organic rice
Lao Arrowny, Lao PDR	rice	organic Japanese rice
Frito-Lay	N/A	chip-grade potatoes
Jain Irrigation Systems Ltd. (JISL)	red onions	white onions
Hui ren	wheat	herbs for traditional Chinese medicine
NOVASEN	oil peanuts	confectionery peanuts
Ugar Sugar Works	sugar	barley
Wens	N/A	broilers, pigs
New Hope Liuhe	N/A	broilers, pigs

^aIn the literature on contract farming, the term “buyers” refers to various buying firms such as processors, exporters or supermarkets.

Why “contract farming” is needed?

Contract farming is required due to several economic, social and technological reasons:

1. To reduce market uncertainty: Farmers are protected from price fluctuations because a fixed price is agreed upon before production.
2. Guaranteed market access: Farmers do not need to search for buyers; the company assures purchase of the produce.
3. Access to modern technology: Companies provide improved seeds, fertilizers, pesticides, machinery and technical advice that small farmers usually cannot access.
4. Higher productivity and quality: Regular guidance and advanced inputs improve yield and quality, helping farmers meet domestic and export standards.
5. Reduced marketing and transaction costs: Farmers save logistics, transportation and market commission costs because the company handles post-harvest marketing.
6. Promotes commercial agriculture: Contract farming encourages farmers to move from subsistence farming to commercial production.
7. Ensures steady raw material supply for companies: Companies, processors and exporters benefit from: continuous supply, required quality standards and reduced procurement risks.
8. Supports rural development: It generates employment, training, additional income and better use of farm resources in rural areas.

Pros/Advantages of contract farming:

Advantages to farmers:

1. Assured market and price: Farmers know the buyer and price in advance, reducing income risk.
2. Access to inputs and credit: Farmers can receive seeds, fertilizers, veterinary supplies, credit, or even machinery on credit or subsidized rates.
3. Technical support: Companies provide modern production techniques, extension services and training, helping farmers adopt scientific farming.
4. Increased income and productivity: Better inputs and guidance lead to improved yield, quality and profitability.
5. Reduced marketing problems: Farmers do not need to deal with middlemen, auctions, traders, or commission agents.
6. Encourages crop diversification: Farmers can grow high-value crops like vegetables, sugarcane, cotton, tobacco, poultry, floriculture, *etc.*

Advantages to companies:

1. Steady and reliable supply: Companies get continuous raw material according to their schedule and processing needs.
2. Quality control: Companies can monitor production from seed to harvest, ensuring required standards.
3. Reduced procurement cost: Purchasing directly from farmers is cheaper than buying from open markets.
4. Improved efficiency and supply chain management: Companies can plan production, transport, processing, storage and marketing more efficiently.

Advantages to the economy:

1. Encourages private investment in agriculture
2. Improves rural employment and infrastructure
3. Helps in development of agro-industries and exports
4. Strengthens national food security systems

Cons/Disadvantages/Problems of contract farming:

Problems faced by farmers:

1. Reduced farmer independence: Farmers must follow company instructions strictly, losing decision-making freedom.
2. Unbalanced bargaining power: Large companies have more power, making contracts unfavourable to farmers.

3. Risk of rejection: Produce may be rejected due to strict quality standards, leading to financial loss.
4. Delayed payments: Some companies delay payments, affecting farmer cash flow.
5. Over-dependence on one buyer: If the company withdraws, farmers may face serious marketing and financial problems.
6. High production risk: If crops fail due to weather or pests, contract conditions may still require repayment of company inputs.

Problems faced by companies:

1. Difficulty in monitoring large numbers of scattered farmers.
2. Risk of side-selling (farmers selling to other traders despite contracts).
3. High cost of extension services and supervision.

Institutional and legal challenges:

1. Weak legal enforcement of contracts
2. Lack of farmer awareness about contract terms
3. Conflicts due to unfair pricing or hidden clauses

Conclusion:

Contract farming offers a practical solution to many challenges that are facing by the farmers in modern agriculture by linking farmers directly with markets. It enhances income stability, productivity and market access while reducing uncertainties. Hence, with transparent contracts and institutional support, it can effectively promote sustainable agricultural and rural development.

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Valorization of Fruit Peel Waste: Bioactive Properties and Industrial Applications



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Overview

Each year, large amounts of fruit peels are produced as by-products from households, food industries, and agricultural processing units. Approximately 42% of fruit and vegetable waste is generated at the household level, 38% arises from the food processing sector, and the remaining 20% comes from other stages of the food industry. These discarded peels are rich sources of phenolic compounds, proteins, lipids, fiber, and polysaccharides, which together account for their high nutritional value. Peels from fruits such as pomegranate, citrus, mango, and fig contain substantial amounts of antioxidants, fiber, protein, and starch. Advances in science and technology have highlighted their potential applications in a wide range of industries, including food, cosmetics, pharmaceuticals, packaging, and energy. In response to increasing concerns about environmental sustainability and efficient resource utilization, fruit peels are being reconsidered as low-cost, renewable raw materials.

Fruit and vegetable wastes are generally regarded as inedible portions that are discarded at various stages, such as harvesting, handling, transportation, and processing. Improper disposal of these wastes has intensified solid waste management challenges and industrial pollution, particularly within the food production sector. Effective utilization of this waste can not only help mitigate environmental issues but also promote human well-being due to its health benefits. These wastes have been extensively studied for their content of dietary fiber, polyphenols, and other bioactive compounds, as they contain significant levels of phytochemicals. The present article provides detailed information on the phytochemical composition of fruit peel waste, their biological properties, and the valorisation of these wastes for the development of functional food products and sustainable packaging materials.

Bioactive Characteristics

Fruit and vegetable wastes, including peels and seeds, contain considerable amounts of essential oils that can be utilized for the production of value-added products. They are rich sources of phytochemical constituents such as carotenoids, anthocyanins, xanthophylls, minerals, vitamins, and organic acids. Both conventional and eco-friendly techniques are employed to extract these bioactive compounds. In addition to traditional extraction methods, alternative approaches such as solvent-free extraction, enzymatic extraction, ultrasonic extraction, and microwave-assisted extraction are increasingly being used. Waste generated from fruit processing can also serve as a substrate for biological fermentation processes, primarily in solid form, enabling the conversion of macronutrients into organic acids such as lactic and succinic acids, along with the production of enzymes including pectinases, hemicellulases, and cellulases.

Fruit peel waste is also abundant in phenolic compounds, including catechin, epicatechin, epigallocatechin, quercetin, caffeic acid, naringin, rutin, kaempferol, and luteolin. These compounds exhibit a strong ability to scavenge free radicals and possess significant antioxidant activity. Antioxidant evaluations of fruit peels have demonstrated a strong correlation between DPPH radical scavenging capacity and ferric-reducing antioxidant power. The antimicrobial properties of fruit peels have been assessed based on their zones of inhibition against various microorganisms, such as *S.epidermis*, *S. pyrogenes*, and *B. subtilis*, etc.

Industrial and Commercial Uses

Functional Foods and Fiber Enrichment

The fruit peel powders discussed earlier are rich sources of dietary fiber, minerals, vitamins, and organic acids, and are increasingly being utilized in food processing because of their high nutritional and functional value. Peel

wastes from fruits such as apples, bananas, citrus, mango, and pineapple contain abundant dietary fibers, including cellulose, hemicellulose, and pectin. These fibers play an important role in enhancing digestive health, reducing cholesterol levels, and regulating blood glucose. With the growing consumer demand for functional foods, food manufacturers are incorporating fruit peel powders into products such as bakery items, breakfast cereals, snack bars, and health foods.

Owing to their antioxidant and antimicrobial properties, fruit peels can also function as natural preservatives. Studies have shown that citrus peels are rich in flavonoids and essential oils, which help inhibit microbial growth. Extracts derived from orange and lemon peels are commonly used to extend the shelf life of food products by reducing oxidation and spoilage. These peel extracts have been applied in the development of cereal-based, fruit-based, meat-based, and dairy-based food products. In meat products such as patties, burgers, and sausages, peel powders and extracts serve as fat replacers as well as sources of antioxidants and antimicrobial agents. Such applications not only enhance the nutritional quality of foods but also reduce reliance on synthetic additives and preservatives, in line with consumer demand for clean-label products. The role of various peel powders in improving product quality is illustrated below.

Peel Powder	Product developed	Enhancement
Orange	Bread	Improving dough's elasticity by modifying the content of fiber, pectin and polyphenol
Jackfruit	Cookies	Improvement in cookie's darkness and decline in spread ratio
Passion fruit	Biscuit	Enhances fat absorption ability, texture and high fiber content
Jamblang	Jam	Increase in total phenols and anthocyanin content
Pomegranate	Noodles	Increased DPPH radical scavenging activity and reduction in pH

Packaging and Biomaterial Applications

The development of edible coatings and films from industrial waste is gaining importance as an effective approach for proper waste utilization. At present, packaging films incorporated with antioxidants and antimicrobial agents are regarded as one of the key strategies in active packaging. Because fruit peels are rich in bioactive compounds with antioxidant and antimicrobial properties, films made from fruit peel powders or extracts are considered promising active packaging materials for a wide range of food products. Fruit peel extracts can also be used to form edible coatings for fruits and vegetables, thereby extending shelf life by minimizing moisture loss and oxidation. These coatings act as wrapping or covering materials that block light and oxygen, helping to prevent microbial contamination. Such films are designed to remain in close contact with food products, ensuring controlled and sustained release of bioactive compounds. In addition, fruit peel powder-based films, owing to their porous internal structure, are used as absorbent pads in meat packaging.

Packaging films incorporated with pH-sensitive pigments represent a form of intelligent packaging that indicates food freshness through visible color changes. Films containing pigments such as anthocyanins or betacyanins have been employed to monitor the freshness of meat products. These films change color under acidic conditions, making them promising CO₂-sensitive indicators for assessing the freshness of fruits and vegetables in future applications.

Organic Manure and Composting

Fruit peels are abundant in essential nutrients and organic matter, making them well-suited for composting. Compost produced from fruit peels enhances soil fertility, promotes microbial activity, and improves the soil's water-holding capacity. In addition, certain bioactive compounds present in fruit peels exhibit insecticidal and antifungal properties that help protect plants from pests and diseases. As a result, many farmers and urban gardeners use fruit peel-based compost as an organic alternative to chemical fertilizers, supporting sustainable agricultural practices.

Citrus fruit peels are commonly used to regulate soil pH, improve soil structure, and meet plant nutrient requirements. They also serve as valuable sources of molasses, pectin, and limonene. Pomegranate peels contain

essential micronutrients such as boron (B), iron (Fe), zinc (Zn), copper (Cu), and manganese (Mn), all of which are vital for plant growth. Liquid organic fertilizers are nutrient-rich solutions obtained from the decomposition of organic matter and provide essential nutrients for crops. Because fruit peels contain fermentable sugars, organic acids, and micronutrients that stimulate microbial activity during fermentation, their biodegradability and availability make them an excellent substrate for the production of liquid organic fertilizers.

Bioenergy and Renewable Fuel Production

Fruit peels are abundant in carbohydrates, sugars, and organic matter, which makes them a valuable renewable resource for energy production. Through anaerobic digestion, fruit peel waste can be transformed into biogas, a mixture of methane and carbon dioxide that can be utilized for cooking, heating, and electricity generation. Peels from fruits such as banana, citrus, and pineapple are particularly suitable for this process because of their high fermentable sugar content. In addition to biogas production, fruit peels can be converted into bioethanol through fermentation using yeast and other microorganisms. Bioethanol produced from fruit waste offers a cleaner alternative to fossil fuels and can be blended with petrol to help lower greenhouse gas emissions. Biofuels derived from fruit peels contribute to addressing energy shortages while simultaneously reducing the burden of organic waste management.

These energy recovery technologies are especially advantageous in rural and agro-industrial areas where large quantities of fruit processing waste are generated. Small-scale biogas plants that utilize fruit peels can support decentralized energy systems and enhance local energy access. Furthermore, the residual material remaining after biogas production can be applied as a nutrient-rich organic manure. Overall, converting fruit peels into energy helps industries minimize disposal costs and carbon emissions, supporting sustainable waste management practices and renewable energy objectives.

Textile Coloring and Fabric Applications

Fruit peels such as pomegranate, citrus, and dragon fruit are rich sources of natural pigments and tannins. These compounds are widely used as eco-friendly dyes in the textile industry. Natural dyes obtained from fruit peels are biodegradable, non-toxic, and safer for both workers and consumers when compared to synthetic dyes. Biochromophores such as carotenoids, anthocyanins, and tannins present in fruit peels provide a wide spectrum of biodegradable colors without the harmful runoff typically associated with coal-tar dyes. In addition to serving as natural colorants, fruit peels are also being repurposed for the production of cellulose-based fibers. The pectin and cellulose extracted from orange peels, for example, can be spun into high-quality yarns that resemble the texture and feel of silk.

The utilization of fruit waste supports a circular economy model by diverting large quantities of organic matter away from landfills while simultaneously reducing the carbon footprint of textile manufacturing. Pomegranate peels are particularly valued for producing yellow to khaki shades, as their high tannin content acts as a natural mordant. Grape skins yield a broad range of grey and purple tones while imparting antioxidant properties to the fabric. Avocado skins and pits produce soft pink to peach hues, with natural oils that help soften textiles. Dragon fruit peels, rich in betacyanins, offer vibrant red, pink, and purple shades. When applied to natural fibers such as cotton, silk, or wool, these pigments provide a non-toxic dyeing alternative, and their color intensity can be adjusted by modifying the pH conditions.

Cosmetics and Personal Care industry

The cosmetic industry is increasingly utilizing fruit peels as sources of natural antioxidants and bioactive compounds. Peels from pomegranate, grape, and citrus fruits are particularly rich in polyphenols and vitamin C, which help neutralize free radicals responsible for skin aging. These compounds are widely incorporated into anti-aging creams, serums, and lotions. Regular application of cosmetics formulated with fruit peel extracts has been associated with improved skin elasticity, reduced wrinkle formation, and enhanced skin radiance, making them appealing natural alternatives to synthetic ingredients.

In addition, dried and finely ground fruit peels are used as natural exfoliating agents in facial and body scrubs. Orange and lemon peel powders aid in removing dead skin cells and excess oil, while papaya peel contains the enzyme papain, which gently exfoliates and supports skin regeneration. Such products are biodegradable, skin-friendly, and environmentally safe.



Figure 1. Industrial Applications of Fruit Peels; Fruit peels are used in different forms- Dried peels, Peel powder, Peel extract, Essential oils

Conclusion and Future Outlook

Among the wastes generated by fruit and vegetable processing industries, peels constitute a much larger proportion than seeds. These byproducts can be effectively utilized across a wide range of industries. Fruit peel extracts have found applications in the pharmaceutical sector for the treatment and prevention of various ailments. Their rich chemical composition and renewable nature make them promising substrates for sustainable development initiatives. As global demand for natural and eco-friendly products continues to increase, innovations based on fruit peels are expected to play a crucial role in building a greener future.

Despite their potential, large-scale utilization of fruit peels faces several challenges, including issues related to collection, storage, standardization, and regulatory approval. Seasonal availability and variations in composition further influence processing efficiency. Moreover, many types of fruit waste remain underutilized. In the future, stronger collaboration among researchers, industry stakeholders, and policymakers will be essential to successfully integrate fruit peel utilization into mainstream industrial practices.

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Protected Cultivation: Is Polyhouse Farming a Goldmine or a Debt Trap?



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In recent years, protected cultivation—particularly polyhouse farming—has been aggressively promoted as a transformative solution for Indian agriculture. Governments showcase it as a pathway to higher yields, improved quality, climate resilience, and increased farmer income. Subsidy brochures, success stories, and training programs often portray polyhouses as near-guaranteed profit engines. Yet, behind the glossy narratives lies a more complex and uncomfortable reality. For every success story, there are multiple farmers quietly struggling with high costs, technical failures, and market uncertainty.

This raises a fundamental question that deserves honest examination: Is polyhouse farming truly a goldmine, or has it become a debt trap for many farmers? The answer is neither simple nor uniform. It lies at the intersection of horticultural suitability, management capability, capital structure, and—most critically—market alignment.

Understanding Protected Cultivation

Protected cultivation refers to the growing of crops under partially or fully controlled environments using structures such as polyhouses, net houses, and greenhouses. These structures modify temperature, humidity, light intensity, and pest exposure, allowing crops to grow under optimized conditions.

Polyhouses, typically made of GI pipes covered with UV-stabilized polyethylene sheets, are the most common form of protected cultivation in India. They are primarily used for high-value horticultural crops such as capsicum, cucumber, tomato, cherry tomato, lettuce, strawberry, cut flowers, and exotic vegetables.

From a scientific standpoint, protected cultivation offers clear advantages. However, these advantages do not automatically translate into economic success.

Horticultural Perspective: Where Polyhouses Make Sense

Crop Suitability Is Non-Negotiable

Not all crops are suitable for polyhouse cultivation, and this is where many projects begin to fail. Polyhouses are economically viable only for high-value, short-duration, and market-responsive crops. Growing low-value crops under expensive structures is a fundamental mismatch.

Crops that generally perform well under polyhouse conditions include:

- ❖ Coloured capsicum
- ❖ English cucumber
- ❖ Cherry tomato
- ❖ Lettuce and leafy greens
- ❖ Strawberry
- ❖ Cut flowers such as gerbera and rose

These crops respond positively to controlled microclimates, show higher yield per unit area, and offer superior quality compared to open-field production.

Yield Advantages: Real but Often Overestimated

Polyhouse cultivation can increase yields by 2–4 times compared to open fields, depending on the crop and management practices. Uniform growth, reduced pest pressure, and efficient fertigation contribute to this improvement. However, yield potential is often confused with realized yield.

Without precise nutrient management, timely pruning, training, pollination support, and disease monitoring, actual yields frequently fall far short of projections presented during subsidy approvals.

Management Complexity Is Underrated

Protected cultivation is management-intensive agriculture, not a passive income system. It requires:

- ❖ Regular monitoring of temperature and humidity
- ❖ Skilled pruning and training
- ❖ Precise fertigation schedules
- ❖ Integrated pest and disease management
- ❖ Continuous labor availability

Many first-time adopters underestimate the learning curve. A polyhouse magnifies errors—nutrient imbalance, irrigation mistakes, or disease outbreaks spread faster and cause larger losses than in open fields.

Agribusiness Perspective: Counting the Real Cost

Capital Cost: The Entry Barrier

The cost of establishing a polyhouse varies widely depending on size, structure type, and region. On average:

- ❖ Naturally ventilated polyhouse: ₹900–₹1,200 per square meter
- ❖ Climate-controlled polyhouse: ₹2,500–₹4,000 per square meter

Even after subsidies (typically 50–70%), farmers often need to invest ₹15–30 lakh per acre. For small and marginal farmers, this usually involves loans.

This immediately changes the nature of farming from subsistence or semi-commercial activity to high-risk capital investment.

Payback Period: Optimistic vs Realistic

On paper, many polyhouse projects promise payback within 2–3 years. In practice, payback periods frequently extend to 4–6 years due to:

- ❖ Delayed learning and initial crop failures
- ❖ Market price volatility
- ❖ Rising input costs
- ❖ Maintenance and replacement expenses (plastic sheets, drip lines, motors)

A polyhouse is not a one-time investment. Poly sheets typically last 3–4 years, and repairs are unavoidable.

Subsidy Reality: Not a Safety Net

Subsidies reduce entry costs but also create false confidence. Many farmers adopt polyhouses because the subsidy is available, not because the business model makes sense for their location or market access.

Moreover:

- ❖ Subsidy disbursement is often delayed
- ❖ Compliance and documentation are complex
- ❖ Subsidies do not protect against market failure

A subsidized failure is still a failure—just a partially financed one.

Market Risk: The Most Ignored Variable

Production Is Planned, Marketing Is Not

The biggest weakness in polyhouse adoption is the production-first mindset. Farmers are trained extensively on crop cultivation but receive minimal guidance on:

- ❖ Market demand cycles
- ❖ Price trends
- ❖ Buyer requirements
- ❖ Contractual arrangements

As a result, many farmers harvest premium produce only to sell it at conventional wholesale markets, competing with open-field produce and suffering price crashes.

Perishability Amplifies Risk

Most polyhouse crops are highly perishable. Without assured buyers, cold storage access, or processing options, farmers are forced into distress sales. High quality does not guarantee high price if timing and market access are wrong.



Absence of Aggregation

Individual polyhouse farmers often lack bargaining power. Without FPOs, cooperatives, or direct buyer linkages, they remain price takers despite high production costs.

When Polyhouse Farming Becomes a Goldmine

Polyhouse farming works when four conditions align:

1. Crop–Climate Match

Crop selection suited to local climate and market demand.

2. Technical Competence

Either through training, experience, or professional advisory support.

3. Market Linkage

Pre-identified buyers such as retail chains, hotels, exporters, or processors.

4. Financial Discipline

Realistic projections, adequate working capital, and risk buffers.

Farmers who treat polyhouse farming as an agribusiness venture, not a scheme, are the ones who succeed.

When It Turns into a Debt Trap

Polyhouse farming becomes dangerous when:

- ❖ Adoption is subsidy-driven rather than market-driven
- ❖ Crop choice is based on hearsay
- ❖ Loans are taken without contingency planning
- ❖ Marketing is left to chance
- ❖ Technical support ends after installation

In such cases, the fixed cost burden and recurring expenses quickly overwhelm farm income, leading to debt accumulation and, in extreme cases, exit from farming altogether.

The Way Forward: Smarter, Not Bigger Adoption

Protected cultivation is not inherently flawed. What is flawed is the one-size-fits-all promotion model.

Key improvements needed:

- ❖ Mandatory market planning alongside technical training
- ❖ Location-specific crop advisories
- ❖ Promotion of cluster-based polyhouse farming
- ❖ Integration with FPOs and contract farming
- ❖ Transparent communication of risks, not just success stories

Policy should shift from “how many polyhouses installed” to “how many polyhouses profitable after five years.”

Conclusion

Polyhouse farming is neither a guaranteed goldmine nor an inevitable debt trap. It is a high-stakes agribusiness model that rewards planning, skill, and market intelligence while punishing haste and blind optimism. For farmers willing to learn, invest strategically, and align production with demand, protected cultivation can significantly enhance income and resilience. For those drawn in solely by subsidies and success stories, it can become an expensive lesson. The real question, therefore, is not whether polyhouse farming works—but for whom, where, and under what conditions it should be promoted.

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Stress Memory in Plants and Its Implications for Crop Resilience



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Abstract

Climates cause abiotic stress which diminishes the productivity of crops, but plants have stress memory, permanent physiological evidence of prior exposure, such that when the stress recurs, the response will be more rapid. This memory preserves major characteristics of photosynthetic stability, precise stomatal regulation, antioxidant capacity, osmotic stability, and root plasticity during drought, heat, salinity and oxidative stresses, unlike temporary acclimation or static tolerance thus assists in sustaining yield in changing environments. This paper describes the various forms of memory, how physiological mechanisms coordinate, the epigenetic basis, and the application of priming in agriculture. Scalability is restricted by constraints in the field, including genetic diversity and timing of exposure, and, therefore, resilience requires the integration of priming and breeding.

Keywords: Stress memory, Plant priming, Crop resilience, Abiotic stress, Physiological adaptation

1. Introduction

The significant limitations to crop productivity worldwide today are due to abiotic stresses, such as drought, heat, salinity, and extreme temperatures. It is expected that their effects will continue to double by the middle of the century on major staple crops, such as rice and wheat, as climate variability rises (IPCC, 2022). Plants have developed highly intricate response strategies to address these problems, but the prevailing paradigm at the time treated stress responses as temporary and reversible. When stress is relieved, the physiological responses (stomatal closure, osmolyte accumulation, and antioxidant up-regulation) typically revert to baseline, and the plant returns to its normal state (Bruce et al., 2007).

Recent developments also disprove this perception by showing that plants can form heritable priming of stress memory through past exposure to stress, reprogramming gene expression, chromatin structure, and metabolic organisation, and altering future responses (Xu et al., 2024) in contrast to short-term acclimation, which entails immune responses in the form of reversible changes that disappear once the assault has ceased, or constitutive tolerance, which is influenced by breeding and stress memory, is retained following mitotic division or even meiosis in offspring, allowing more vigorous and prompt defences against repeated injury.

The phenomenon has significant physiological implications for crop resilience, increasing yield stability against episodic stresses every day in rainfed agroecosystems. This article integrates molecular, physiological, and agronomic explanations to examine how crops can be strengthened against climate uncertainty through stress memory exploitation via priming agents, breeding, and cultural practices. Figure 1 illustrates the concept of plant stress memory and its impact on subsequent stress responses.

2. What Is Stress Memory in Plants?

Plants possess an analogous type of stress memory, such that after exposure to abiotic stress, prior conditions lead to the development of more durable physiological, biochemical, or molecular changes that endure even in the absence of stressors and induce a greater response to future challenges (Charng et al., 2023). These changes are reflected as persistent changes in genomic expression, protein retention, or metabolic rate flux, including increased basal levels of heat shock proteins or osmoprotectants, that speed up the defence response on repeated occasions and thereby mitigate damage and maintain productivity.

In essence, stress memory is quite distinct from short-term acclimation, which is characterised by rapid, reversible adaptations such as stomatal control or proline production that fade quickly after the removal of the stress. It is also the opposite of immediate responses, which are aroused by every stress incident, and constitutive tolerance, a trait that is genetically fixed and is independent of previous exposure (Xu et al., 2024). Instead, memory can be produced through priming: a low-intensity, non-lethal stress creates the impression of increased responsiveness, allowing faster mobilisation of resources without impairing growth in a benign environment.

This ability differs significantly among species, developmental stages, and stress categories. For example, some crops, such as rice, have a shorter drought memory associated with the tillering stage than a robust heat memory in the form of histone modification found in *Arabidopsis* (Charnng et al., 2023). It is such variability that highlights the adaptive subtlety of stress memory in the field settings.

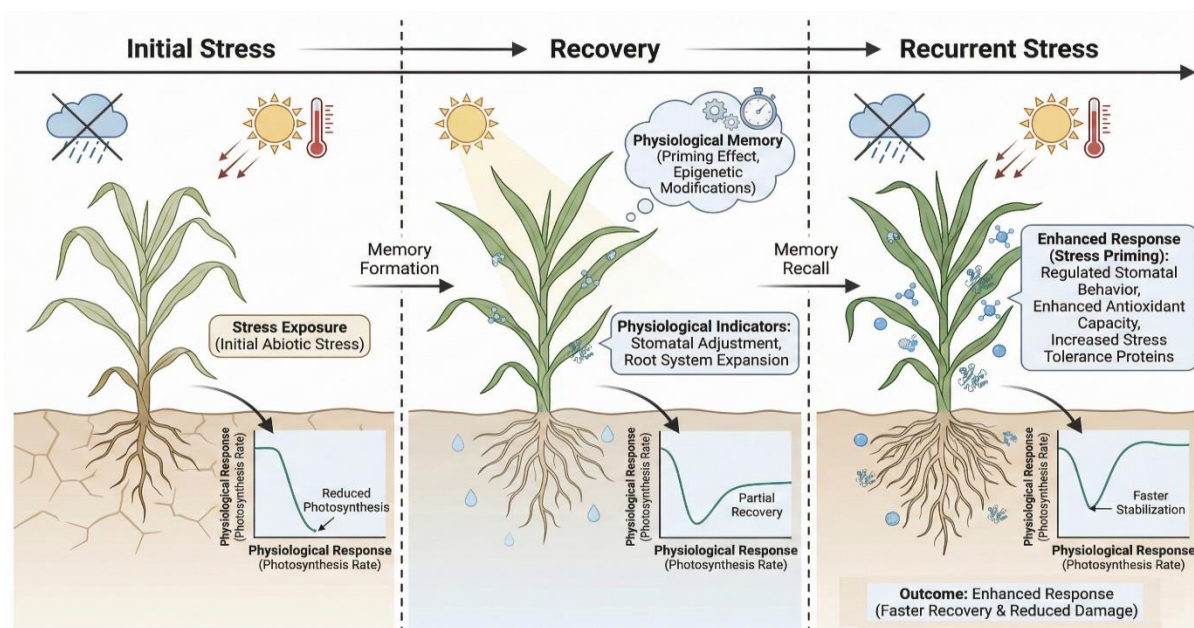


Figure 1: Conceptual Model of Plant Stress Memory

3. Types of Stress Memory in Plants

Stress memory can take many forms, depending on the abiotic stressor and the physiological mechanisms underlying it, and thus provides insight into adaptive plasticity rather than a uniform response. Previous exposure to drought, such as maintaining augmented water relations, consisting of more water-receptive aquaporin action and root hydraulic conductance, in recurring deficits, reinforces stomatal conductance and leaf water potential and reduces recovery lags (Fgaier et al., 2023). Heat memory has a similar stabilising influence on photosynthesis by maintaining upregulation of Rubisco activase and strengthening of thylakoid membranes to counter photoinhibition in crops like linseed.

Salinity priming increases ion compartmentalisation and Na^+ exclusion, thereby maintaining K^+ homeostasis and growth after repeated exposure. Oxidative stress memory, by contrast, enhances networks of antioxidants, such as the ascorbate-glutathione cycling, to counter lipid peroxidation and maintain membrane integrity (Xu et al., 2024). Similar trends are present across these illustrations: faster defence priming, smaller oxidative bursts, and faster biomass recovery, but stress-specific characteristics remain, including the attention to hydraulic changes in drought versus heat, and to proteostasis.

Time scales range from short-term (hours to days, as with immediate heat priming) to intermediate (weeks, as seen in salinity) to long-term (seasonal or transgenerational through epigenetic marks), and are also dependent on the intensity of stress and plant ontology (Kinoshita & Seki, 2014). These physiological immunophenomena highlight the importance of memory in fine-tuning resilience. Table 1 summarises the major types of stress memory and their respective physiological characteristics.

Table 1: Types of Stress Memory in Plants and Associated Physiological Traits

Type of Stress	Nature of Stress Memory	Key Physiological Traits Involved	Functional Significance for Resilience
Drought	Sustained hydraulic and osmotic priming	Enhanced root conductance, stomatal sensitivity, and proline accumulation	Stabilises water status, accelerates recovery
Heat	Persistent proteostasis and photosynthetic priming	Rubisco activase upregulation, thylakoid stability, and antioxidant elevation	Maintains carbon assimilation under recurrence
Salinity	Ion homeostasis and exclusion priming	Na ⁺ compartmentalisation, K ⁺ retention, osmotic adjustment	Preserves growth and ion balance in cycles
Oxidative	Redox buffering and enzyme priming	Ascorbate-glutathione cycle, SOD/catalase activity, membrane integrity	Curbs ROS damage, supports metabolic continuity

4. Physiological Basis of Stress Memory

Stress memory relies on lasting physiological adaptations, which are maintained after an initial stressor, which is why primed plants respond to subsequent stressors more quickly and efficiently. Photosynthetic regulation has been used to exemplify this process at the leaf level: when the plant is stressed before, high rates of basal electron transport and Rubisco efficiency are maintained, and thus recovery after photoinhibition is faster, and carbon assimilation is maintained during the next heat or drought episode (Charng et al., 2023).

Sensitivity to abscisic acid (ABA) gets augmented, and water-use efficiency is intensified by means of more rigid control of stomatal aperture without affecting CO₂ uptake. The redox homeostasis is supported by antioxidant systems, which ensure the high activities of superoxide dismutase and catalase to prevent the burst of reactive oxygen species, and osmotic adjustment, through the accumulation of proline or glycine betaine, to stabilise cellular water relations and turgor.

These leaf-based characteristics are orchestrated by root system plasticity; recollection enhances lateral root growth and hydraulic conductance, and enhances the water status and nutrient foraging of the shoot. All these coordinated physiological changes lead to the formation of stress-memory, as evidenced in Figure 2. The effectiveness of primed plants is based on their integration throughout the entire plant and not on the organ-specific responses: non-primed individuals are slow to activate defences, and they lose a greater amount of biomass, and memory coordinates fast cross-talk through hormonal signals, including ABA and cytokinins (Kinoshita & Seki, 2014). The physiological persistence thus contributes to the functional resilience in the changing environment.

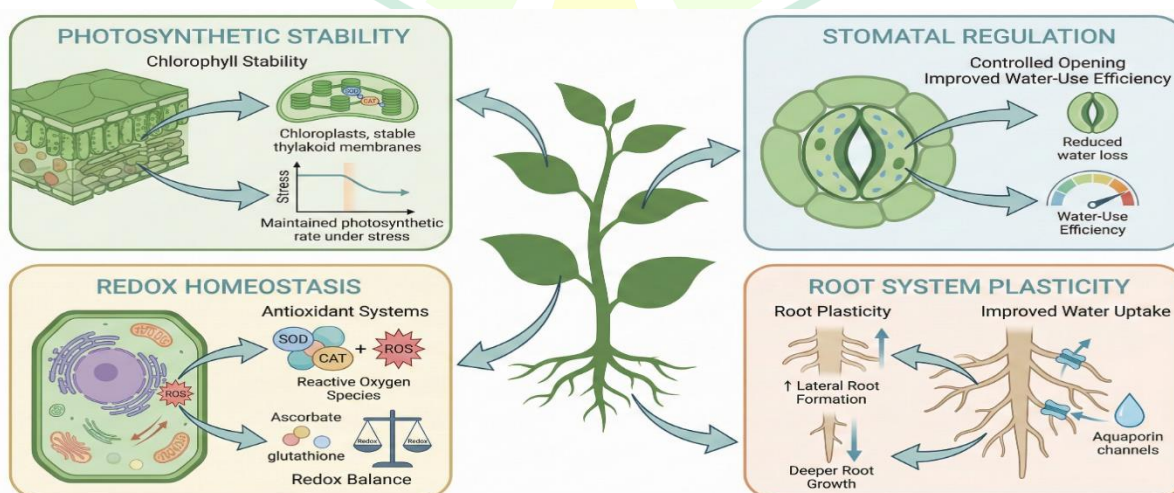


Figure 2: Physiological Processes Underlying Stress Memory

5. Molecular and Epigenetic Components

Molecular and epigenetic controls assist the organisms in recording stress by labelling genes, in order to respond swiftly when the stress is removed. This connects short-term signals (cues) with long-term physiological changes. Stress-reactive genes, that is, the genes of the heat shock factors or LEA proteins, are pre-primed: when they are re-exposed to stress, they react more quickly and intensively to it, as there are already prepared enhancers, rather than having to begin afresh (Song & Ryu, 2018).

This priming is supported by epigenetic mechanisms. Promoters can be switched off or on to change their access to DNA methylation. Chromatin is maintained in an open state by histone modifications, such as elevated levels of H3K4me3 or reduced levels of H3K27me3. SWI/SNF complexes are further chromatin remodelers that enhance access to the gene regions (Charng et al., 2023). The marks are reversible and can modify the time and probability of expression, but do not affect the DNA sequence. The pattern of marks is determined by the type of stress, e.g. drought leads to methylation modifications primarily on roots, heat mostly on histones of leaves, and may differ between different tissues or developmental stages.

Epigenetic memory is not inherited in nature; it is labile and deteriorates with generations, but plays a paramount role in the upholding of priming in an organism. There are uncertainties regarding the degree of faithfulness of this memory to the successive crop generation

6. Stress Memory and Crop Resilience.

The memory of a type of stress makes crops resistant to stressors, maintaining performance in fluctuating conditions and enabling farmers to focus on the yield consistency and rapid recovery instead of pursuing the highest yield possible. Sustained signalling is a process that makes plants more sensitive to stress when in a primed state. They safeguard themselves through increased photosynthesis, water conservation and faster recovery through preserving root functioning and reproductive sinks. This is reflected in cereals, which retain grain fill during recurrent droughts or heat waves (Fgaier et al., 2023).

Memory works better under the unpredictable conditions in fields as opposed to constitutive tolerance, which merely endures extremes. It adjusts the characteristics like stomatal regulation and antioxidant ability to the demands of each stress event. The functioning of memory is context-dependent and is dependent on genotype, stage of development, and the environmental context.

7. Can Stress Memory Be Used in Agriculture?

Stress memory can be utilised in agricultural systems to prepare crops for better performance. Field tests, however, yield less than controlled trials. Practices such as nursery stages with mild and controlled drought or heat are beneficial to the transplantation of rice. It assists in sustaining the root activity as well as photosynthetic preparedness on their arrival at the field (Bruce et al., 2007). Osmotic priming of seed or hormonal priming also develops antioxidant preparedness in crops like linseed. This accelerates salinity emergence without long-term demands. Restrictions decrease passion. Priming windows are restricted to particular stages of development; thus, timely mistakes are detrimental to growth. Individual variations in genotype need differentiated procedures. And environmental variations shorten the memory duration. Soils are less accurate than the lab environment, and scaling proves difficult due to gradients in soil moisture and pests. A combination of these practices with breeding for high base tolerance and cautious agronomic timing has viable advantages. It is concerned with stability and not radical change.

8. Conclusion

Physiological and epigenetic evidence of past abiotic stresses retained by plants promotes their recovery in response to analogous stresses at higher and more adaptively responsive rates. This memory alters our perception of adaptation, and it does not focus on high tolerance in changing climates but on stable performance. But there are field-scale problems and genetic diversity that remain difficult. With these insights coupled with breeding and farm management, we will be able to create more precise resilience strategies.

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Sericulture By-products as Organic Inputs for Sustainable Crop Production



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Abstract

Sericulture generates substantial quantities of organic residues, including mulberry leaf leftovers, silkworm larval litter, rearing waste, and reeling by-products. Although traditionally underutilized, these wastes possess significant potential for value addition due to their high organic matter content, essential macro- and micronutrients, and bioactive compounds. This paper reviews the scope, composition, and nutrient value of sericulture waste and highlights its conversion into beneficial agricultural inputs through composting, vermicomposting, and microbial inoculation. Emphasis is placed on the role of earthworms and microbial consortia such as *Trichoderma viride* and *Bacillus subtilis* in accelerating decomposition and improving nutrient availability. Additional applications—including biogas production, protein-rich animal feed, liquid organic manures, and mushroom substrate preparation—demonstrate the diverse utility of seri-waste. Effective management and reutilization of these by-products not only reduce environmental burden but also enhance soil health and provide up to 30–40% additional income for farmers, thus promoting sustainable and economically viable sericulture systems.

Keywords: Seri-waste, vermicomposting, organic manure, sustainable agriculture, mushroom substrate.

Introduction

Sericulture is the practice of cultivation of silkworms for production of silk. It is an agro-based industry of great economic importance in countries such as India, China, Japan, and Thailand having capability of generating substantial employment particularly in rural areas. India is the second largest producer of silk in the world. India has the unique distinction of being the only country producing all the five known commercial silks, namely, mulberry, tropical tasar, oak tasar, eri and muga, of which muga with its golden yellow glitter is unique and prerogative of India. The resultant by-products of silk production whose economic values are less than the total cost involved in their reprocessing for beneficial use are often termed as 'sericulture waste' or 'seri-waste'. The major wastes and by-products includes mulberry plant residues, silkworm litter, pupae, pierced cocoons, reeling waste, sericin, fibroin, and seri-industrial wastewater, each of which holds significant potential for value addition. The effective utilisations of these products are very much essential for placing sericulture as a promising occupation in farmers' mind. Therefore, the present sericulture not only focuses on income generation through silk but also through multiple reutilisations of by-products that can produce around 30-40% of additional benefit. In sericulture, large volumes of leftover mulberry leaves, bed refuse, and larval litter are generated, rich in organic matter and plant-derived bioactive compounds. These wastes have been effectively converted into organic manure and biofertilizers through composting and vermiculture methods. Ahmed et al. (2020).

Scope & Composition of Seri-waste

Silkworms eat only about 40% of the mulberry leaves provided in the trays. Out of this, only 55% is actually digested, and the remaining part comes out as silkworm faeces. From rearing silkworms, farmers can get around 2,416 kg of litter per acre under irrigated conditions and 440 kg per acre under rainfed conditions (Hanumappa and Prabhakar, 1985). According to Nagarajan *et al.* (1990), silkworm larval litter contains 3.47% nitrogen, 0.03% phosphorus, and 1.50% potash.

From a one-hectare mulberry field, about 2472.80 kg of mulberry leaves (dry matter) are produced. Out of this, silkworm larvae digest only 620.70 kg, which is then converted into 211.20 kg of silk or cocoon shells. This means silk production forms only 8.54% of the total dry matter from mulberry leaves. In contrast, various waste materials—such as leftover leaves, excreta, and pupae amount to 2061.60 kg, which is about 83% of the dry matter being converted into waste products (Mariaichim *et al.*, 2008).

Sericulture waste is rich in organic matter and essential plant nutrients, making it an excellent base for producing high-quality organic fertilizers and soil conditioners.

Sericulture waste, particularly silkworm larval litter and mulberry residues, is rich in both macro- and micronutrients, often surpassing the nutrient content of traditional farmyard manure (FYM).

Nutrient	Farm Yard Manure (FYM) (approx. %)	Silkworm Rearing Waste Compost (approx. %)
Potassium (K)	1.0 - 2.48%	0.3 - 0.6%
Nitrogen (N)	1.875 - 3.11%	0.3 - 0.5%
Phosphorus (P)	0.39 - 1.0%	0.2 - 0.4%

Micronutrients: The compost also contains valuable micronutrients such as zinc (Zn), iron (Fe), manganese (Mn), and copper (Cu).

Organic Matter: Sericulture waste is high in organic matter (83-90% in silkworm feces), which improves soil structure, aeration, and water retention capacity.

Bioactive Compounds: Silkworm faecal matter and mulberry residues contain undigested phytochemicals, dietary fibers, and bioactive compounds (like flavonoids and chlorophyll) that contribute to soil health and plant growth promotion.

Composting of the Waste

Vermicomposting is a biological method where earthworms such as *Eisenia fetida* and *Eudrilus eugeniae* help convert organic wastes into a nutrient-rich product called vermicast. This eco-friendly technique is now widely accepted as a sustainable way to handle agricultural wastes, including sericulture residues, which contain plenty of organic matter (Walia & Kaur, 2024). The digestive activity of earthworms helps break down complex organic materials into simpler and more available nutrients, making vermicompost highly valuable for improving soil fertility and supporting plant growth (Walia & Kaur, 2023; Walia & Kaur, 2024).

Vermicomposting proceeds much faster than normal composting because earthworms increase microbial activity within the waste. Their movement helps aerate the material and encourages beneficial microorganisms that speed up the breakdown and stabilization of organic matter (Ganesan *et al.*, 2022). As a result, good-quality compost can be produced in a relatively short time. However, when using sericulture waste, a pre-decomposition stage is essential. This phase usually lasts about 10 to 15 days and allows the waste to partially break down, lowering harmful pathogens and making it easier for earthworms to consume. It also helps prevent damage to the worms caused by the heat and acidity released during the early stages of decomposition (Venugopal *et al.*, 2010).

To improve the efficiency of the process, sericulture waste is commonly mixed with cow dung in proportions such as 1:1 or 2:1. This blend helps maintain an ideal carbon-to-nitrogen ratio, moisture level, and microbial balance required for effective decomposition (Ganesan *et al.*, 2022; Venugopal *et al.*, 2010). Cow dung functions both as a buffering agent and as a microbial starter, while also enriching the nutrient content of the finished compost. Studies have shown that this mixture results in vermicompost with higher levels of nitrogen (N), phosphorus (P), and potassium (K), along with improved microbial diversity. These qualities enhance soil structure, aeration, and water-holding capacity (Ganesan *et al.*, 2022; Karmakar *et al.*, 2024; Kiruthika *et al.*, 2024).

Applications of Seri-waste

Organic Manure and Biofertilizer: The most common use is composting or vermicomposting of mulberry plant residues, leftover leaves, and larval litter to produce nutrient-rich organic manure. This compost provides a slow and steady release of nutrients to the soil. Notable organisms such as *Trichoderma viride* and *Bacillus subtilis*

have been successfully applied to accelerate the breakdown of seri-waste, producing compost rich in nutrients and beneficial microbes (Manjunath et al., 2020; Wani et al., 2020; Ojha et al., 2020).

Trichoderma, a mesophilic fungus that can break down cellulose into glucose can be used. *Bacillus* species are mesophilic bacteria that mainly consume easily degradable carbohydrates and proteins. They play a major role in breaking down proteins, amino acids, peptones, and blood meal (Gaur, 1982).

Soil Conditioner: The high organic carbon content and beneficial microbial biomass enhance soil fertility, structure, and microbial activity, leading to healthier soil and increased crop yields.

Biogas Production: Silkworm litter can be used as a raw material in biogas plants to produce fuel, with the resulting slurry also used as an organic fertilizer.

Animal Feed Supplement: Discarded silkworm pupae, rich in protein (around 50%) and lipids, are repurposed into high-nutritional feed for poultry and aquaculture, which indirectly supports the agricultural ecosystem. Dried silkworm meal can also replace soybean meal that is used as rabbits feed.

Liquid Organic Manures: Liquid formulations like "Panchagavya" and "vermiwash" derived from sericulture waste are used as foliar sprays to stimulate plant growth and reduce pest incidence in mulberry gardens and other crops.

Substrate For Mushroom Cultivation: Sericulture waste can be used as a substrate for mushroom cultivation because it is rich in nutrients, biodegradable, and can be a cost-effective alternative to traditional substrates. It has been successfully used to grow various species, such as oyster and button mushrooms, often mixed with other materials like paddy straw.

Conclusion

Sericulture generates large quantities of nutrient-rich organic waste, which, instead of being discarded, can be effectively converted into valuable agricultural inputs. Through processes such as vermicomposting, microbial inoculation, and blending with cow dung, seri-waste is transformed into high-quality compost that enhances soil fertility, microbial activity, and crop productivity. Additionally, seri-waste supports multiple value-added applications, including biogas production, animal feed, liquid organic fertilizers, and mushroom cultivation. Overall, efficient management of sericulture waste not only reduces environmental pollution but also provides farmers with an additional 30–40% economic benefit. Thus, seri-waste utilization plays a vital role in promoting sustainable agriculture, strengthening soil health, and improving the profitability of sericulture-based livelihoods.

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Vanishing Indigenous Fruits of North Eastern India



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Since long many wild, indigenous edible fruits are traditionally grown and consumed by the local rural communities of North Eastern India. North Eastern Region of India is the treasure house of many potential hidden and untapped plant food resources. The fruits are one of them. They play a pivotal role in the livelihood development and nutritional security of the rural Indian people. But unfortunately, they are vanishing rapidly due to destruction of plants for industrialisation, construction of roads and railways, urbanisation, bringing land under agriculture, lack of traditional knowledge about their nutritional and medicinal values, their proper identification, harvesting and conservation procedure. Occurrence of this event impacting enormously on food, nutritional and health security and maintenance of livelihood of the vast rural communities of this area.



1. Kendu (*Diospyros melanoxylon*): Kendu is found to grow in the hot and dry lateritic regions of India. Comprising the states Jharkhand, Orissa, Bihar and West Bengal. The plant is a tall tree which can grow up-to 15-20m in height. Orange coloured round shaped fruits ripen during summer season. This fruit is deeply associated with the lives and culture of tribal people. Ripe fruits are eaten fresh and also made, jam, and juice. The leaves are used locally for making bidi. 100g edible fruit pulps contain 27g carbohydrates, 2.7g fibers, 2.1g proteins, 0.71g fats, 28mg Vitamin-C, 416mg carotene, 123mg. Potassium, 0.26mg Iron, 58mg calcium and 20mg phosphorus with bioactive compounds like saponine, flavonoids and phenols. Due to the cooling effect of the fruits kendu helps to combat summer heat. It helps in relieving from health complaints including flatulence and dysentery and also boosts immunity.

2. Falsa (*Grewia asiatica*): This is typically a tropical fruit which is grown in the eastern states like Jharkhand, Orissa, West Bengal and Tripura. It is highly drought tolerant. Small and round fruits turn pinkish colour when ripen. The ripe fruits are eaten fresh and made into juice, syrup and squash. Ripe fruits are well blended with sour and sweet taste. Fruits are the rich sources of carbohydrates (14-21g), fibers(2-5g), protein(0.5-1-5g), vitamin C (22-40mg), vitamin A(300 IU) and minerals like potassium (372mg), Calcium (125-135mg), iron and phosphorus and antioxidants including flavonoids, phenols and tanins. Fruits are being rich sources of fiber and low in glycaemic index helps to manage blood sugar. They are excellent for meeting of thirst during hot summer. Antioxidant helps to fight -against free radicals.



3. Piyal (*Buchanania Lazan*): Piyal or chironji fruits grow well in dry lateritic regions of India. It is very popular among the tribal communities. The plant is a big tree which can attain the height upto 10m. Small round fruits turn reddish purple colour when ripe and are available during summer. Sweet and sour tasted fruits are eaten fresh. The ripe fruits are packed with proteins, vitamin C and dietary fiber and low in calories. It's various parts have a wide array of medicinal uses in Ayurveda and Unani. The fruits act as a laxative and used to treat, cough, asthma, thirst, fever and body pain. It also helps to regulate blood - sugar level and strengthen the body immune system.

4. Dheua (*Artocarpus laccucha*): Dheua is a big tree with broad elliptical leaves. The tropical fruits are irregular in shape and have velvety outer texture. Unripe fruits are green in Colour which turns into yellow when ripe. The fruits have yellow Colour edible pulp which is sweet and sour in taste. Ripe fruits are eaten fresh and also made into curries and chutney. The fruits are nutritious and rich in carbohydrate (21.2g), dietary fiber (1.5-2.5g), vitamin-E (13.4-15.7mg) and minerals like Potassium (425mg), Calcium (32mg) along with antioxidants, flavonoids and phenolic compounds. The fruits have antiviral, antidiabetic, anticancer and anti-inflammatory properties and also serve as purgative due to its pulp and seed content. It also act as liver tonic and refresher.



5. Paniala (*Flacourtia jangomas*): Paniala is predominantly found to grow in the Sub Himalayan regions of India. It is also known as Governor's plum and Lasora. The Plant is a small deciduous shrub or tree that attains the height of 6-8m. The ripe fruits have a tart and slightly sweet taste. They are eaten fresh and also used to make jams, jellies and marmalades. They are also used for treating a number of ailments like cold, cough, diarrhoea and dysentery and also helps to improve memory. The fruits are rich in nutrients and 100g serving size of which contains 24.2g carbohydrates, 0.59 proteins, 0.6g fats, 1.2g fibers, vitamin-C and minerals like potassium (171mg), calcium and iron respectively.

6. Longan (*Dymocarpus longan*): Longan is typically a lychee like minor indigenous fruits of sub-tropical regions. Locally it is known as 'Anshfal'. The plant is a tree which grows up to the height of 10-12 m. The plant externally looks almost like lychee plant. The plants produce flower during February and the fruits mature in Summer. The edible part is white fleshy aril. Due to high water content, the fruits help to quench thirst during hot summer. The fruits are rich in nutrients containing 11-15g carbohydrates, 0.9-1.3g protein, 1-1.1g fiber, 84mg vitamin-C and minerals including 266mg potassium, 21mg phosphorus and 0.13mg iron along with antioxidants polyphenols like gallic acid, per 100g. The fruits are good for liver function and immunity.



7. Wood Apple (*Limonia acidissima*): Wood apple is a native Indian Fruit which is locally Called 'Koyet bael'. This hardy fruit trees grows upto 12-15m in height with bearing many spiny branches. The fruits are typically round in shape, with a hard and woody shell and distinctive fibrous brownish pulp inside. The fruit pulp is edible and used to made food products like chutney, jam, jelly, pickle and sharbot. Wood apple is a nutrient-dense fruit which contains 12.3g carbohydrates, 1.6g proteins, 0.7g fats, 2.9g dietary fibers, 270mg vitamin-C, 89mg calcium, 43mg iron, 88mg folic acid, flavonoids and polyphenols per 100 g of edible flesh. It has also medical properties which aids digestion and also exhibits anticancer and microbial properties.

8. Kaphal (*Myrica esculenta*): Kaphal predominantly thrives well in the hill forest areas of the North Eastern Himalayan States encompassing Meghalaya, Assam, Darjeeling and Kalimpong districts of West Bengal. It is widely distributed in the foothills of Himalaya. Kaphal is an evergreen medium tree attaining the height of about 6-8m. The fruit is globose succulent drupe with wart like appearance on the skin. The fruits are sweat and sour in taste which ripe during may-June. They are enriched with various nutrients including 16g carbohydrates, 1.4g proteins, 0.3g fats, 3g fiber, 87 mg vitamin A, 32mg vitamin-C and 1.6mg iron. The people of rural communities eat unripe fruits



mixing with salt for quenching thirst. Refreshing drink is also prepared in hot summer. It is useful for treating the ailments like toothache, cold and cough and headache.



9. Golden Raspberry (*Rubus ellipticus*): This lesser known fruit is found in the temperate Himalaya regions of West Bengal, Sikkim, Nepal and Meghalaya. It is also known as 'ainselu' and yellow raspberry. The plant is a thorny shrub which can grow upto 5m in height. Golden yellow coloured ripe fruits are sweet in taste which perish quickly after harvesting. Ripe fruits are eaten directly or used to make jams, juice, wines and squash. The fruits are packed with nutrients including 27g carbohydrates, 0.97g proteins, 2.4-3.2g fat, 2.3g fibers, 3-5mg vitamin-C, 1.82mg potassium, 0.95mg cal per 100g and antioxidants like flavonoids, anthocyanin and phenolic acids. It is traditionally used for treating various ailments like diarrhoea, fever, diabetes, ulcer, skin infection and joint pain.

10. Mahua (*Madhuca indica*): Mahua fruit plant is deeply associated with the socio-economic culture of rural tribal communities of red and lateritic regions of West Bengal, Orissa, Jharkhand and Bihar. It is truly high valued for its delicious flowers and fruits which have a great demand in the production of various foods. This fruit plant is a medium sized deciduous tree which thrives well in the hot and dry climate. The fruits are consumed fresh or used to make different foods like sweets, curries, snacks, jams, and jellies and alcoholic drinks. They are a good source of nutrients like 23g carbohydrates, 1g proteins, 2g fats, 10g fiber, 40mg vitamin C, 307 mg carotene, 22mg phosphorus, 4 mg calcium and 0.12mg iron per 100g. The fruits also contain the bioactive compounds like flavonoids and phenolic acids that act as antioxidants. They are used for treatment of ailments pharyngitis and chronic tonsillitis.



11. Tamarind (*Tamarindus indica*): Tamarind is an indigenous tropical fruit which thrives well in dry lateritic regions of India. It is a long living hardy medium tree which grows up to the height of 20-25 m. The fruits are indehiscent elongated pod that turn brown to reddish brown colour at maturity. Tamarind is a sour and sweet tasted fruit. Unripe fruits are used in making savory dishes, pickles, chutneys, curries, sauces traditional drinks like sharbot and syrup. 100g raw fruits contain 63g carbohydrates, 3g proteins, 0.4g fats, 3g fibers and 26.6g Water. The sour taste is due to presence of tartaric acid (10%). Tamarind fruits have several Ayurvedic applications for treating a number of ailments. It is very effective against the health problems like indigestion, Joint pain, drug addiction, cold and cough and also reduces the chance of Stone formation in urinary bladder. Its antioxidant property helps to build up body immunity and reduce inflammation.

12. Palmyra Palm (*Borassus flabellifer*): Palmyra palm is found in India as tropical fruit to under hot and dry climate. It is called "Kalpabriksha" due its versatile uses. It is a dioecious fruit plant that grows upto the height of 30m producing a hard, blackish, straight un-branched trunk. The fruits are round shaped and brownish-black in colour. The pulp of the ripe fruits is used for making khir, sweets, bara, bread, puri, pitha, flakes and candy. The sap obtained traditionally by tapping the top shoots are collected in a hanging earthen pot or bamboo made bottle. The Juice offer fermentation is converted to a drink which is locally called 'Tadi'. Freshly collected Juice after straining and subsequent boiling tal jaggery is prepared which is used as natural



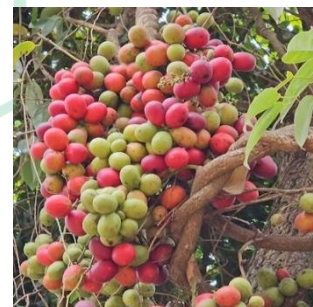
sweetener with low glycaemic index, Ripe fruits pulp is enriched with nutrients including carbohydrates (11-14%), proteins (2.78%), fat(1.2%), fibers (1.5%), vitamin-E (28.5mg), beta-carotene (3.2mg), phosphorus (15mg), iron (1.2mg) and potassium (21.5mg). The Fruits have medicinal properties for which they can help to reduce weight gain, heals wound, prevents constipation and reduces the chance of heart attack.

13. Latka (*Baccaurea motleyana*): Latka is a popular wild edible fruit of Sub-Himalayan regions of West Bengal including Darjeeling, Jalpaiguri, Kalimpong and Alipurduar districts. It is an evergreen tree which grows upto 10-12 m. in height. The fruits have pinkish yellow and brown velvet skin that wrinkle at maturity. The edible pulp is sweet to sour in taste. The fruits are eaten fresh or made into jam and wine. The fruits are nutrient rich containing 1.42g protein, 0.45g fats, fibers, 0.3mg vitamin B1, 0.19mg vitamin B-2 and mineral like potassium, calcium and iron per 100g serving size. The fruits being fiber rich paid bowl movement and weight management. The presence of a numbers of vitamins helps to build up Immune function of the body. Traditionally the leaves have found very effective for treating diarrhoea, stomach, ulcer and also act as a remedy for vomiting.



14. Kusum (*Schleichera oleosa*): Kusum or Ceylon Oak is a wild fruit which has been found domesticated in the dry lateritic regions of Jharkhand, Orissa and West Bengal. It holds a significant role in the diet, traditional medicine and culture among the local tribal communities. Small size fruits (Plums) have a pleasant sour taste at maturity. The edible succulent aril is loaded with an array of nutrients including 939g carbohydrates, 1.5g proteins, 0.8g fats, 14.2 mg vitamin, 1.35mg carotenoids and minerals like 15mg calcium. The fruits are the powerhouse of antioxidants like carotenoids and phenolic acids which help to combat against free radical damage inside the body. The fruits also help to improve digestion, appetite and taste and treat the ailments like diarrhoea, skin disease, fever and bleeding disorder. It also helps to strengthen and promote hair growth.

15. Blood Fruit (*Haematocarpus validus*): This lesser known edible fruit has originated from South East Asia. It is traditionally grown in Meghalaya, Nagaland and Andaman and Nicobar Islands. The plant is a climber which bears blood red fruits in bunches. The ripe fruits are acidic and sweet in taste. Deep red colour is due to the presence of natural plant pigment 'anthocyanin' which is a potent source of natural food colourant and antioxidant. Ripe fruits are enriched in carbohydrates, proteins, vitamin A and C and minerals. The fruits have also medicinal properties. It helps to boost up body immunity, aids digestion, helps in weight management, supports skin health and controls blood sugar level.



16. Ankol (*Alangium salvifolium*): Ankol is a small bushy tree with dense canopy and short trunk. The edible fruits are spherical berries which turn red at maturity. The reddish fleshy part of the fruit is eaten for its sweet taste and mild flavour. They are eaten as substitute food source during the time of seasonal food scarcity. The presence of nutritional and bioactive compounds like anthocyanin and flavonoid has made this fruit a potent source of food. Ankol fruits are rich in nutrients including 11.67g carbohydrates, 2.07g proteins, 0.12g fats, 46-62mg vitamin C, 168mg potassium, 1.37mg iron, 12mg calcium and 19 mg magnesium per 100g. The fruit pulp is used in the traditional medicines for its carminative properties for managing gastrointestinal problems like constipation, indigestion and flatulence.

Agri-Tourism: A Fast-Expanding Rural Economy Opportunity



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Introduction

Agriculture has always been the backbone of rural economies, but in recent years, it has begun to take on a new dimension—tourism. Agri-tourism, the fusion of farming and tourism, is rapidly expanding across the globe as a sustainable and innovative way to diversify rural income, preserve cultural heritage, and reconnect urban populations with the countryside. From **farm stays** and **farm cafés** to **petting zoos** and **experience tourism**, this sector is redefining how people engage with food, nature, and community. This article explores the opportunities, challenges, and future of agri-tourism, with a special focus on India's rural economy, while drawing lessons from international models.



Agri-tourism

What is Agri-Tourism?

Agri-tourism refers to activities that bring visitors to farms or rural areas to experience agricultural life firsthand. Unlike conventional tourism, which often emphasizes luxury or urban attractions, agri-tourism is rooted in authenticity. It allows tourists to participate in farming activities, taste fresh produce, interact with animals, and immerse themselves in rural traditions.

Key features include:

- Direct interaction between farmers and visitors.
- Educational experiences about food production and sustainability.
- Recreational activities like fruit-picking, fishing, or cooking.
- Cultural immersion through folk art, crafts, and festivals.

Agri-tourism is not just leisure—it is a bridge between urban curiosity and rural livelihood.

Key Opportunities in Agri-Tourism

1. Farm Stays

Farm stays offer tourists the chance to live on a working farm. Guests wake up to the sound of roosters, help with milking cows, or join in harvesting crops. This immersive experience appeals to urban dwellers seeking respite from city life.

2. Farm Cafés and Farm-to-Table Dining

Farm cafés serve fresh, locally grown produce directly to visitors. The farm-to-table concept is gaining popularity worldwide, as consumers increasingly value organic and sustainable food. A farm café not only generates income but also builds brand identity for the farm.

3. Petting Zoos and Animal Interaction

Families with children are drawn to petting zoos, where kids can safely interact with goats, rabbits, or ponies. This creates memorable experiences while educating the younger generation about animal care and farming.

4. Experience Tourism

Experience tourism goes beyond observation. Visitors actively participate in activities such as fruit-picking, pottery-making, or cooking traditional meals. These hands-on experiences deepen cultural appreciation and foster emotional connections with rural life.

5. Seasonal Festivals and Events

Harvest festivals, flower shows, or organic fairs attract large crowds. Farmers can showcase their produce, crafts, and traditions, turning seasonal cycles into profitable events.

Economic and Social Impact

Agri-tourism is more than a niche—it is a driver of rural transformation.

- **Diversified Income:** Farmers earn beyond crop sales by hosting tourists, reducing dependence on unpredictable agricultural markets.
- **Employment Generation:** Local youth find jobs in hospitality, guiding, event management, and handicrafts.
- **Cultural Preservation:** Traditional farming practices, crafts, and folk performances gain renewed relevance.
- **Environmental Awareness:** Visitors learn about sustainable agriculture, organic farming, and conservation.
- **Community Development:** Villages benefit from improved infrastructure, better roads, and digital connectivity.

Global Context

Agri-tourism is thriving worldwide:

- **Italy:** Known for agriturismo, where vineyards and olive farms host tourists. Italy's model emphasizes culinary experiences and cultural immersion.
- **USA:** Farm stays, pumpkin patches, and corn mazes are popular, especially during harvest seasons. Many farms combine tourism with education programs for schools.
- **Japan:** Rice-planting festivals and tea ceremonies attract tourists seeking cultural depth.
- **Australia:** Sheep-shearing demonstrations and wine tours blend agriculture with entertainment.

These models show that agri-tourism can be tailored to local culture and geography, making it universally adaptable.

Indian Context

India, with its vast rural landscape and diverse agricultural practices, is uniquely positioned to benefit from agri-tourism. States like Maharashtra, Himachal Pradesh, and Kerala have pioneered initiatives, offering farm stays, spice plantation tours, and organic experiences.

Government schemes such as *Dekho Apna Desh* and *Swadesh Darshan* support rural tourism, while private entrepreneurs are investing in eco-resorts and farm cafés. Agri-tourism in India not only boosts rural GDP but also empowers farmers by giving them direct access to consumers.

Challenges Ahead

Despite its promise, agri-tourism faces hurdles:

- **Infrastructure Gaps:** Rural areas often lack roads, sanitation, and digital connectivity.
- **Training Needs:** Farmers require skills in hospitality, marketing, and customer service.
- **Seasonal Dependency:** Tourism peaks only during harvest or festive seasons, leading to uneven income.
- **Policy Support:** Clear regulations and financial incentives are essential for growth.
- **Balancing Authenticity and Commercialization:** Over-commercialization risks diluting the rural charm that attracts visitors.

Case Studies

Case Study 1: Maharashtra's Agri-Tourism Development Corporation (ATDC)

ATDC has successfully promoted farm tourism across Maharashtra, offering packages that include bullock cart rides, crop harvesting, and traditional meals. This initiative has increased farmer incomes and created rural employment.

Case Study 2: Himachal Pradesh's Apple Orchards

Apple farmers in Himachal Pradesh host tourists during harvest season, allowing them to pick apples and learn about orchard management. This has boosted tourism in hill regions while diversifying farmer income.

Case Study 3: Kerala's Spice Plantations

Kerala's spice plantations attract international tourists eager to learn about cardamom, pepper, and cinnamon cultivation. Guided tours and cooking classes add value to the experience.

Future Outlook

Agri-tourism is poised to grow exponentially in the coming decade. Key trends include:

- **Digital Integration:** Online booking platforms and social media marketing will expand reach.
- **Eco-Tourism Synergy:** Agri-tourism will merge with eco-tourism, emphasizing sustainability.
- **Wellness Tourism:** Yoga retreats and organic diets on farms will attract health-conscious visitors.
- **Smart Farming Demonstrations:** Tourists will witness modern technologies like drones, hydroponics, and AI in agriculture.
- **Global Collaborations:** Partnerships with international travel agencies will bring foreign tourists to Indian farms.

Conclusion

Agri-tourism is more than a trend—it is a sustainable model that strengthens rural economies, bridges the urban-rural divide, and reconnects people with the roots of food production. By investing in infrastructure, training, and policy support, this sector can become a cornerstone of innovative agriculture and rural prosperity.

For farmers, agri-tourism is not just an opportunity—it is a revolution. For tourists, it is not just a holiday—it is a journey back to the soil.

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Development and Evaluation of a Fermented Whey-Based Beverage Enriched with Orange and Bael



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Abstract

Whey is a valuable by-product of the dairy industry that is often discarded, leading to environmental pollution despite its high nutritional value. Whey contains high-quality proteins, lactose, minerals, and bioactive compounds that can be effectively utilized for the development of functional beverages. The present study aimed to develop and evaluate a fermented whey-based beverage enriched with orange and bael, two fruits known for their nutritional and therapeutic properties. Orange provides vitamin C and antioxidants, while bael is traditionally used for digestive health. The beverage was prepared by fermenting whey using a suitable starter culture, followed by the addition of orange and bael pulp in different proportions. The developed product was evaluated for sensory attributes such as colour, flavour, taste, texture, and overall acceptability. Basic physicochemical parameters were also assessed. The results indicated that fermentation improved the flavour and acceptability of whey, while fruit enrichment enhanced nutritional value and sensory quality. The study concludes that a fermented whey-based beverage enriched with orange and bael can be a nutritious, refreshing, and sustainable functional drink with good consumer acceptability.

Keywords: Whey, Fermentation, Functional beverage, Orange, Bael, Sensory evaluation

Introduction

The increasing demand for functional foods and beverages has encouraged researchers and food technologists to utilize natural and nutritious ingredients for product development. Whey is a major by-product of cheese and paneer manufacturing and is often treated as waste. However, whey contains valuable nutrients such as lactose, whey proteins, calcium, phosphorus, and water-soluble vitamins. Improper disposal of whey causes environmental pollution due to its high biological oxygen demand (BOD). Therefore, effective utilization of whey is important from both nutritional and environmental perspectives.

Fermented beverages prepared from whey offer improved digestibility, enhanced flavour, and extended shelf life. Fermentation also increases the bioavailability of nutrients and supports gut health by introducing beneficial microorganisms. Incorporation of fruits into whey beverages further improves taste, colour, and nutritional quality.

Orange is a rich source of vitamin C, flavonoids, and antioxidants, which help boost immunity and improve overall health. Bael (*Aegle marmelos*) is a traditional medicinal fruit widely used in India for its digestive, anti-diarrheal, and cooling properties. Combining whey with orange and bael can result in a functional beverage with enhanced nutritional and therapeutic benefits.

The present study focuses on the development and evaluation of a fermented whey-based beverage enriched with orange and bael, aiming to create a healthy, cost-effective, and acceptable functional drink.

Materials and Methods

Fresh skimmed milk was procured from a local dairy and used for whey preparation. The milk was heated to 85°C and coagulated using 1–2% citric acid with continuous stirring. The coagulated mass was filtered through muslin cloth to obtain clear whey, which was cooled to room temperature. The whey was inoculated with a lactic acid bacteria starter culture at 2% and fermented under controlled temperature conditions until mild acidity was achieved, after which fermentation was terminated by refrigeration.

Fresh oranges and ripe bael fruits were sourced locally, washed thoroughly, and processed. Orange juice was extracted manually, while bael pulp was separated, deseeded, and blended into a smooth paste. Both fruit extracts were filtered prior to use. The fermented whey was blended with orange juice and bael pulp in varying

proportions along with a fixed quantity of sugar. The mixture was homogenized to obtain a uniform beverage and stored under refrigeration until analysis.

Sensory evaluation of the beverage samples was conducted by a semi-trained panel using a 9- point hedonic scale to assess colour and appearance, flavour, taste, mouthfeel, and overall acceptability. Physicochemical analysis, including pH, titratable acidity, and total soluble solids (TSS), was performed using standard methods. All analyses were carried out in triplicate, and the results were statistically analysed to determine product quality and acceptability.

- **Utilization of whey:** Converts dairy industry by-product into a value-added functional beverage, reducing environmental pollution.
- **Enhanced nutritional quality:** Combination of whey proteins with bioactive compounds from orange and bael improves overall nutritive value.
- **Probiotic potential:** Fermentation enhances gut-friendly microorganisms, supporting digestive health.
- **Improved sensory properties:** Orange adds refreshing citrus flavor, while bael contributes natural sweetness and aroma.
- **Functional health benefits:** Acts as a functional beverage supporting immunity, digestion, and hydration.
- **Cost-effective production:** Uses low-cost whey with locally available fruits, suitable for small-scale and rural entrepreneurship.

Disadvantages

- **Shorter shelf life:** Fermented beverages are prone to microbial spoilage if not properly refrigerated.
- **Flavor acceptability issues:** Bael has a strong characteristic taste that may not be preferred by all consumers.
- **Processing challenges:** Requires controlled fermentation conditions to maintain product consistency.
- **Lactose intolerance concern:** Whey contains lactose, which may not be suitable for lactose-intolerant individuals.
- **Stability issues:** Possible phase separation or sedimentation during storage.

Nutritional Benefits

- **High-quality proteins:** Whey provides essential amino acids for muscle repair and growth.
- **Rich in vitamins:**
 - Orange → Vitamin C (antioxidant, immunity booster)
 - Bael → Vitamins A, B-complex, and C
- **Mineral content:** Calcium, potassium, phosphorus, and magnesium from whey and fruits support bone and electrolyte balance.
- **Dietary fiber:** Bael contributes soluble fiber aiding digestion and bowel regularity.
- **Antioxidant properties:** Flavonoids and phenolic compounds from orange and bael reduce oxidative stress.
- **Low fat & refreshing:** Suitable for health-conscious consumers as a light, nutritious drink.

Results and Discussion

The fermentation process significantly improved the flavour and palatability of whey by reducing its bland taste. Addition of orange juice imparted a refreshing citrus flavour and enhanced vitamin C content, while bael pulp contributed mild sweetness and digestive properties. Sensory evaluation results showed that the sample containing balanced proportions of orange and bael received the highest scores for overall acceptability.

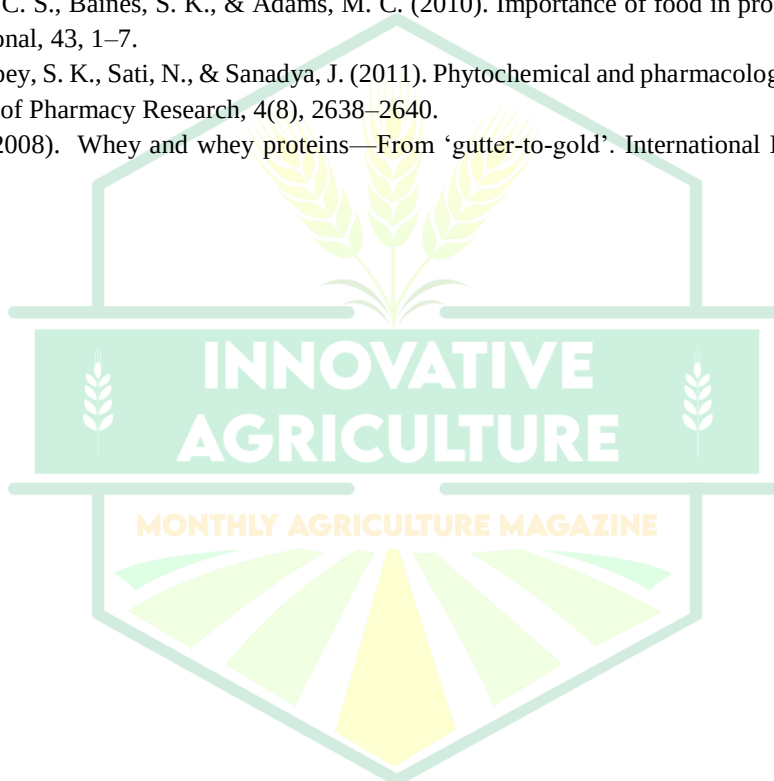
The beverage exhibited acceptable pH and acidity levels, indicating good fermentation quality and product safety. The combined effect of fermentation and fruit enrichment resulted in a nutritious beverage with improved taste, aroma, and functional value. The findings suggest that whey can be successfully utilized as a base for fermented fruit beverages, reducing waste and promoting sustainability.

Conclusion

The study demonstrated that a fermented whey-based beverage enriched with orange and bael can be successfully developed with good sensory acceptability and nutritional benefits. Fermentation enhanced the flavour and digestibility of whey, while fruit incorporation improved its nutritional and functional properties. The developed beverage has the potential to serve as a healthy alternative to synthetic soft drinks and can contribute to effective whey utilization. This product may also offer opportunities for small-scale dairy and beverage industries to develop value-added functional drinks.

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Fruit Crops for Border Planting: Turning Field Boundaries into Profit Zones



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Border cropping is an important agronomic practice in sustainable agriculture that involves growing specific crops along the boundaries of fields to provide multiple benefits such as additional income, protection from wind and pests, efficient land use, and ecological balance. Fruit crops, due to their perennial nature, economic value, and multifunctional benefits, are increasingly being recognized as ideal border crops for main agricultural crops. This article discusses suitable fruit crops for border planting, their compatibility with major agricultural crops, advantages, selection criteria, and region-specific examples. This article delivers more ideas to the farmers and readers for their agricultural techniques along with acceptable border fruit crops.

1. Introduction

In Indian farming systems, a significant portion of cultivable land remains underutilized along field borders, bunds, and fence lines. Border cropping with fruit crops transforms this unused space into a productive zone, enhancing farm income without affecting the main crop yield. Fruit crops used as border crops also contribute to windbreaks, soil conservation, biodiversity enhancement, and climate resilience. With increasing pressure on land resources and the need for diversified income, integrating fruit crops as border crops is a sustainable and climate-smart strategy for small and marginal farmers.

2. Concept of Border Cropping

Border crops are grown along the periphery of main crop fields. Fruit crops selected for border planting should:

- Have minimal shading effect on main crops
- Possess deep or non-competitive root systems
- Be hardy and low-maintenance
- Provide economic returns
- Act as protective or beneficial components

3. Advantages of Fruit Crops as Border Crops

- Additional income without sacrificing main crop area
- Windbreak effect reducing crop lodging
- Reduction of soil erosion
- Barrier against stray animals
- Microclimate moderation
- Pollinator attraction
- Year-round farm employment
- Carbon sequestration and ecological stability

4. Criteria for Selection of Fruit Crops for Border Planting

1. Growth habit (bushy, dwarf, or columnar preferred)
2. Root system compatibility
3. Tolerance to pruning
4. Market demand and shelf life
5. Climatic and soil adaptability
6. Resistance to pests and diseases

5. Suitable Fruit Crops for Border Cropping (With Examples)

5.1 Banana (*Musa spp.*)

- **Main crops:** Sugarcane, turmeric, cotton, maize, vegetables
- **Advantages:** Fast growth, wind protection, early returns
- **Spacing:** 2.0 × 2.0 m or single row along borders
- **Special role:** Acts as a living windbreak



5.2 Papaya (*Carica papaya*)

- **Main crops:** Pulses, vegetables, groundnut, cereals
- **Advantages:** Early bearing (6–8 months), high returns
- **Spacing:** 2.0 × 2.0 m
- **Special role:** Efficient space utilization



5.3 Guava (*Psidium guajava*)

- **Main crops:** Paddy, vegetables, oilseeds
- **Advantages:** Hardy, tolerant to pruning, regular income
- **Spacing:** 4–5 m
- **Special role:** Pollinator-friendly crop



5.4 Pomegranate (*Punica granatum*)

- **Main crops:** Cotton, pulses, oilseeds
- **Advantages:** Drought tolerant, high market value
- **Spacing:** 3–4 m
- **Special role:** Suitable for arid and semi-arid regions



5.5 Aonla (*Emblica officinalis*)

- **Main crops:** Mustard, gram, cereals
- **Advantages:** Highly hardy, long lifespan
- **Spacing:** 6–8 m
- **Special role:** Medicinal and nutraceutical value



5.6 Ber (*Ziziphus mauritiana*)

- **Main crops:** Millets, pulses, oilseeds
- **Advantages:** Thrives in poor soils, drought tolerant
- **Spacing:** 6 m
- **Special role:** Ideal for dryland farming



5.7 Custard Apple (*Annona squamosa*)

- **Main crops:** Groundnut, sesame, sorghum, sunflower
- **Advantages:** Low input crop, high price
- **Spacing:** 4–5 m
- **Special role:** Rainfed ecosystem suitability



5.8 Citrus (Lime, Lemon, Sweet Orange)

- **Main crops:** Vegetables, legumes, spices
- **Advantages:** Regular harvest, export potential
- **Spacing:** 4–6 m
- **Special role:** Aromatic barrier reducing pest movement



5.9 Fig (*Ficus carica*)

- **Main crops:** Cotton, vegetables
- **Advantages:** Hardy, drought tolerant
- **Spacing:** 5–6 m
- **Special role:** High value in fresh and dry markets



5.10 Jamun (*Syzygium cumini*)

- **Main crops:** Paddy, fodder crops
- **Advantages:** Long-term income, climate resilient
- **Spacing:** 8–10 m
- **Special role:** Carbon sequestration and biodiversity



5.11 Karonda (*Carissa carandas*)

- **Main crops:** Cereals, pulses
- **Advantages:** Thorny, ideal fencing crop
- **Spacing:** 1.5–2.0 m
- **Special role:** Natural bio-fence



5.12 Phalsa (*Grewia asiatica*)

- **Main crops:** Wheat, mustard, vegetables
- **Advantages:** Short-lived, quick returns
- **Spacing:** 3 m
- **Special role:** Summer fruit for heat stress regions



5.13 Pineapple (*Ananas comosus*)

- **Main crops:** Coconut, arecanut, plantation crops
- **Advantages:** Ground cover, erosion control
- **Spacing:** 90 × 60 cm
- **Special role:** Bund and contour planting



6. Region-Specific Border Crop Recommendations

Region	Suitable Fruit Crops
Arid	Ber, Aonla, Pomegranate, Custard apple
Semi-arid	Guava, Fig, Karonda
Tropical	Banana, Papaya, Pineapple
Sub-tropical	Phalsa, Citrus, Peach
Coastal	Coconut, Jamun, Banana

7. Management Practices

- Regular pruning to avoid shading
- Separate fertilizer application
- Drip irrigation preferred
- Integrated pest management
- Timely harvesting

8. Constraints and Precautions

- Avoid tall fruit trees on southern borders
- Prevent root competition
- Ensure market access
- Control pest harboring

9. Future Scope

- High-density border planting models
- Climate-resilient fruit varieties
- Integration with organic farming
- Digital mapping for border utilization
- Agri-horti-silviculture models

10. Conclusion

Fruit crops as border crops represent an efficient, eco-friendly, and economically viable strategy for modern agriculture. Proper selection and management can significantly enhance farm profitability, sustainability, and resilience without compromising the productivity of main crops.



Agriculture patent a driving innovation in the farming sector



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Introduction:

Agricultural patents protect innovations in farming, covering machinery (drones, sensors), biotech (GMOs, gene editing), processes (fertilizers, composting), and digital tools, though methods of agriculture itself aren't usually patented in places like India, which also has specific laws for plant varieties (PPVFR Act). These patents grant exclusive rights to inventors for a period, driving R&D and ensuring returns, with major patenting activity seen in Asia (China, India, Japan, Korea). Agriculture patents are crucial drivers of innovation, protecting new crop varieties (like drought-resistant ones), biotech traits, machinery, and digital tools (AI, drones, IoT) that boost yields, sustainability, and efficiency, attracting investment by granting exclusive rights, sharing technical knowledge, and fostering R&D, thereby addressing global challenges like food security and climate change. They cover everything from genetic advancements to precision farming technologies, encouraging investment in high-risk AgTech and enabling licensing for broader adoption, transforming farming into a more data-driven, automated, and productive sector. Agriculture patents are significant because they **incentivize innovation** in a costly, time-consuming sector by granting exclusive rights, driving investment in new technologies (like GMOs, machinery, precision ag), and enabling commercialization, ultimately boosting productivity and food security while balancing creators' rights with public access. They protect inventions such as new crop varieties, agrochemicals, and biotech processes, allowing developers to recoup costs and fund further R&D, which benefits farmers and society. Patents in the field of agriculture may be obtained under the Indian Patents Act for processes involving agrochemicals, growth promoters and regulators, drugs, vaccines, hides and wool, dairy technology, food technology, fuel and biogas production, bioreactors, standardisation of various laboratory protocols, environment management, and similar things.¹² However, there are several limitations pertaining to the issuance of agricultural innovations under the Act.

Agriculture Patents primarily fall under **Utility Patents** (for processes, machines, GM crops), **Plant Patents** (for new asexually reproduced plants like fruit trees), and sometimes **Design Patents** (for product appearance), with specific protections like **Plant Variety Protection (PVP)** for sexually reproduced plants also existing, covering innovations from biotech like CRISPR to smart farming tools and new fertilizer methods, protecting everything from genetic modifications to farm machinery.

Key Types of Agriculture Patents:

1. **Utility Patents:** Broadest protection for new, useful inventions, processes, or improvements in agriculture.
 - **Examples:** Gene-editing techniques (CRISPR), genetically modified seeds (GMOs), precision farming tech (sensors, drones), slow-release fertilizers, bioreactors, and farm machinery.
2. **Plant Patents:** For new, distinct plant varieties that are asexually reproduced (cuttings, grafting).
 - **Examples:** New rose bushes, fruit trees, or ornamental plants.
3. **Plant Variety Protection (PVP):** A certificate (not a traditional patent) for new, sexually reproduced plant varieties (grains, potatoes).
 - **Key Feature:** Allows for limited seed saving and research use.
4. **Design Patents:** Protects the unique ornamental appearance of an agricultural product or device.

Areas Covered by Agriculture Patents:

- **Biotechnology & Genetics:** GM crops, gene editing, new plant breeding methods.
- **Machinery & Automation:** Drones, harvesters, robotic planters, irrigation systems.
- **Agrochemicals:** Novel fertilizers, pest management solutions (including biologicals).

- **Food Tech:** Processing, storage, and food chemistry advancements.
- **Smart Farming:** IoT, connectivity, mapping, and data management software.

Other Intellectual Property in Agriculture:

- **Trademarks:** Brand names for agricultural products (e.g., 'Fuji' apples).
- **Trade Secrets:** Confidential farm practices or formulas.
- **Geographical Indications (GIs):** Protects products from specific regions (e.g., Champagne).

Key Roles of Patents in Agriculture:

- **Investment & R&D:** Safeguard high R&D costs for new seeds and tech, attracting capital for complex developments like biotech traits and automated systems.
- **Knowledge Sharing:** Patent applications detail inventions, creating a public repository of technical data that inspires further innovation in the industry, say Lexology and [ScienceDirect.com](https://www.sciencedirect.com).
- **Driving Specific Innovations:**
 - **Biotech:** Protecting new crop varieties with enhanced traits (disease/drought resistance).
 - **Precision AgTech:** Covering drones, AI/IoT sensors, satellite monitoring, and automated machinery.
 - **Sustainability:** Encouraging development of water-efficient systems and climate-resilient crops.
- **Market & Policy:** Inform investors about market trends and help policymakers create supportive regulations, say ScienceDirect.com.
- **Strategic Assets:** Allow licensing and partnerships, speeding technology transfer from labs to fields, according to [Legal Advantage](https://www.legaladvantage.com) and [Agriwow.com](https://www.agriwow.com).

Key Areas of Innovation (Covered by Patents):

- **Digital & Data-Driven Farming:** AI-driven analytics, IoT sensors, satellite monitoring, blockchain.
- **Biotechnology:** [Genomics](#), gene editing, new plant varieties.
- **Automation & Robotics:** [Drones](#), autonomous tractors, automated irrigation.
- **Sustainable Solutions:** [Smart irrigation](#), nutrient management.

Agricultural patents in India cover innovations like agrochemicals, equipment, biotech processes (GMOs), and food tech, governed by the [Indian Patents Act](#), with key exclusions for plants/seeds (covered by PVPFR) but allowing patents for processes with significant human intervention, fostering innovation in areas like precision farming and bio-pesticides, primarily by public bodies and private firms.

What Can Be Patented?

- **Agrochemicals & Biocides:** New pesticides, herbicides, and plant growth regulators.
- **Equipment & Processes:** Innovations in farm machinery, irrigation systems (e.g., solar aquaponics), and novel preparation methods (e.g., bio-diesel from jatropha)
- **Biotechnology:** Genetically modified organisms (GMOs) and biotech processes, provided they meet patentability criteria.
- **Food Technology:** Processes for food products, dairy tech, and novel food compositions (e.g., gluten-free mixes).
- **Animal Husbandry:** New breeds and related technologies.

Key Legal Framework:

- **Indian Patents Act:** Allows patents for agricultural inventions, though with specific exclusions.
- **Section 3(j) Exclusion:** Generally excludes plants, animals, and essentially biological processes for propagation, but allows patents if there's significant human technical intervention.
- **Plant Variety Protection & Farmers' Rights (PVPFR) Act:** Provides a separate system for protecting new plant varieties, offering breeders, researchers, and farmers specific rights, distinct from patents.

Who Files Patents?

- **Public Sector:** Indian Council of Agricultural Research (ICAR) institutions and agricultural universities (e.g., UAS Bangalore, Anand Agricultural University) are significant patent holders.
- **Private Sector:** Companies like Corteva and BASF lead in areas like crop protection and seed tech, focusing on innovation.

Trends & Focus Areas

- **Increased Activity:** Growth in patents for biocides, new plant processes, and animal husbandry.
- **Innovation in Tech:** Patents in precision farming (drones, sensors) and sustainable agriculture are growing.
- **Focus on Sustainability:** Development of bio-pesticides and eco-friendly formulations.

The future of agricultural patents in India involves balancing innovation with farmer rights, focusing on new tech like AI, biotech, and data, and strengthening the unique *sui generis* system (PPV&FRA) alongside traditional patents for processes/machinery, moving towards self-reliance (e.g., date palm patents) and encouraging investment in agri-tech while protecting traditional knowledge. Expect more patents for digital farming tools, biotech, sustainable practices, and precision agriculture, driven by NITI Aayog's vision for a tech-led transformation, but policymakers must ensure equitable access and benefit sharing.

Key Trends Shaping the Future:

1. **Digital & Biotech Innovations:** Increased patents for AI-driven advisory, data analytics, biotech-enhanced seeds, robotics, and precision farming tools.
2. **Sustainable Agriculture:** Growing focus on patents for climate-resilient crops, bio-pesticides, and sustainable food solutions (e.g., alternative proteins).
3. **Data as New Soil:** Shift towards sovereign data systems and intellectual property around agricultural data, notes this NITI Aayog roadmap.
4. **Self-Reliance & Domestic Patents:** Examples like the date palm patent show a push for indigenous innovation and patents for locally developed varieties, reducing import dependence.

The Indian IP Framework:

- **Patents Act:** Protects processes, machinery, agrochemicals, and food tech.
- **PPV&FRA (2001):** A unique system protecting new plant varieties (farmer/breeder rights) while safeguarding farmers' rights to save and share seeds, as per Vintage Legal and HIMCOSTE.

Challenges & Opportunities:

- **Balancing Act:** Need to incentivize private R&D (via patents) while ensuring accessibility for smallholder farmers, say FSII and Global Patent Filing.
- **Protecting Traditional Knowledge:** Stronger national and international protection for India's rich genetic heritage (like turmeric, neem) is crucial, notes this HIMCOSTE report.
- **Policy & Implementation:** Collaboration between policymakers, researchers, and farmers to create a supportive ecosystem for tech adoption, as highlighted.

In essence, the future involves a hybrid approach: leveraging patents for core tech/processes and the PPV&FRA for plant varieties, all while fostering an inclusive, technology-driven agricultural landscape, according to this NITI Aayog roadmap.

Agricultural patents serve as a vital, high-growth driver of innovation in the modern farming sector by encouraging research, securing investment, and enabling the development of sustainable, high-efficiency technologies. As the sector faces increasing challenges from climate change and population growth, patents act as essential legal protection for advances in biotechnology, precision farming, and automation.

Key Drivers of Innovation through Agricultural Patents:

- **Encouraging Research & Development:** Patents provide inventors with exclusive rights (typically 20 years), allowing them to recoup the significant time and financial investments required to create new seeds, pesticides, or machinery.
- **Driving Sustainable Practices:** Patents are crucial in developing water-saving irrigation systems, biofertilizers, and pest-resistant crops, directly supporting eco-friendly agriculture.
- **Facilitating Technology Transfer:** Patents allow for licensing, which enables the transfer of technology from research institutions to the commercial market, speeding up the adoption of new, efficient farming methods.
- **Empowering AgTech Startups:** For startups, patents act as essential assets that attract venture capital, helping to modernize agriculture through IoT devices, data analytics, and artificial intelligence.

- **Enhancing Competitiveness:** Patents protect intellectual property against unauthorized use, allowing firms to differentiate their products and maintain market position.

Filing an agriculture patent in India is a structured process designed to protect novel, non-obvious, and useful inventions in the farming sector, such as new machinery, sustainable farming tools, automated irrigation systems, or advanced agrochemical formulations. The process involves rigorous documentation and adheres to the Patents Act, 1970, with recent 2024 amendments speeding up the process for startups and individuals.

1. Driving Innovation in Key Agricultural Sectors

Patents are essential for safeguarding intellectual property in several crucial areas, transforming traditional farming into a high-tech industry:

- **Biotechnology & Seed Tech:** Development of genetically modified organisms (GMOs) and CRISPR-based gene-editing techniques creates pest-resistant and higher-yield crops.
- **Precision Agriculture:** Patents cover IoT devices, AI-powered soil sensors, and satellite-guided systems that enable tailored, site-specific farming to optimize resource use.
- **Automation and Robotics:** AI-driven drones, autonomous tractors, and robotic harvesters reduce reliance on manual labor, allowing for 24/7, precise, and efficient operations.
- **Sustainable Technologies:** Innovations in biofertilizers, biopesticides, and water-efficient irrigation systems are essential for environmental sustainability.

2. The Significance of Patents in Farming

- **Securing Investment:** Because agricultural R&D is capital-intensive and time-consuming (taking 10-15 years for new seeds), patents are vital to ensure investors can recoup their investment, thereby attracting more funding.
- **Promoting Technology Transfer:** Patents facilitate licensing deals, allowing technologies to be shared between innovators and commercial partners, accelerating the spread of new solutions.
- **Enabling Competitive Advantage:** Companies can protect their innovations from being duplicated, enabling them to differentiate their products in the market.
- **Enhancing Sustainability:** Patents encourage the development of eco-friendly farming practices, such as low-emission tractors, soil health sensors, and fertilizers from organic waste, aiding in combating climate change.

3. Impact on the Future of Farming

The role of patents is expanding rapidly, with digital agriculture patents showing a high compound annual growth rate, far exceeding other technical fields. As the world looks to technologies like blockchain for traceability, digital twins for simulation-based planning, and climate-resilient crops, patents are becoming the "shield and sword" for the future of food production.

While patents can lead to higher short-term costs, they are considered indispensable for long-term sustainability and advancements in the agricultural sector.

1. Key Criteria for Agricultural Patentability

To be eligible for a patent, your agricultural innovation must satisfy three main criteria:

- **Novelty:** The invention must be completely new and not disclosed publicly in India or elsewhere before the filing date.
- **Non-Obviousness (Inventive Step):** It must not be obvious to a person skilled in the relevant technical field. It should represent a significant improvement over existing technology.
- **Industrial Applicability (Utility):** The invention must have a practical, usable application in agriculture, such as enhancing yield, improving efficiency, or enhancing sustainability.

Note: Conventional farming techniques or methods of agriculture/horticulture (e.g., a new method of planting) are generally not patentable under Section 3(h) of the Indian Patent Act.

2. Steps to File an Agriculture Patent (India)

1. **Conduct a Patent Search (Prior Art Search):** Before filing, check if your invention already exists. Search databases like the Indian Patent Office, USPTO, and WIPO.

2. **Draft the Patent Application:** This is a crucial techno-legal document. It should include:

Title and Abstract: Briefly describing the invention.

Background and Summary: Explaining current technology and the improvements your invention brings.

Detailed Description: Comprehensive, technical details enabling others to implement the invention.

Claims: Precisely defining the scope of protection sought.

File the Application: You can file a **Provisional Application** first (to lock in a priority date for an idea that is still under development) or a **Complete Application** (if the invention is fully ready).

Publication: The application is published automatically 18 months after the filing date.

Request for Examination (RFE): You must file a request for examination (Form 18) within **31 months** of the filing date, as per 2024 amendments.

Responding to Office Actions: The patent office will issue a First Examination Report (FER) listing objections. You must file a response within 12 months to address these, or the application may be abandoned.

Grant of Patent: Once all objections are resolved, the patent is granted and published.

3. Required Documents & Fees

- **Forms:** Form 1 (Application), Form 2 (Provisional/Complete Specification), Form 3 (Undertaking), and Form 5 (Declaration of Inventorship).
- **Fees (2024):** The government fee for filing for individuals is Rs. 750 and Rs. 4,000 for legal entities.
- **Costs:** Costs range from Rs. 10,000 to over Rs. 1,00,000 depending on the complexity, attorney fees, and search costs.

4. Tips for Success in Agriculture Patents

- **Focus on Technical Advancements:** Emphasize how your invention solves a specific technical challenge (e.g., "AI-powered, camera-based precision weed remover") rather than just a process.
- **Use Professional Help:** Given the legal complexity, hiring a patent agent or attorney is highly recommended to ensure strong claims and prevent rejection.
- **Expedited Examination:** If you are a startup, woman inventor, or educational institution, you can opt for an expedited examination to get the patent granted within 1–2 years.

5. Alternative: Plant Variety Protection

If your innovation is a new plant variety (seed) rather than a machine or process, it should be registered under the Protection of Plant Varieties and Farmers' Rights Authority Act, 2001 (PPV&FRA), not the Patents Act.

Conclusion:

In conclusion, agriculture patents are not merely legal tools for protecting intellectual property; they are central to the transformation of the agricultural sector into a modern, resilient, and sustainable industry. By balancing the need for incentivizing R&D with the necessity for food security, patents drive the innovation required to meet global agricultural challenges. **Agriculture Patents are a primary driver of innovation and hold immense significance for new technology in the farming sector.** They act as a catalyst by providing legal protection that encourages investment in high-risk research and development, enabling the creation of advanced technologies that increase efficiency, sustainability, and productivity to meet the needs of a growing global population. Yes, it is accurate to conclude that **agriculture patents act as a primary driving force for innovation in the farming sector.** By providing exclusive rights, patents incentivize significant investment in research and developments, allowing for the creation of new, more efficient technologies that help meet growing global food demands, enhance sustainability, and improve crop resilience.

Role of cut flowers in floriculture industry in India



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Introduction:

Cut flowers are crucial to India's floriculture, driving export earnings, empowering farmers (especially smallholders) through income generation, and boosting related sectors like landscaping and floral design, while meeting rising domestic demand for decoration, events, and gifts, transforming traditional uses into modern commercial opportunities. They serve as a key economic driver, providing livelihoods and valuable foreign exchange, with India growing crops like roses, gladiolus, and carnations for global markets. Cut flowers are flowers and flower buds (often with some stem and leaf) that have been cut from the plant bearing it. It is removed from the plant for decorative use. Cut greens are leaves with or without stems added to the cut flowers for contrast and design purposes. In recent years, the market demand for fresh-cut flowers has continued to expand. In order to adjust the balanced supply of cut flowers in the off-season and improve the ornamental value of cut flowers, in addition to efforts in variety selection and cultivation management, the storage and preservation of cut flowers has become an important link in the production of commercial flowers. Since, it is currently a common means of extending the life of vase. Vase life is one of the most important factors in determining the marketability of cut flowers, which is greatly affected by postharvest physiology. This review summarized some postharvest physiological changes in fresh-cut flowers, including moisture, respiratory metabolism, cell membranes, pigments, carbohydrate levels, and antioxidant systems, and how these physiological changes are affected by some exogenous substances. Although these compounds are widely used in the postharvest preservation of fresh-cut flowers and provide the basis for the preservation of other fresh-cut flowers, the preservation effect may vary by cultivar. Therefore, it is also necessary to create new, efficient, and popular preservation technologies to prolong the life of cut flowers, improve ornamental quality and economic benefits. Cut flowers are commercially grown, harvested blooms (like roses, lilies, carnations) essential to floriculture, providing significant economic returns, supporting rural livelihoods, and meeting global demand for decoration, gifts, and cultural ceremonies, driving innovation in cultivation and post-harvest care to extend vase life and value. Their importance lies in high profit margins, job creation, boosting pollinator health on farms, and serving diverse markets from luxury bouquets to essential oil extraction.

Economic Significance

- ❖ **Foreign Exchange:** Cut flowers are a major export, bringing in foreign currency from markets in Europe, the Middle East, and the USA.
- ❖ **Income & Employment:** They create jobs for farmers, farm managers, designers, and retailers, fostering rural development.
- ❖ **Diversification:** Moving beyond traditional loose flowers (like marigold for garlands), cut flowers for bouquets and arrangements are a profitable new segment.
- ❖ **Impact on Farmers & Economy**
- ❖ **Empowerment:** Even small and marginal farmers can use small land parcels for high-value flower crops, notes the Vikaspedia portal.
- ❖ **Traditional vs. Modern:** While traditional loose flowers remain vital for religious and cultural use, cut flowers cater to the growing urban demand for home décor and gifting.
- ❖ **Value Addition:** It supports ancillary industries, including nurseries, essential oil extraction, and the growing floral design sector,

Key Crops & Production

- ❖ **Popular Varieties:** Roses, carnations, gladiolus, orchids, and gerberas are leading cut flowers, grown in both traditional open fields and modern greenhouses,
- ❖ **Growing Centers:** States like Tamil Nadu, Karnataka, West Bengal, and Maharashtra are key production hubs, notes the APEDA report.

In essence, cut flowers bridge traditional practices with modern commerce, acting as a significant economic engine and employment generator within India's dynamic floriculture sector.

Importance in Floriculture:

The commercial importance of cut flowers lies in their high economic value, generating significant revenue and employment through domestic sales and exports, driven by cultural uses (weddings, festivals) and increasing urban demand, offering high returns per area for farmers, and supporting related industries like floral design, tourism, and processing (essential oils, gulkand). As a high-growth sector, it provides opportunities for small farmers and entrepreneurs, boosting rural economies and earning foreign exchange, despite challenges in post-harvest management. Cut flower has become an important commercial activity in agriculture sector in the post globalization era. Cut flower activity has marked as a viable and profitable trade area with a potential to activate self-employment among low and middle income farmers, and earn the very essential foreign exchange in the developing countries such as India. The world Cut flower production is growing at a rate of 10 per cent per year. Almost 45 to 50 countries are active in the production of Cut flower on a large scale. In terms of production value, the Thailand, Netherlands, USA, UK and China are in the top. The economic slowdown has affected the Cut flower industry internationally with demand for Cut flower products were declined in major countries, such as Europe, The USA and Japan. Depression in pricing has been observed across the product segments. The Cut flower sector in India is facing several challenges at the production level mostly related to availability of basic inputs, proper irrigation and skilled manpower. At the marketing stage also Indian traders are facing major challenges related to product diversification and product differentiation. With increasing involvement of super markets in flower business, managing transport is also becoming a critical factor for the Indian flower traders.

1. **Economic Powerhouse:** A massive global industry (USD 40 billion), generating high income per area compared to other crops and driving export economies, especially from countries like the Netherlands, Colombia, and Kenya.
2. **Income & Livelihoods:** Offers profitable opportunities for farmers, including smallholders, and creates jobs in cultivation, processing, and trade, with potential for good returns (high benefit-cost ratios).
3. **Cultural & Social Value:** Fulfills demands for celebrations (weddings, birthdays), religious rites, funerals, and home decoration, becoming integral to daily life and cultural expression.
4. **Biodiversity & Farm Health:** Growing cut flowers attracts diverse pollinators and beneficial insects, improving yields for other crops and enhancing farm resilience.
5. **Diversification:** Supports related industries like dried flowers, natural colors, and essential oils (rose, jasmine), reducing reliance on single crops.
6. **Innovation Driver:** Promotes advanced techniques in greenhouses, pest management (IPM), and crucial post-harvest technologies (conditioning, water treatment) to improve vase life and market value.
7. **High Income:** Floriculture offers higher returns per unit area compared to many traditional field crops, making it a lucrative agricultural venture.
8. **Export Revenue:** Cut flowers are a major export commodity, earning valuable foreign exchange for countries like India, with strong markets in Europe, the Middle East, and Asia.
9. **Value Addition:** Processing flowers into products like *gulkand* (rose petal preserve) or tinting petals creates higher-value products, increasing market prices.
10. **Job Creation:** Provides year-round employment in cultivation, harvesting, packaging, marketing, floral design, and landscaping.
11. **Empowerment:** Offers self-employment and entrepreneurship opportunities, especially for rural women and youth.

12. **Cultural Integration:** Flowers are integral to Indian culture, used in religious ceremonies, festivals, weddings, and as gifts, ensuring consistent domestic demand.
13. **Aesthetic & Mental Health:** Enhance surroundings, improve mental well-being, and are used in therapeutic settings (hospitals, rehabilitation centers).
14. **Sunrise Sector:** Governments often promote floriculture as a high-growth, sunrise industry due to its potential for rapid development and export earnings
15. **Diversification:** Supports related sectors like nurseries, seed production, landscaping, and essential oil extraction.

The cut flower industry faces challenges like perish ability, post-harvest loss, supply chain issues (cold chain, transport), high production costs (labor, inputs, capital), climate variability, pests/diseases, and managing ethylene; however, opportunities lie in growing domestic/online demand, sustainable practices, value-added products (oils, cosmetics), protected cultivation, technological adoption (vertical farming, breeding), niche markets, and government/tech support to overcome these hurdles.

Key Challenges:

- **Perish ability & Post-Harvest Loss:** Flowers have a short vase life, requiring strict cold chains, proper handling, and protection from ethylene (a ripening hormone) to prevent wilting and spoilage, leading to high losses (up to 30%).
- **Supply Chain & Infrastructure:** Inadequate cold storage, refrigerated transport, and efficient logistics hinder quality, especially during peak demand, notes this article.
- **Resource & Cost Pressures:** Competition for land and water, rising labor costs, and high capital investment for modern greenhouses challenge profitability.
- **Climate & Environment:** Unpredictable weather (rain, temperature) affects yield, while growing environmental concerns pressure reduced pesticide/fertilizer use,
- **Pests & Diseases:** Damage from pests (thrips, aphids) and diseases reduces marketability, requiring integrated pest management.
- **Technical & Skill Gaps:** Lack of specialized skills in cultivation, post-harvest tech, and management, plus poor government support, hinder growth, according to this article and this article.

Key Opportunities:

- **Growing Demand:** Rising disposable incomes, online sales, and demand from hospitality/events fuel market growth, especially in urban areas.
- **Protected Cultivation:** Greenhouses/polyhouses enable year-round, high-value production.
- **Technology & Innovation:** Drip irrigation, vertical farming, advanced breeding (CRISPR), and micropropagation improve efficiency and quality, according to this article and this article.
- **Sustainability & Value Addition:** Growing interest in sustainable practices creates niches; diversification into essential oils, cosmetics, and medicinal products offers new revenue streams.
- **Market Niches:** Developing unique or native varieties for domestic and export markets, and improving coordination, can boost market share.
- **E-commerce:** Online platforms provide direct access to consumers, notes

The cut flower market shows strong, growing demand driven by rising incomes, urbanization, events, and lifestyle trends, moving beyond special occasions to everyday use, with major players like the Netherlands, Kenya, and Colombia dominating supply through advanced logistics. Supply is increasing but often lags behind demand, leading to imports, with global growth projected consistently, despite challenges like volatile air freight and cold chain management. Key trends include e-commerce growth, sustainability focus, and technological adoption (LEDs, automation).

Supply & Production:

- **Major Exporters:** The Netherlands, Colombia, and Kenya are key global suppliers, leveraging technology and logistics.

- **Technology:** Advancements in protected cultivation (LEDs, climate control) increase yield and reduce resource use, while better cold chain logistics improve shelf life.
- **Local Markets:** Even in production-heavy countries, local demand can be so high that imports are necessary, as seen in the Philippines.

Market Trends & Challenges

- **Growth:** The market is projected for substantial growth, with global figures reaching tens of billions of dollars.
- **Sustainability:** Demand for sustainable floral solutions is increasing, with certifications commanding price premiums.
- **Logistics:** Air freight costs and cold chain capacity remain significant challenges for international trade.

- **Product Focus:** Roses dominate, but tulips are also seeing significant growth due to year-round production.

The future of cut flowers is bright, driven by e-commerce, subscription models, and DIY trends, but faces challenges from climate change, pushing innovation in sustainable farming, biotechnology for hardier/unique varieties, and tech-driven supply chains for better efficiency, all while meeting growing consumer demand for eco-friendly, long-lasting, and exotic flowers. Expect more unique colors and resilient blooms, increased online sales, and a stronger focus on water conservation and sustainable practices in production.

Key Trends & Innovations:

- **Biotechnology & Breeding:** Developing flowers with longer vase life, disease resistance, unique colors (like blue chrysanthemums), and better adaptation to climate stress.
- **Sustainability:** Growing demand for eco-friendly methods like drip irrigation, integrated pest management, water harvesting, and biodegradable packaging to appeal to green consumers.
- **E-commerce & Subscriptions:** Rapid growth in online sales, floral subscriptions, and direct-to-consumer models.
- **Lifestyle & Wellness:** Increased use of flowers in aromatherapy, home decor, and wellness products, beyond traditional gifting.
- **Advanced Farming:** Investment in technology for controlled environments, improving yield and quality.

Market & Production Shifts:

- **Global Growth:** Strong growth projected, reaching potentially over \$40 billion by 2030, with new opportunities in emerging economies.
- **Production Centers:** Expansion in Asia, Africa, and Latin America, while traditional growers focus on high-tech, high-productivity methods.
- **Supply Chain:** Digitalization improving efficiency, though logistical challenges (like shipping capacity) persist.

Challenges & Solutions:

- **Climate Change:** Water scarcity (like in Kenya) and unpredictable weather threaten production, driving investment in water-efficient tech.
- **Post-Harvest Care:** Complex science focuses on improving vase life through better pre-harvest conditions (light, water, nutrition) and post-harvest handling.

Based on the analyzed reports, the economic importance of cut flowers in India is characterized by high-profit potential per unit area, acting as a "sunrise industry" with significant export-oriented growth, despite being a small percentage of the global market. It has evolved from traditional, small-scale farming into a commercial, high-tech, and profitable agro-business, offering employment opportunities, particularly in rural areas and for women.

Key Economic Facts:

- **High Profitability and Returns:** Commercial cut flower production, particularly under protected conditions (polyhouse/greenhouse), offers higher returns per unit area compared to traditional field crops. Studies indicate that net income from crops like gerbera and rose can be significantly higher than conventional agriculture.
- **Export-Oriented Growth:** The government has recognized it as a 100% export-oriented industry, with major exports going to the US, Europe, and the Middle East. Cut flowers and dried flowers represent a significant share of the total floriculture export value.

- **Rapidly Growing Industry:** The sector has seen a rapid increase in the area under cultivation (from 53,000 hectares in 1993-94 to over 2,78,000 hectares by 2016-17) and is growing at a high compound annual growth rate (CAGR), indicating positive, sustainable, and rapid growth.
- **Employment Generation:** The industry provides significant employment, including in labor-intensive activities like nursery management, harvesting, post-harvest handling, and packaging.
- **Key Producing Regions:** Tamil Nadu, Karnataka, Madhya Pradesh, and West Bengal are leading in production, with specific hubs concentrating on high-value flowers like Roses, Gerberas, and Carnations.
- **Challenges and Future Focus:** Despite the high potential, the industry faces constraints due to a lack of cold chain infrastructure, high air freight costs, and, at times, inconsistent quality.

Conclusion:

In India, cut flowers are a crucial and high growth component of the rapidly expanding floriculture industry, acting as a bridge between traditional farming and modern commercial agribusiness. The industry is expected to continue growing due to rising domestic demand (urbanization, weddings, gifting) and expanding international markets, with a focus on improving post-harvest, cold-chain, and quality standards to enhance its share in the global market. As we can say they have transformed from a niche luxury product to a significant economic driver, particularly driven by urbanization, changing lifestyles and international demand.



Smart Sensors & IoT Integration in Post Harvest Technology



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Introduction

Post-harvest losses are one of the biggest global concerns, threatening food security and financial stability. The traditional approaches often do not do justice in terms of conserving perishable produce, resulting in large-scale wastage. In this case, the pairing of Artificial Intelligence (AI) with the Internet of Things (IoT) and using Smart Sensors in transforming post-harvest management. Through real-time monitoring, predictive analysis, and automated action, these technologies provide unprecedented scope for extending shelf life, preventing waste, and improving the general efficiency and sustainability of food supply chains.

Integration of Smart Sensors & IoT in post-harvest management

1. Quality and grading of fruits and vegetables: Quality assessment through traditional methods often rely on human inspectors, which is time consuming and subjective. So, it's reliance on AI-driven techniques ensuring consistency and accuracy are increasing. Convolutional Neural Networks (CNNs) are particularly effective for image recognition tasks, enabling the automated grading of produce based on visual attributes such as size, colour and surface defects. This automation not only enhances the efficiency of grading processes but also produces human errors, ensuring only highest quality products reach consumers. Further, techniques such as image processing combined with Machine Learning (ML) algorithms can identify physical defects such as bruises, blemishes, or inconsistencies in shape and size.

2. Smart sensors for real time monitoring and cold chain logistics and processing: It is a critical component in post harvest management of horticultural crops which ensures that product maintains their quality and safety from the point of harvest to the final consumer. Smart sensors provide accurate and timely data that allow for informed decision making. A Smart sensor is a device that takes input from the physical environment such as temperature, humidity and gas composition and uses built in compute resources to perform predefined functions. Temperature and humidity sensors are deployed within storage facilities and transport containers to continuously monitor environmental conditions. For instance, maintaining a temperature of 0– 4°C for fruits like strawberry can significantly prolong its shelf-life. If the temperature rises above 4°C, automated notifications can prompt corrective actions, such as adjusting cooling systems or redistributing products to maintain optimal conditions. Additionally, the integration of GPS tracking with cold chain monitoring systems enhances visibility and control throughout the transportation process.

Gas composition sensors utilize electrochemical or infrared detection technologies to monitor gases such as oxygen, carbon dioxide and nitrogen in controlled atmosphere storage. Ethylene sensors, often based on metal oxide semiconductor (MOS) technology, detect concentration of ethylene gas emitted by ripening fruits. By integrating these sensors into storage and packing areas, stakeholders can manage ripening schedules more effectively.

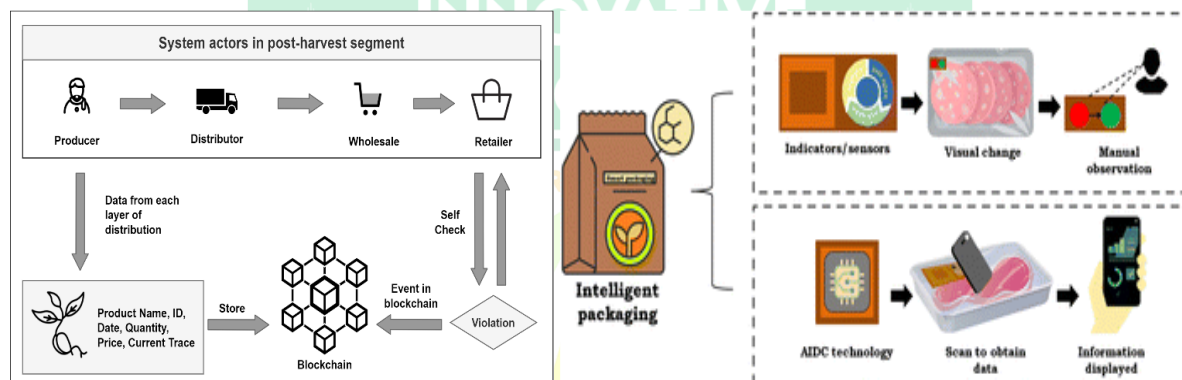
3. Intelligent Packaging Solutions: By incorporating active and smart features, intelligent packaging systems can interact dynamically with their environment, ensuring that the produce remains fresh and safe for consumers. Smart packaging technologies incorporate sensors and indicators that provide real time feedback on the condition of the produce. Furthermore, integrating QR codes or Near Field Communication (NFC) technology allows consumers to access detailed information about the product's journey, including its origin, handling conditions, and freshness history. This level of transparency builds consumer trust and promotes accountability among retailers.

4. Machine Learning for decision making: Machine learning (ML) has emerged as a powerful tool in post harvest decision making, significantly enhancing the management of horticultural crops. ML can optimize storage practices, improve product quality and reduce waste which is particularly relevant in the context of rapidly evolving agricultural markets and increasing consumer demand for high-quality produce.

5. Block chain for traceability and supply chain transparency in fresh and processed products:

Traditional traceability systems often suffer from fragmentation, with data stored in various data bases and formats, making it challenging to track produce effectively. Block chain technology has emerged as a transformative tool for enhancing traceability and transparency in the supply chain, particularly in the post-harvest management of horticultural crops. It facilitates quality assurance by creating a transparent and verifiable record of every transaction and condition encountered during the supply chain. Radio frequency identification technology (RFID) and IoT sensors for tracing the condition of materials during the transportation, and these models are also able to identify the diseases and rotten fruits and bad quality food materials, humidity and temperature during the process of food supply chain and helps correctly identifying the target places. IoT sensors can continuously monitor conditions such as temperature, humidity, and gas levels during storage and transportation.

6. Predictive analytics for shelf-life optimization: It is one of the most effective applications of AI in post harvesting. AI models can predict the shelf-life of produce based on past information regarding crop properties, environmental factors, and patterns of spoilage and using this information make dynamic adjustments in the conditions of the stores, routing of the transport, and timing of market arrival, increasing product freshness and avoiding early spoilage possibilities. For instance, in case of increased risk of fungal growth in specific produce based on relatively higher humidity levels predicted by the AI model, dehumidification processes can be automatically triggered or proactive early distribution advised. This approach immensely lowers losses otherwise faced through unexpected spoilage.



Conclusion

Innovative technology, specifically the synergetic blending of Artificial Intelligence and Internet of Things, has the potential to transform post harvest management. Through offering unmatched capacities real-time monitoring, predictive analysis and automated intervention, they provide an effective weapon against food loss and food waste. Adopting these tools is more than a technological advancement but also amounts to a qualitative change towards greater sustainability and food security for farmers, consumers and the planet as well.

Guarantee for Rozgar & Ajeevika Mission-Grameen (G RAM G)



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The Mahatma Gandhi National Rural Employment Guarantee Act (MGNREGA) enacted in 2005 and that provided 100 days of guaranteed wage employment to adult members of rural households willing to do unskilled manual work is now a history. The Act was a landmark achievement of the then UPA government giving a legal guarantee for right to work. The Mahatma Gandhi National Rural Employment Guarantee Act (MGNREGA) played a key role in providing wage employment, stabilizing rural incomes and creating basic infrastructure and assets in rural settings. Now after about two decades, government replaced it with Viksit Bharat Guarantee for Rozgar and Ajeevika Mission-Grameen (G RAM G). The new programme aligns rural employment with the long-term vision of Viksit Bharat @ 2047, while strengthening accountability, infrastructure outcomes and income security.

Since Independence, a lot of employment initiatives have been started by various governments that aimed at rural development along with creation of employment opportunities. The employment generated through various programmes was of two type self employment as well as wage employment. Self employment opportunities were created through provision of loans to youths for setting up their own business units like loans under Micro Units Development and Refinance Agency (MUDRA). Wage employment programmes primarily focused on providing wage employment to under privileged and poor especially in rural areas. The Jawahar Rozgar Yojana (JRY), Sampoorna Grameen Rozgar Yojana (SGRY) which was later merged with MGNREGA was a wage employment programme. All the programmes focused on reducing poverty, improving agricultural productivity and creating employment for surplus and underemployed rural labour. Over the period of time, wage employment programmes have gradually evolved as key instruments for supporting rural livelihoods while also strengthening basic infrastructure, with approaches adapting to changing socio-economic conditions over time.

The Mahatma Gandhi National Rural Employment Guarantee Act (MGNREGA) was started as a flagship programme aimed at enhancing livelihood security by providing at least 100 days of guaranteed wage employment each year to rural households willing to undertake unskilled manual work. The programme was a unique one in many ways and within a few years, the act achieved many things which many other rural development schemes of the past could not achieve. A range of administrative and technological reforms strengthened its implementation, leading to notable improvements in participation, transparency, and digital governance. What was worth of the act was the women's participation in the scheme. It rose steadily from 48 per cent to 58.15 per cent between FY 2013-14 and FY 2025-26. The use of ICT in this programme in the shape of Direct Benefit Transfer, Aadhaar seeding with Bank accounts of beneficiaries added to the wider coverage of this scheme.

Despite success of this programme, some issues started emerging putting a question mark on the efficiency and implementation of scheme. Research studies done in various states revealed gaps. These gaps related to the no. of works which were not found on the ground, expenditure did not matched physical progress, use of machines in labour-intensive works, and frequent bypassing of digital attendance systems. Besides wages were drawn against the persons who were no more in this world. Things worsened during post pandemic period. As the no. of years passed on misappropriation accumulated and only a small proportion of households were able to complete the full one hundred days of employment in the post pandemic period.

The government on Dec. 16, 2025 introduced the Viksit Bharat Guarantee for Rozgar and Ajeevika Mission Gramin Bill in the Lok Sabha which was passed by both the houses on Dec. 18, 2025. The Bill also got the presidential assent and is now an act that has replaced MGNREGA. The Viksit Bharat G RAM G guarantees 125 days of wage employment per rural household in each financial year to such rural households whose adult members volunteer to undertake unskilled manual work, contributing to income security by increasing the no. of

days of employment in a year by 25. Under the new act, there is a 60 days no work period to ensure the availability of agricultural labour during peak sowing and harvesting season. Workers will receive 125 guaranteed days of employment within the remaining 305 days, ensuring that both farmers and labourers benefit. The disbursement of daily wages shall be made on a weekly basis or, in any case, not later than a fortnight after the date on which such work was done. Under MGNREGA, if a person seeking work is not provided employment within 15 days, the state government must pay them an unemployment allowance. The Bill retains this provision.

Employment generation will be under four broad categories. These four categories are of works are ensuring water security through water-related works like construction of canals, check dams, water harvesting structures, rejuvenation of existing water bodies and afforestation works; works to create core-rural infrastructure like roads, bridges, buildings, health institutions, electricity transmission; works related to livelihood- related infrastructure like storage structures, dairy infrastructure, rural business haats and special works to mitigate extreme weather events like construction of folds/cyclone shelters, embankments and forest fire management etc. Further all assets created will be aggregated into the Viksit Bharat National Rural Infrastructure Stack, ensuring a unified, coordinated national development strategy. Planning under VB G RAM G has been decentralized through Viksit Gram Panchayat Plans, which are to be prepared locally and spatially integrated with national systems such as Prime Minister Gati Shakti.

The new Bill represents a major upgrade over MGNREGA, fixing structural weaknesses while enhancing employment, transparency, planning, and accountability. Under MGNREGA works were scattered and lacked clear focus. On the other hand works under G RAM G have been broadly categorized into four categories. Earlier MGNREGA was a central sector scheme while G RAM G is a centrally sponsored scheme with states also bearing 40 per cent of the budget. In case of Northeastern and Himalayan states the funding pattern is 90:10. However in case of UTs without legislature the central government has to bear all the expenditure. In the new architecture, states share both cost and responsibility through a normative allocation framework creating stronger incentives for effective implementation and preventing misuse. Planning is grounded in regional realities through Gram Panchayat Plans. The Centre will set the standards, while states will execute with accountability, resulting in a cooperative partnership that improves efficiency and strengthens outcomes.

The Act also provides that the central government will determine state-wise normative allocation for each financial year. The parameters for these allocations will be prescribed by the central government under rules. The state government will bear any expenditure incurred in excess of this allocation. MGNREGA had established Councils at the central and state levels to undertake implementation and monitoring. The new act retains these provisions and also provides that their composition will be specified under Rules. It also constitutes a National Level Steering Committee which will provide high-level oversight, and recommend normative allocations. It also has Steering Committee for each state. The state committee will oversee convergence with other programmes, aggregation of district plans into state plans and coordinate with the National Committee.

To conclude, the act will strengthen the rural economy by linking employment generation with productive asset creation, leading to higher household incomes and improved resilience. The guarantee of 125 days of employment will lead to household earnings, stimulate village-level consumption and help reduce distress-driven migration. The support in the form of digital attendance, fixed interval payments and data-driven planning has the potential to steer rural economies to new heights.

The Breath of Life: The Transition from Anaerobic to Aerobic Earth



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Abstract

The transition of Earth's atmosphere from an anaerobic (oxygen-free) to an aerobic (oxygen-rich) state represents the most significant environmental transformation in the planet's 4.5-billion-year history. This article explores the biological and geochemical journey of this shift, focusing on the pivotal role of plant ancestors and modern flora. For the first two billion years, Earth was dominated by anaerobic prokaryotes thriving in a methane-heavy atmosphere. The emergence of oxygenic photosynthesis in cyanobacteria approximately 2.7 billion years ago introduced free oxygen (O_2) into the oceans, eventually saturating mineral "sinks" and leading to the Great Oxidation Event (GOE). While this event caused a massive extinction of anaerobic life, it provided the energetic foundation for the evolution of complex eukaryotes through endosymbiosis, the process by which cyanobacteria became chloroplasts. The subsequent formation of the ozone layer shielded the land from ultraviolet radiation, allowing plants to colonize terrestrial environments. This article details the structural adaptations necessary for this transition, including the evolution of stomata for gas exchange, lignin for structural support, and vascular systems for nutrient transport. Finally, it examines modern adaptations like C4 photosynthesis in response to fluctuating atmospheric CO_2/O_2 ratios. Understanding this deep evolutionary history highlights the fundamental role of plants as the primary architects of the global oxygen cycle and the essential "lungs" of the modern biosphere.

Keywords: Great Oxidation Event (GOE), Cyanobacteria, Endosymbiosis, Anaerobic to Aerobic, Plant Evolution, Stomata, C4 Photosynthesis.

1. Background:

The world known to us today is defined by the air we breathe and the lush green forests that provide us with food and shelter. However, for the majority of Earth's history, the planet would have been unrecognizable and deadly to modern organisms. Roughly 3.5 to 4 billion years ago, during the Hadean and Archean Eons, the atmosphere was a thick, hazy envelope composed primarily of methane (CH_4), carbon dioxide (CO_2), and nitrogen (N_2). There was no protective ozone layer, meaning the surface was bombarded by lethal levels of ultraviolet radiation. The sky likely appeared a dusty orange or hazy pink, and the oceans were deep green, tinted by massive amounts of dissolved "ferrous" iron.

In this "anoxic" (oxygen-free) world, life was restricted to simple, single-celled organisms known as anaerobes. These bacteria and archaea did not need oxygen; in fact, for many, oxygen was a lethal poison that would tear their delicate cellular structures apart. These organisms were masters of chemical survival, obtaining energy through fermentation or by "breathing" minerals like iron, sulfur, or nitrates in the deep ocean vents and sediment layers. This anaerobic way of life was the only way to exist for over a billion years. The transformation of this alien, breathless world into our oxygen-rich environment was a slow-motion revolution driven by the evolution of plants and their ancient ancestors (Martin & Sousa, 2015).

2. The Great Oxidation Event: Life's First Major Shift

The turning point in Earth's history occurred with the evolution of cyanobacteria. These microscopic pioneers developed a process called oxygenic photosynthesis. While earlier bacteria used light to get energy from hydrogen sulfide releasing sulfur as waste cyanobacteria "invented" a way to split water (H_2O) molecules. This gave them an unlimited supply of electrons but produced oxygen (O_2) as a waste product (Fischer et al., 2016).

Initially, the Earth's chemistry resisted this change. For hundreds of millions of years, the oxygen produced by cyanobacteria was immediately sucked up by "sinks." The most significant sink was the ocean itself, which

contained vast amounts of dissolved iron. When oxygen met this iron, it formed iron oxides—essentially rust—which precipitated and sank to the seafloor. These deposits created the **Banded Iron Formations (BIFs)**, which today provide the iron ore used in global steel production.

By approximately 2.4 billion years ago, these natural sinks became saturated. Oxygen began to leak out of the oceans and accumulate in the atmosphere. This period, known as the **Great Oxidation Event (GOE)**, was Earth's first true environmental crisis. For the dominant anaerobic life forms of the time, the rising oxygen levels were a "Great Poisoning," leading to a massive extinction. However, for the survivors, oxygen was a biological "superfuel." Aerobic respiration allows cells to produce up to 38 molecules of ATP (energy) from a single sugar molecule, compared to just 2 molecules in anaerobic systems (Müller et al., 2012). This massive energy surplus allowed life to dream bigger—to become larger, move faster, and eventually become multicellular.

3. Creating the First Plant:

The transition to an aerobic world was not just about the atmosphere; it was about the architecture of the cell itself. Modern plants exist because of a unique biological partnership called **endosymbiosis**. About 1.5 billion years ago, a larger, complex cell (a eukaryote) engulfed a photosynthetic cyanobacterium. Instead of digesting the bacterium, the two formed a permanent bond.

The cyanobacterium eventually evolved into the **chloroplast**, giving the host cell the ability to manufacture its own food from sunlight (Müller et al., 2012). This "merger" was a massive evolutionary shortcut. Instead of waiting millions of years to evolve the complex machinery of photosynthesis, the ancestors of plants simply "hired" an expert. A similar process happened with **mitochondria**, the organelles that allow cells to use oxygen for energy. With both mitochondria and chloroplasts, these early plant cells had the "batteries" and the "solar panels" needed to dominate the planet. This gave rise to the first green algae, the aquatic ancestors of all land plants (Schirrmeyer et al., 2013).

4. Conquering the Land: The Ozone Shield and Structural Inventions

For a long time, even after oxygen levels rose, life stayed in the water. The sun's ultraviolet (UV) radiation was so strong that it would destroy the DNA of any organism on land. However, as oxygen levels in the upper atmosphere increased, the molecules reacted with sunlight to form the **ozone layer (O₃)**. This acted as a planetary umbrella, blocking harmful radiation and making the continents habitable for the first time about 470 million years ago (MacIver & Finlay, 2021).

As plants moved from water to land, they faced a gravity problem and a dehydration problem. In the ocean, water supports the plant's weight and provides constant moisture. On land, a plant would simply collapse and dry out. To survive, plants evolved three groundbreaking structures:

- **Stomata:** These are microscopic "valves" on the surface of leaves. They open to let in CO₂ for photosynthesis and close to keep water from evaporating. They are the "nostrils" of the plant world (Hetherington & Woodward, 2003).
- **Lignin and Cellulose:** Plants began producing tough, woody materials to reinforce their cell walls. **Lignin** provided the strength needed to grow tall against the pull of gravity, allowing the first forests to reach for the sky (Choi et al., 2023).
- **Vascular Tissue:** Plants developed a complex "plumbing" system. **Xylem** acts like a straw, pulling water from the roots up to the leaves using the power of evaporation, while **Phloem** carries the sugary energy made in the leaves down to the roots (Niklas, 1997).

5. Advanced Evolution: The C4 Pumping System

Evolution did not stop once the land was green. About 30 million years ago, Earth's atmosphere changed again, and CO₂ levels dropped significantly while O₂ remained high. Plants faced a new challenge: an enzyme called **RuBisCO**, which is responsible for capturing CO₂, often gets "confused" and grabs O₂ instead. This mistake, called photorespiration, wastes a massive amount of the plant's energy and water.

In response, a new group of plants evolved **C4 photosynthesis**. These plants (like corn, sugarcane, and many grasses) developed a specialized internal anatomy that acts like a carbon dioxide pump. They concentrate CO₂ in a specific part of the leaf (the bundle sheath cells), making their photosynthesis much more efficient in hot, dry, and high-oxygen environments (Gowik & Westhoff, 2010). This allowed grasslands to expand across

the globe, fundamentally changing the diet of many animals, including early human ancestors who relied on these grasslands for hunting and foraging (Samal & Martin, 2013).

6. Conclusion:

The transition from an anaerobic to an aerobic world is more than just ancient history; it is a process that continues every second. Today, the relationship between plants and the atmosphere is a perfect, reciprocal cycle. Plants act as the planet's "lungs," taking in the carbon dioxide we produce and returning the oxygen we need to fuel our high-energy lives.

This balance, which began with tiny bacteria billions of years ago, is what keeps our planet alive and habitable. However, as human activity rapidly increases CO₂ levels and destroys forest ecosystems, we are testing the limits of this ancient system. Understanding the history of the Great Oxidation Event and the resilience of plant adaptation reminds us that the air we breathe is a precious legacy, a gift from the billions of plants that have been shaping our world for eons.

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An Essay on Early Issues in INDIAN Environmentalism: Land, Forest and Water



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If we look back and turn the pages of history, we will find that there has always been a conflict in our human civilization and the conflict is mainly based on the resources that we have in our nature. Even if we look at the primitive era when man just learnt to discover fire and made tools, they started a hit just for partitioning of the resources among themselves, some even invaded the other's community just to have control over their resources.

If we see in our INDIAN context, there are numerous examples where we find that the conflict was prevalent between the dominating and the dominated groups. There has always been division and discrimination in society in terms of power, wealth and property, caste, etc.

The conflict over the resources is also a result of the Economic dimensions. People who are economically weak are always the sufferers who generally belong to 'ecosystem people'. Mainly for the weaker sections it is very hard to avail ourselves of the resources which they need while the wealthy section can have very easy access to the resources. It is very regretful for us that there always exist a gap between the Economically weaker and the wealthy section where the former is the sufferer while the latter is the capitalist. However, if we see, the capitalists are always smaller in number dominating over a larger section of people through their money power in every aspect.

Now, if we look deeper into the past we will find several examples of issues on environmentalism. One of the majors was the Amrita Devi Bishnoi Movement which took place around early 1700s in the Khejrali, Marwar region of Rajputana Agency. The movement was basically to prevent cutting down of trees by the men ordered by the Maharaja of Jodhpur. In this movement we find that it was mainly led by the Village Women who protect the trees without caring for their lives. It was just a Non-violent movement. Since then, our ancestors were aware of the importance of the forests and their role in their livelihood. Importance of the Forests in protecting the land and improving the water quality, providing the basic livelihood like fruits, fuel wood, fallen leaves, etc. It might appear that these are very simple and common, but the importance of forests is as pure as the nectar to them. Forests also have got cultural values in the life of several communities. Like the sacred groves which mainly serve as the places for worship for the tribal people and these places have further been taken up for conservation by the forest authorities.

Sometimes there are some sensitive zones in some places where tribal communities residing in a particular place become sensitive to their thoughts and become prey to political ideologies. Just like the Santhal dominated region has often been brainwashed by the communist inclined people that their land will be encroached if the Government brings some project. This agitates the innocent tribal people who in turn oppose the developmental activities which would have been a boon to them. However, there are solutions to these sensitive problems like the Government can outreach these people and do extension activities where they would be made understood that this forest, this land, these water bodies belong to You people only and none. Also, the products generated from the forests will be of Yours share. Government agencies can create several bodies for tribal welfare. Just like we have seen the formation of Joint Forest Management Committee (JFMC) in the State of Bengal in the early 1980s by a DFO Dr. Ajit Kumar Bannerjee. Then there is enactment of Forest Rights Act (FRA), 2006.

Similarly, we find the example of the Chipko Movement that took place in Tehri Garhwal in the State of Uttarakhand in the Year 1974. There also we find the scenario same as that of the Amrita Devi Bishnoi Movement, where Women who are Mountain village dwellers defended the trees from being cut by a sport goods company. Here is the second example where we find how much the Mountainous people are dependent on the Forests, land and the Natural resources of the Forests. Their movement took a valiant form under the leadership of

environmentalists named Sundar Lal Bahuguna and Chandi Prasad Bhatt. However, their movement was too a non-violent one which was a Gandhian form of protest and after a severe struggle at the end they came up with success. Other movements that were significant include the Jungle Bachao Andolan, which took place in the Singhbhum district of Bihar but now in Jharkhand where the tribal leaders joined to protest the cutting of natural Sal Forest and replacing it with commercial teak forests. Here we see that the protest is against changing the whole natural vegetation of the region.

There are several facts based on which protests and movements are being conducted. It might be the dependency and need of the forest dwellers on the forest, not to disturb the original natural vegetation of a region which has got a significant value over the biodiversity of the region, or the protest might be based on the cultural values which the community has got related to the forest, etc. Even there are similar examples regarding uprooting the natural vegetation like in The Andaman and Nicobar Islands, where Andaman Padauk or *Pterocarpus dalbergioides* is a native species was initially removed and replaced with teak but after the Forest department in the region understood its significance they stopped removing the native species. It is because the site quality and species selection play a major role in this process and here Nature is the best Silviculturist who has got the proper knowledge regarding the species choice means where to establish which species.

One of the most important parts of this topic is political biasness. Suppose a movement takes place anywhere and the people there whose prior importance is their needs, and when being supported by a political organization who is in the opposition, the ruling party marks the movement as if it has been provoked by the opposition. This happens in every case whenever a movement is initiated. And in most cases the political party gets benefited while the claim of the innocent rural people remains unsolved, and they continue to suffer. Hence, for a movement whether it might be social, environmental, whatever might be there is a need to have leadership which is totally apolitical. We have seen the Farmers protest 3 years back which was ultimately marked as a political movement since the Farmer leaders were also politically biased.

Hence, the issues of Environmentalism are really of great concern, and we must have a proper strategy to counter these issues. If we can solve the environmental issues in a successful manner, we can solve our social issues too and for that correct leadership is needed which is free from any political biasness and can lead the movement in a successful manner.

Engineering NLR Receptors: Custom Plant Defenses Against Evolving Pathogens



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Abstract

Plants face relentless attacks from pathogens that evolve quickly, threatening food supplies worldwide. Nucleotide-binding leucine-rich repeat (NLR) receptors serve as key sentinels, detecting invader molecules called effectors to trigger strong defenses. Recent breakthroughs in engineering these NLRs by swapping binding parts or mimicking host targets create tailored shields that recognize broad pathogen families, promising durable crop protection. This article explores how scientists redesign NLRs like rice's Pik-1 to counter fungal blasts, using tools like CRISPR for real-world farming gains. Advances show engineered NLRs resist evasion through robust interfaces, offering hope for resilient agriculture amid climate pressure.

Keywords: NLR receptors, plant immunity, effector recognition, bioengineering, crop resistance

Introduction

Imagine crops standing firm against invisible armies of fungi and bacteria that mutate faster than nature can keep up. Each year, plant diseases destroy enough food to feed billions, costing billions more in losses. Enter NLR receptors: proteins inside plant cells that act like burglar alarms, spotting pathogen "keys" (effectors) meant to sabotage defenses. When triggered, NLRs spark explosive responses cell death, chemical barrages that halt invasions. Traditional NLRs shine in labs but falter in fields as pathogens dodge detection via tiny mutations. Enter engineering: scientists now customize NLRs, borrowing from host proteins pathogens target or redesigning interfaces for stickier grips. Rice's Pik-1 NLR, which battles rice blast fungus (*Magnaporthe oryzae*), exemplifies this. By grafting a host mimic like OsHIPP43 onto Pik-1, researchers flipped its target from one effector to a whole family, including Pwl2 variants that plague cereals. Crystal structures reveal why: vast contact surfaces resist single tweaks, unlike fragile natural matches. This revolution builds on structure-guided tweaks, CRISPR precision, and helper NLR pairs for signaling. From lab assays showing cell death in model plants to potential field trials, engineered NLRs promise broad, lasting resistance. As climate shifts favor pathogens, these custom defenses could safeguard staples like rice and wheat Gu *et al.*, 2025.

NLR Basics: Nature's Immune Sensors

NLRs dominate plant intracellular immunity, named for nucleotide-binding (NB) and leucine-rich repeat (LRR) domains that sense and bind effectors. They split into CC-NLRs (coiled-coil starters) and TNLs (TIR-domain terminators), often pairing as sensor-helper duos. Pik-1 (sensor) teams with Pik-2 (helper) in rice; RGA5 with RGA4 against blasts. Pathogens inject effectors via haustoria or hyphae to suppress frontline guards (PRRs). NLRs counter by direct binding or "guardee" surveillance effectors tweaking host proteins flags danger. *Magnaporthe oryzae*'s MAX effectors, like AVR-Pik or Pwl2, fold similarly yet vary to slip past. Pwl2 blocks weeping lovegrass infection but fails on rice; engineering exploits this mismatch. Integrated domains (IDs) in NLRs like heavy metal-associated (HMA) motifs evolved from host targets, directly grabbing effectors. Pik-1's HMA binds AVR-Pik; swapping creates new locks. Yeast screens and co-IPs confirm tight bonds, nanomolar affinities via ITC. Robustness stems from multi-site grips: mutate one, others hold Zdrzałek *et al.*, 2024.

Engineering Feats: Swapping Domains for New Targets

Bioengineers treat NLRs like Lego: excise IDs, insert alternatives. In a landmark, Pikm-1's HMA swapped for OsHIPP43 Pwl2's rice target yielding Pikm-1^ΔOsHIPP43. Co-expressed with Pikp-2 in *Nicotiana benthamiana*, it ignores AVR-PikD but blasts cells on Pwl2, Pwl2-2/3, even distant Pwl1/4. Co-IPs prove direct ties; no response

sans helper. Why broad? Pwl family shares 42-79% identity; all bind OsHIPP43 tightly. Crystal structure (1.8Å) unveils Pwl2's MAX fold plus C-terminal helix looping over HMA's helices and sheets. Interfaces span 1,977Å² double AVR-PikD's via H-bonds, π -stacks, hydrophobic nests. Mutants like Pwl2^ΔSNW (triple) or ^ΔDEY retain ~350nM affinity; only septuple ^ΔSNDEYWY evades, barely stable. Similar wins: RGA5 HMA resurfaced for AVR-Pib; nanobodies fused for custom ligands. CRISPR edits endogenous NLRs, dodging autoimmunity via allele mismatches. Helpers amplify: NRCs boost CC-NLRs. Field potential? Transgenic rice with Pik variants curbs blasts; OsHIPP43 chimeras next Li *et al.*, 2025.

Challenges Overcome: Durability and Evasion Resistance

Pathogens evolve fast AVR-Pik variants dodge via surface tweaks. Engineered NLRs counter with "trap" IDs mimicking essential hosts; mutate effector, lose virulence. Pwl2's interface shrugs singles: seven dispersed swaps still trigger death. Quadruples weaken; septuples disrupt fully, but cripple folding. Auto activity plagues chimeras Pikm-1^ΔOsHIPP43 self-kills sans Pikp-2 mismatch. Expression tuning, C-terminal tweaks stabilize. Broad-spectrum? PWLs stud *M. oryzae* genomes, even wheat blast strains threatening breadbaskets. Combine with PRRs for layers. Protease engineering adds flair: cleavable "codes" activate NLRs on pathogen cues. AI predicts interfaces; AlphaFold guides swaps. Trees like poplar gain via RLP fusions. Risks? Stacking NLRs boosts but invites breakthroughs; diversity via alleles key Yang *et al.*, 2025.

Real-World Impact: Bridging Labs to Farmlands

Engineered NLR receptors stand on the cusp of transforming agriculture, moving swiftly from controlled experiments to open fields where they promise to shield vital crops against devastating diseases. In regions like Asia, where rice blast caused by *Magnaporthe oryzae* ravages yields annually, Pik gene variants have already demonstrated robust field performance, curbing outbreaks that traditional breeding struggles to contain. Similarly, innovative PWL effector traps designed to ensnare a wide array of pathogen variants hold potential against global blast strains, including those infiltrating wheat belts and threatening food security far beyond rice Gu *et al.*, 2025.

Wheat offers a striking example of this progress with the dual-function NLRs Yr87 and Lr85, which simultaneously thwart stripe rust and leaf rust pathogens that together wipe out millions of tons yearly. Such rare versatility sidesteps the narrow specificity that dooms single-gene resistances. As climate change intensifies, warmer nights and erratic rains supercharge pathogen lifecycles, amplifying disease pressure by up to 20-30% in vulnerable tropics. Resilient crops engineered with these NLRs could slash fungicide applications by 30-50%, easing environmental strain from chemical runoff and cutting farmer costs significantly Li *et al.*, 2025.

Economically, the shift to precision editing accelerates timelines dramatically bypassing decades-long backcrossing for months of targeted tweaks via CRISPR-Cas9. In India, the world's largest rice producer, initiatives tied to Prime Minister's Research Fellowships are fast-tracking trials of NLR-enhanced varieties in states like Punjab and Odisha. Leading biotech companies now integrate stacked NLR cassettes into elite breeding lines, amplifying resistance without yield drag. For consumers, this translates to abundant, pesticide-light staples at stable prices, bolstering food sovereignty amid rising global demands Zdrzałek *et al.*, 2024.

Future Prospects: Next-Generation Innovations

Looking ahead, scientists envision "universal" NLRs armed with protease-cleavable motifs that activate only on pathogen cues, minimizing fitness costs while maximizing responsiveness. Artificial intelligence accelerates this by modeling effector-NLR clashes with unprecedented accuracy, predicting stable chimeras before wet-lab validation. Complementing these advances, pairings with beneficial microbiomes unlock integrated disease management (IDM) strategies synergizing molecular shields with microbial allies to suppress soilborne threats holistically, a perfect fit for ongoing rice pathology research Gu *et al.*, 2025.

Hurdles and Horizons: Navigating Challenges Forward

Off-target effects, a perennial worry in gene editing, find strong countermeasures in high-resolution structures that guide precise domain swaps, ensuring edits stay laser-focused. Regulatory landscapes brighten too, with streamlined approvals for SDN-1 CRISPR edits in jurisdictions like the US and India, classifying them as non-GMO equivalents. Equity remains paramount: open-source NLR toolkits empower smallholder farmers in the Global South, democratizing access to elite traits without corporate gatekeeping. The horizon sparkles with expanded frontiers NLRs like Sw-5b tackling viral foes, novel constructs battling bacteria, and multi-pathogen

pyramids stacking defenses for ironclad durability. For specialists probing rice fungicide resistance, metabolomics emerges as a powerhouse, pinpointing NLR regulatory networks to forge holistic solutions. Ultimately, these custom NLRs signal a biotech renaissance: plants evolving faster than pathogens, locking in bountiful harvests for generations ahead Yang *et al.*, 2025.

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Turning Sunlight Into Profit: Modernizing Poultry Farming Through Solar Energy



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Abstract

The Indian poultry industry has a growing need for energy due to the adoption of controlled housing, automated feeders, and climate control. Increasing electricity costs, the erratic supply of electricity in rural parts of the country, as well as increasing climate change, have emerged as significant challenges for poultry production. Against this background, solar energy has emerged as a feasible and innovative alternative for a technological transformation in poultry production. This paper focuses on the application of solar photovoltaic (PV) energy for the revolutionization of poultry farming through the provision of a constant power supply for the purpose of ventilation, cooling, lighting, water management, and automation. The application of solar energy for poultry farming provides a cost-effective solution and lowers the reliance on main power and diesel generators. This increases the health of the poultry through better thermal comfort, thereby increasing their growth rate, rate of feed intake, and survival rate. However, solar energy provides an automation feature that assists the farmer. Beyond economic gains, solar-integrated poultry farming contributes to climate-smart agriculture by lowering carbon emissions and strengthening the resilience of farms to heat waves, power outages, and fuel price volatility. The article also highlights the importance of extension support, policy convergence, and innovation ecosystems in accelerating adoption, particularly among young farmers and agri-entrepreneurs. As solar-powered poultry farming is presented as a scalable, forward-looking pathway for achieving sustainable, climate-resilient, and profitable poultry production.

Keywords: Solar power, Poultry, Energy, Innovative, Climate-smart, Profitable

Introduction

Poultry farming in India is experiencing a major shift. What was once mostly a backyard or small-scale activity has grown into a modern, commercial enterprise supported by advanced technologies. Today's poultry farms depend heavily on a constant supply of electricity to run ventilation systems, cooling equipment, lighting programs, automated feeders, and water management systems. These improvements have helped farmers achieve better productivity and efficiency. At the same time, however, they have increased day-to-day operating costs and made farms more sensitive to power interruptions. Rising electricity prices, frequent power cuts in rural and semi-urban regions, and growing climate stress, especially intense heat waves, are now having a direct impact on farm performance and profitability. Taken together, these issues underline the need for practical innovation in poultry farming, particularly in how energy requirements are addressed to support long-term sustainability and resilience (FAO, 2022; NABARD, 2021).

Poultry Farming at a Turning Point

Poultry farming today depends heavily on energy, making a steady and reliable power supply crucial for farm success. Modern poultry units require continuous electricity to keep ventilation fans, cooling systems, and temperature controls running, especially during hot and humid weather. When power failures occur, ventilation stops, sheds quickly heat up, and birds suffer from heat stress. This often leads to reduced feed intake, slower growth, increased disease risk, and higher mortality. During the summer months, such losses can multiply rapidly, causing serious financial strain for farmers (FAO, 2020; ICAR, 2021). At the same time, poultry farmers are becoming increasingly vulnerable due to their dependence on grid electricity and diesel generators. Rising electricity tariffs, unpredictable fuel prices, and frequent interruptions in power supply create daily operational

challenges. Although diesel generators provide short-term backup, they increase running costs and contribute to air pollution and noise. Together, these issues have added uncertainty to poultry farming, affecting both day-to-day management and long-term profitability. This growing pressure clearly shows that traditional energy sources alone can no longer meet the changing demands of modern poultry production, highlighting the need for more reliable, affordable, and sustainable energy solutions (NABARD, 2021).

Solar Energy as a Game-Changing Farm Innovation

Solar energy is more than just an alternative to grid electricity, it represents a fundamental shift in the way poultry farms manage their energy needs. By installing solar photovoltaic (PV) systems, farmers can produce their own electricity right on the farm, reducing dependence on unstable grid supply and fossil fuels. It change towards on-farm power generation gives farmers greater control over their operations, improves energy security, and protects farms from disruptions caused by power cuts and voltage fluctuations (MNRE, 2023). Solar energy fits naturally within the goals of sustainable and climate-resilient agriculture. By replacing electricity generated from fossil fuels and reducing the use of diesel generators, solar-powered poultry farms help lower carbon emissions and environmental pollution. At the same time, cleaner and more reliable energy strengthens the long-term resilience of poultry operations, allowing farmers to adapt more effectively to climate stress and energy uncertainties (IPCC, 2022).

Smart Energy for Smart Poultry Houses

Modern poultry houses function as carefully controlled spaces where managing temperature, airflow, and lighting is critical for bird health and performance. Solar-powered systems can run ventilation fans, cooling pads, lighting programs, automatic feeders, and monitoring devices smoothly and without interruption. With a steady power supply, farmers are able to maintain comfortable conditions inside the shed throughout the day, even when the grid power fails. This consistency creates a less stressful environment for birds, helping them eat better, grow uniformly, and produce eggs more efficiently. When birds experience stable conditions, feed is used more effectively and overall flock performance improves. In this way, reliable solar energy becomes the backbone of smart poultry houses, supporting precision-based management practices and more efficient, modern farm operations (ICAR, 2021; FAO, 2022).

From Energy Cost to Economic Opportunity

For many poultry farmers, electricity and diesel have long been unavoidable day-to-day expenses that steadily eat into profits. Solar energy changes this situation by turning what was once a recurring cost into a long-term investment. After a solar system is installed, monthly electricity bills drop sharply, and the need for diesel generators is greatly reduced, leading to savings on fuel and maintenance. Medium and large poultry farms, which use more electricity on a daily basis, often recover their investment faster because the cost savings are higher. Over time, solar energy allows farmers to convert free sunlight into a stable and reliable source of savings, strengthening income security and improving overall profitability. By reducing dependence on purchased power and protecting farms from future increases in electricity and fuel prices, solar energy offers poultry farmers greater financial confidence and long-term stability (NABARD, 2021; MNRE, 2023).

Enhancing Bird Welfare Through Clean Energy

Bird comfort plays a major role in determining both productivity and farm income. When ventilation and cooling systems run reliably on solar energy, poultry sheds remain cooler and more comfortable, even during periods of extreme heat. Stable temperatures help birds eat well, grow steadily, lay eggs consistently, and survive better, reducing losses that often occur during hot weather. Healthier birds that experience less stress also make better use of feed and other inputs, which means fewer resources are needed to produce the same output. In this way, reliable and clean energy does more than keep systems running—it supports better bird welfare, improves production efficiency, and lowers the overall environmental impact of poultry farming. By ensuring uninterrupted power through solar energy, farmers can achieve gains in animal health, farm performance, and sustainability at the same time (FAO, 2020; ICAR, 2021).

Building Climate-Resilient Poultry Systems

Climate change is making poultry farming more challenging than ever. Heat waves are becoming more frequent, power supply is increasingly unreliable, and fuel prices continue to fluctuate. For energy-dependent poultry farms,

these pressures are felt most strongly during the summer months, when uninterrupted electricity is critical to keep ventilation and cooling systems running. Solar energy helps farms cope with these challenges by providing a dependable, on-site source of power that continues to operate even during grid failures or peak demand periods. With reliable energy available at the farm level, poultry farmers can maintain essential operations, protect bird health, and reduce the risk of production losses during climate-related stress situations (FAO, 2020; NABARD, 2021). At the same time, shifting from fossil-fuel-based electricity and diesel generators to solar power contributes to broader climate action. Solar-powered poultry farms generate fewer greenhouse gas emissions and reduce local air pollution associated with conventional energy sources. By incorporating renewable energy into daily farm operations, poultry farming moves closer to climate-smart and environmentally responsible practices, supporting both adaptation to climate change and long-term mitigation efforts (IPCC, 2022).

Solar Energy and Automation

The future of poultry farming is steadily moving toward automation, precision-based management, and the use of data to guide everyday decisions. Modern poultry houses are increasingly equipped with sensors and control systems that continuously track temperature, humidity, airflow, lighting, and feed distribution. For these technologies to work effectively, a reliable power supply is essential. Solar energy provides that stability, ensuring automated systems continue to function smoothly even in areas where grid electricity is weak or unreliable (ICAR, 2021). With dependable solar power, farmers can run automated feeders, climate controllers, and monitoring devices without worrying about sudden power cuts. This reduces the need for constant manual intervention, lowers the risk of human error, and allows more accurate use of resources. Feed, water, and energy are managed more efficiently, leading to better productivity and less waste. Together, these improvements reflect the essence of next-generation, innovative agriculture, where farms are not only more efficient but also more resilient and environmentally sustainable (FAO, 2022).

Role of Extension and Innovation Ecosystems

Even though solar-powered poultry systems offer clear technical and economic benefits, their wider adoption largely depends on strong extension support and a supportive innovation ecosystem. Many farmers need clear guidance and hands-on training to understand aspects such as system size, installation, day-to-day operation, and basic maintenance. Practical learning through demonstration farms and pilot projects allows farmers to see the benefits in real farm conditions, helping reduce doubts and the perceived risks of adopting new technologies (FAO, 2020). Digital advisory services, mobile-based extension tools, and exposure visits can further strengthen the flow of information and build farmer confidence. When renewable energy solutions are linked with existing livestock development programs, climate-resilience initiatives, and innovation-driven schemes, adoption can happen more quickly and on a larger scale. Close coordination between agricultural, livestock, and renewable energy institutions is especially important to ensure that farmers receive timely technical guidance and easy access to credit and subsidies, making solar-powered poultry farming a practical option rather than a distant idea (MNRE, 2023; NABARD, 2021).

Pathway for Young Farmers and Agri-Entrepreneurs

Solar-integrated poultry farming creates promising opportunities for young farmers and agri-entrepreneurs who are looking for business models that are both sustainable and future ready. With more reliable energy, predictable power costs, and less dependence on external electricity supply, solar-powered poultry farms offer greater financial stability and lower operational risk. At the same time, adopting clean energy supports sustainability goals and strengthens green branding, which can improve market acceptance, especially within organized value chains and among environmentally aware consumers (FAO, 2022). For agri-entrepreneurs, solar-powered poultry systems open the door to innovation-led enterprises such as integrated production units, contract farming arrangements, and energy-efficient poultry clusters. These models encourage efficiency, scalability, and long-term growth. Importantly, they also align closely with current policy priorities focused on renewable energy, climate action, and sustainable livelihoods, making solar-integrated poultry farming an attractive option for investment, startup development, and institutional support.

Conclusion

Solar energy is changing the way poultry farming works by turning electricity from a constant expense into a valuable asset owned by the farm itself. By cutting energy costs, ensuring better living conditions for birds, supporting automation, and protecting farms from climate and power-related disruptions, solar-powered poultry farming offers a practical and future-ready solution. As agriculture steadily moves toward smarter, cleaner, and more sustainable practices, turning sunlight into profit is no longer just an idea, it has become a realistic and scalable path for modern poultry farmers.

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Transforming Poultry Byproducts into Agricultural Resources



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Abstract

In recent decades, poultry production has expanded rapidly to fulfill worldwide needs for meat and eggs. This increase, however, has resulted in large quantities of waste, presenting considerable management difficulties. Rather than seeing poultry waste only as a disposal issue, modern farmers and scientists are increasingly recognizing its value as a useful resource for farming. Processed poultry litter and manure—often termed "liquid gold"—enrich soil by supplying key nutrients, enhancing soil texture, and improving water-holding capacity. Furthermore, methods such as anaerobic digestion and biodiesel production are turning waste materials into renewable energy, offering extra revenue and lowering greenhouse gas outputs. These approaches help divert substantial waste from landfills and can create jobs in rural areas through processing, feed production, and fertilizer manufacturing. By converting feathers, manure, and other byproducts into feed supplements, compost, and energy, the poultry sector demonstrates the principles of a circular economy—turning waste into valuable assets, supporting soil and animal health, and promoting sustainable food systems.

Keywords: Poultry, Composting, Microorganisms, Waste Management, Sustainable Agriculture

Introduction

The Challenge of Poultry Waste: Poultry farming generates significant amounts of manure, litter (a mix of bedding and manure), feathers, and hatchery residues. For example, a single broiler farm can produce several tons of litter annually. Poorly handled waste leads to various environmental issues:

- **Water Pollution:** Runoff can introduce nitrates, phosphates, and harmful microorganisms into water sources.
- **Air Quality Issues:** Ammonia released from poultry facilities contributes to air pollution and respiratory concerns.
- **Soil Problems:** Excessive application of untreated manure may cause nutrient unevenness and increased soil salt content.

Turning Waste into a Resource: Innovative methods are redefining poultry waste as an agricultural asset rather than a burden. Key approaches include:

1. **Poultry Manure as Fertilizer:** Poultry manure contains important plant nutrients—nitrogen, phosphorus, potassium—along with trace elements and organic material. When appropriately composted or treated, it serves as an effective organic fertilizer that boosts soil quality and decreases dependency on chemical fertilizers.

Advantages:

- Enhances soil fertility by adding organic matter, which improves structure, moisture retention, and nutrient access.
- Lowers farming costs and reduces environmental effects linked to synthetic fertilizer production.
- Nutrients are released slowly, providing lasting nourishment for crops.
- Has been shown to increase crop yields across different farming systems.

2. **Composting for Safe and Efficient Use:** Composting is a managed biological process that converts raw poultry waste into a stable, humus-rich product. Proper composting lowers pathogen levels, removes odors, and makes nutrients more accessible to plants.

Common Composting Techniques:

- **Windrow Composting:** Waste is arranged in long piles and turned periodically to aerate.
- **In-Vessel Composting:** Waste is placed in a controlled chamber to regulate temperature, moisture, and air flow.
- **Vermicomposting:** Earthworms digest the waste, producing nutrient-dense castings.

3. Anaerobic Digestion: Producing Energy and Fertilizer: Anaerobic digestion uses microorganisms to decompose organic matter without oxygen, generating biogas—a renewable fuel for heat, power, or transportation. The remaining digestate is a nutrient-rich fertilizer (Prabakarana & Ezhil Valavan, 2021).

Benefits of Anaerobic Digestion:

- Creates renewable energy, reducing reliance on fossil fuels and greenhouse gas emissions.
- Preserves nutrients from the waste, yielding a valuable fertilizer.
- Greatly lessens unpleasant odors.
- Reduces pathogens present in the waste.

4. Insect Farming: Converting Waste into Feed: A growing industry uses insects like black soldier fly larvae to process organic waste. These larvae consume poultry waste rapidly, converting it into insect biomass that can be used as protein- and fat-rich animal feed.

Advantages of Insect Farming:

- Decreases waste volume while creating useful products.
- Provides a sustainable alternative to conventional protein sources like soybean meal in feed.
- Concentrates nutrients from the waste for further use.

Challenges and Future Prospects: Although poultry waste holds great promise for agriculture, some obstacles remain:

- **Transport Expenses:** Moving large volumes of waste can be costly, often restricting use to local farms.
- **Nutrient Concerns:** High phosphorus content may cause environmental issues if not managed properly.
- **Pathogen Risks:** Untreated waste can harbor organisms harmful to health.
- **Regulatory Variability:** Rules for using poultry waste as fertilizer differ by region, creating uncertainty.

Despite these challenges, opportunities are extensive. Ongoing research, technology advances, and supportive policies can help transform poultry waste from an environmental concern into a resource for sustainable farming (Wang *et al.*, 2023).

Conclusion

As agriculture shifts toward circular and sustainable models, poultry waste is set to become increasingly important. By adopting innovative technologies and sound management practices, farmers can change this waste stream into an economic opportunity—improving soil quality, lessening environmental harm, and strengthening food security. The ability to find value in materials once considered waste may well shape the future of agriculture.

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Biotic Stresses in Maize



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Defining Biotic Stresses

Biotic stresses encompass interactions between maize (*Zea mays* L.) and living organisms such as fungi, bacteria, viruses, nematodes, insects, and weeds, leading to metabolic disruptions, reduced photosynthesis, and yield declines. Unlike abiotic stresses, which involve non-living environmental factors, biotic agents trigger specific defense responses in plants, including signal transduction pathways and reactive oxygen species production. Globally, these stresses account for approximately 10% of annual maize yield losses, exacerbating food security challenges amid projected 70% increased demand by 2050.

Understanding Biotic Stress Mechanisms

Biotic stresses arise from living agents—fungi, bacteria, viruses, nematodes, insects, and weeds—that exploit maize's nutritional resources, eliciting defense responses such as hypersensitive reactions, pathogenesis-related protein synthesis, and systemic acquired resistance via salicylic acid or jasmonic acid pathways. Unlike abiotic stressors (e.g., drought or salinity), biotic factors propagate actively, evolving rapidly under climatic pressures like elevated temperatures and humidity, which favor pathogen sporulation and insect migration. In maize, initial invasion often occurs at vegetative stages through wounds or natural openings, leading to vascular occlusion, toxin production, and mycotoxin accumulation that compromise kernel quality and human/animal health. Plants counter these invasions via constitutive barriers (e.g., thick cuticles, silica deposition) and inducible responses, including reactive oxygen species bursts and volatile organic compound emissions to attract natural enemies. However, pathogen effectors and insect elicitors often suppress these defenses, resulting in metabolic reallocations that prioritize survival over reproduction. Globally, biotic stresses contribute to 10% yield losses, with projections indicating heightened risks as food demand surges 70% by 2050 amid climate variability.

Key Diseases in Maize

Major fungal pathogens dominate maize diseases, with northern corn leaf blight (caused by *Bipolaris zeicola*) and southern corn leaf blight (*Bipolaris maydis*) causing foliar lesions that impair grain filling. Ear and stalk rots from *Fusarium* spp. and *Gibberella* spp. reduce kernel quality and produce mycotoxins, while *Aspergillus flavus* induces aflatoxin contamination, diminishing market value. Other notable diseases include banded leaf and sheath blight (*Rhizoctonia solani*), grey leaf spot (*Cercospora zeae-maydis*), and viral mosaics.

Disease Causal Pathogen

- Northern Leaf Blight- *Bipolaris zeicola*
- Southern Leaf Blight- *Bipolaris maydis*
- Banded Leaf & Sheath Blight- *Rhizoctonia solani*
- Fusarium Ear & Stalk Rot- *Fusarium* spp.
- Gibberella Ear Rot- *Gibberella* spp.
- Aflatoxin Contamination- *Aspergillus flavus*
- Grey Leaf Spot- *Cercospora zeae-maydis*
- Mosaic Virus- Various viruses

Prominent Insect Pests

Lepidopteran pests like the fall armyworm (*Spodoptera frugiperda*), a polyphagous transboundary invader with rapid reproduction and no diapause, devastate foliage and ears across continents. Stem borers such as *Chilo partellus* and *Sesamia inferens* tunnel into stalks, weakening plants and promoting lodging, while earworms (*Helicoverpa zea*) target reproductive structures. Root and storage pests, including termites, western corn rootworm, and maize weevils, further compound losses post-harvest.

- Maize Stem Borer- *Chilo partellus*
- Maize Shoot Fly- *Atherigona soccata*
- Corn Earworm- *Helicoverpa zea*
- Fall Armyworm- *Spodoptera frugiperda*
- Southwestern Corn Borer- *Diatraea grandiosella*
- European Corn Borer- *Ostrinia nubilalis*
- Sugarcane Borer- *Diatraea saccharalis*
- Pink Stem Borer - *Sesamia inferens*
- Termites- Various spp.
- Western Corn Rootworm- *Diabrotica virgifera*
- Maize Weevil- *Sitophilus zeamais*



Figure 1. Fall Army Worm (FAW)
Source: syngentaseedcare.com

Breeding Strategies for Resistance

Conventional breeding employs backcrossing for monogenic traits (e.g., Ht genes for leaf blights) and recurrent selection for polygenic resistance, yielding gains like linear ECB2 tolerance from 1930-1991 hybrids. USDA-ARS released Mp313E, Mp420, Mp715, Mp717, and NC388 for aflatoxin resistance via field phenotyping. Inbreds from Antigua GP02 confer SWCB/FAW tolerance.

Molecular tools accelerate progress: QTL mapping identifies bins 9.03/4.06 for FAW leaf damage and qRfr1/10/17 for Fusarium resistance, enabling marker-assisted selection (MAS). MaizeGDB facilitates candidate gene flanking markers. Bt transgenics (Cry1Ab, Cry1A.105, Cry2Ab2, Vip3A) control lepidopterans, but field-evolved resistance (e.g., MON810 vs. *Busseola fusca*, 10% failure by 2005) demands pyramid stacks like MON89034. Gene editing (CRISPR-Cas9) and RNA interference target effectors for durable resistance.

Gene pyramiding Combining both durable multiple disease and multiple insect resistance

FAW and its impact in Africa was reviewed by Matova *et al.* (2020) as well as past and present control strategies for this pest. Cultural practices, host-plant resistance, natural enemies, pesticides, integrated pest management (IPM) and plant breeding approaches were examined as possible control strategies. It was concluded that an IPM control strategy coupled with an insect-resistance management strategy is the best way to manage FAW in Africa. Breeding for multi-trait host-plant resistance may strengthen these strategies through stacking of genes for different modes of control of the pest.

Management Recommendations

Integrated pest management combines cultural practices, host resistance, biological controls, and judicious pesticides, reducing overreliance on chemicals. Emerging climate-driven pathogen races underscore the need for genomic tools like MaizeGDB for candidate gene mapping. Multitrait breeding via gene stacking enhances durable resistance, safeguarding productivity in heat-stressed regions like Punjab.

Between Devotion and Destruction: Stray Cattle as a threat to Agriculture in India



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The problem of stray cattle (awara gaay) is becoming a serious and unexpected issue in India. In our country, farming is not only a way to earn a living but also an important part of our culture. The cow is respected as a sacred animal and is seen as a symbol of kindness, devotion, and prosperity. However, today many cows that are old, abandoned, or can no longer give milk are seen roaming around and entering farms. They destroy crops and cause big losses to farmers.



This problem is growing fast in major farming states like Uttar Pradesh, Rajasthan, Madhya Pradesh, and Haryana. To protect their crops, farmers are forced to stay awake all night. This leads to tiredness, stress, and financial problems. While the income from farming is going down, the cost of farming is increasing. ¹According to the 20th Livestock Census (2019), there were more than 11.84 lakh stray animals in Uttar Pradesh alone. To solve this issue, the Uttar Pradesh government kept aside ₹2,000 crore in its 2025–2026 budget. Out of this, ₹140 crore was used to build cow shelters (gaushalas), and ₹123 crore was used to improve veterinary services. Now, around 12.5 lakh cattle are staying in 7,713 working cow shelters across the state. Also, under the Mukhyamantri Sahbhagita Yojana, 1.63 lakh cows were given to rural families. These families get ₹50 per day to take care of each cow. ²In addition, the Central Government gave ₹4,840.40 crore to the Department of Animal Husbandry and Dairy in its 2025–2026 budget (Table 1). This money will help in animal welfare, healthcare for livestock, and controlling diseases. Today, the problem of stray cattle is no longer just about religion or values. It has become a serious issue related to agriculture policy. If we do not take proper steps using facts and good planning, this problem will continue to hurt farmers, affect the rural economy, and even harm the country's food supply.

Table: 1. Detailed Stray Cattle Crisis in India

Category	Details
Cultural Significance	Cow revered as sacred; symbol of compassion and prosperity
Current Issue	Abandoned/non-milking cows damaging crops; farmers face stress and losses
Major Affected States	Uttar Pradesh, Rajasthan, Madhya Pradesh, Haryana
Farmer Impact	Crop loss, night guarding, fatigue, rising costs, declining productivity
UP – Stray Cattle (2019)	1.184 million stray cattle
UP – Cow Shelters (2025)	7,713 shelters housing ~1.25 million cattle
UP Budget (2025–26)	₹2,000 crore total ₹140 crore – cow protection ₹123 crore – vet services
Mukhyamantri Sahbhagita Yojana	1.63 lakh cows to rural families ₹50/day/cow support
Central Govt. Budget (2025–26)	₹4,840.40 crore – Animal Husbandry & Dairying (welfare, health, disease control)

What is the issue with stray cattle?

In India, the stray cattle problem has rapidly become a major administrative, social, and agricultural crisis. The issue mainly involves old, sick, or non-milching cows, which are no longer useful for milk production. Since caring for such animals is expensive and offers no economic return, many farmers are forced to abandon them. Once released, these animals wander through villages, towns, roads, and farmlands. They often enter crop fields, damaging standing crops and causing farmers losses ranging from thousands to lakhs of rupees each season. In some cases, these stray cattle have attacked farmers, especially when farmers try to guard their fields at night. This growing problem not only affects rural livelihoods but also puts pressure on local administration and public safety.

Impact of Stray Cattle on Agriculture

Stray cattle have become a huge problem in rural India, which is affecting agriculture economically, socially and mentally. This problem is especially difficult for marginal farmers who are already struggling with limited resources and climate challenges. (Table 2)

Table: 2. Impact of Stray Cattle on Agriculture and Rural Livelihoods

Impact	Details
Crop Loss	Standing crops such as wheat, mustard, chickpeas, vegetables, sugarcane, and so on are eaten or trampled by stray cattle.
	In certain places, the loss per hectare ranges from Rs. 10,000 to 25,000.
	During the Rabi season, which runs from November to April, the most damage occurs.
	Farmers frequently discover that their whole crop has been lost overnight, which lowers morale and reduces production.
Increased Cost	Vigilance Farmers' lifestyles and health are impacted by having to patrol fields all night.
	Costs are increased by 20–30% for temporary fencing, hiring guards, watchtowers, and illumination.
	Family members alternately oversee the fields at night under some rotational systems.
Change in Cropping Pattern	To prevent damage, farmers cultivate harder or less lucrative crops (coarse cereals, millet, and berseem).
	Crop diversity and intercropping systems are harmed, and land productivity is decreased.
	As fewer vegetables and pulses are grown, nutritional security declines.
Rural Distress and Migration	Financial stress and debt result from ongoing agricultural losses that are not compensated for.
	The rural economy and food supply are impacted by the large number of farmers who relocate to cities in search of labor.
	Some farmer suicides are attributed to crop loss by stray animals (NCRB reports).

Why the Problem of Stray Cattle is increasing?

There are numerous contributing elements to India's quickly growing stray animal problem. The primary cause is the stringent prohibition on cow slaughter in most states. Although the goal of these rules is to protect cows, they do not offer sufficient alternatives for handling frail, elderly, or unproductive livestock. A number of interrelated reasons are contributing to India's fast-expanding stray cattle problem. The severe prohibition on cow slaughter in several states is one of the primary causes. Although the goal of this legislation is to safeguard cows, it does not provide sufficient alternatives for the management of elderly, unproductive, or sick animals. Farmers no longer profit from cows once they stop producing milk, but the expense of feeding and maintaining them persists.

Table: 3. Reasons for Rising Stray Cattle Problem in India

Reasons	Details
Ban on Cow Slaughter	Strict laws in many states prohibit cow slaughter but lack alternatives for old or non-productive cattle.
No Economic Use for Old Cattle	Once cows stop giving milk, they no longer generate income, but maintenance costs remain high.
Lack of Gaushalas and Funding	Insufficient number of cow shelters; existing ones are overcrowded, underfunded, and poorly managed.
Decline of Grazing Lands	Urbanization and changing land use reduce common grazing areas, forcing cattle to enter fields and towns searching for food.

Many farmers find it difficult to keep these animals, which results in their abandonment due to the high care costs and lack of revenue. Furthermore, the issue is made worse by the lack of suitable infrastructure. The growing number of stray animals cannot be housed in the available gaushalas (cow shelters). Due to inadequate financing, overpopulation, and bad management, many gaushalas now in operation are unable to adequately house all of the stray animals. Another significant factor is the rapid decline in grazing lands. Common lands that were once available for cattle to graze have been shrinking due to urbanization, industrial development, and changing land use patterns. As a result, stray cattle often wander into agricultural fields and residential areas in search of food, causing crop damage and becoming a public nuisance (Table 3). In summary, the combination of strict slaughter bans without proper rehabilitation mechanisms, economic non-viability of keeping old cattle, lack of sufficient shelter facilities, and loss of grazing lands has collectively fueled the increase in stray cattle populations, making it a complex and growing challenge for both rural and urban India.

Challenges in Addressing the Stray Cattle Issue

The problem of stray cattle in India is complex and deeply intertwined with cultural, political, and administrative challenges, making it difficult to address effectively.

- One of the foremost challenges is the religious sentiment associated with cows in Indian society. Cows are considered sacred and revered, especially in Hinduism, which creates sensitivity around any discussion related to their management or slaughter. This cultural reverence often limits open dialogue and complicates the framing of practical policies to handle stray cattle.
- Another significant hurdle is political hesitation. Many politicians are reluctant to take firm actions against stray cattle due to fear of backlash from religious groups and voters. This results in weak enforcement of laws, inadequate funding, and a lack of comprehensive plans to manage the problem.
- The issue is further compounded by inadequate data and poor coordination between various government departments such as Animal Husbandry, Agriculture, and Panchayats. Without accurate data on the number and location of stray cattle, formulating targeted interventions becomes nearly impossible. Moreover, the overlapping responsibilities and lack of communication among departments lead to inefficiencies and gaps in action.
- Additionally, there is poor monitoring of cattle ownership and tagging. Many cattle are unregistered, making it difficult to hold owners accountable for abandonment or negligence. The absence of effective cattle identification systems leads to challenges in tracking and managing stray animals.
- Overall, these challenges create a complex environment where the stray cattle problem persists, affecting farmers, public safety, and the rural economy. Addressing these issues requires sensitive yet pragmatic policies, improved inter-departmental coordination, and community participation to balance cultural respect with agricultural and social needs.

Possible Solutions to the Stray Cattle Problem

The stray cattle issue can be addressed effectively through a combination of scientific management, community involvement, and government support. Here are some practical solutions:

1. **Strengthening Gaushalas:** Creating well-managed, scientifically run gaushalas (cow shelters) is crucial. These shelters should provide proper healthcare, nutrition, and living conditions for abandoned and non-milch

- cows. To support this, the government can provide grants and encourage public-private partnerships (PPP). Additionally, Corporate Social Responsibility (CSR) funds can be channeled to maintain and improve these shelters, ensuring long-term sustainability.
2. **Cow Adoption & Tagging:** Encouraging the digital tagging of cattle with GPS collars will help track ownership and prevent abandonment. This system will also hold owners accountable for their animals, reducing the number of stray cows. Promoting cow adoption among rural and urban households can also help in reducing the burden on shelters and open grazing areas.
 3. **Fodder Banks & Feed Subsidy:** Many farmers abandon old or non-milch cows due to the high cost of feed. Establishing fodder banks where subsidized fodder is available to poor farmers can encourage them to keep their cattle. Community fodder reserves can also be promoted, ensuring regular availability of feed and reducing the incentive to abandon animals.
 4. **Fencing Subsidies:** Subsidies for solar fencing, bio-fencing, or community fencing can help farmers protect their fields from stray cattle. Solar-powered electric fences are effective and eco-friendly, providing a long-term solution to crop damage.
 5. **Utilizing Cow Dung & Urine:** Creating economic value from cow dung and urine can incentivize farmers to care for non-milch cows. Promoting biogas plants, organic manure production, and panchagavya-based products will not only reduce waste but also generate income and employment.
 6. **Zoning and Grazing Corridors:** Designating specific zones for cattle grazing, reviving wastelands, and creating green belts will provide safe spaces for stray cattle. Grazing corridors help prevent animals from wandering into crop fields or urban areas, reducing conflict.

By combining these measures, India can create a balanced approach that respects cultural sentiments while addressing the agricultural and social challenges posed by stray cattle.

Conclusion

The problem of **awara gaay** (stray cattle) goes far beyond just being an animal welfare issue. It has become a complex challenge affecting agriculture, the economy, society, and politics in India. Stray cattle damage crops, increase farmers' costs, and cause distress in rural and urban areas alike. If this issue is not addressed with practical and inclusive solutions, it will continue to harm the productivity and well-being of the farming community, which forms the backbone of the nation's food security. A successful resolution requires a balanced approach that respects both the cultural and religious sentiments attached to cows and the livelihood needs of farmers. Policies must be secular, data-driven, and farmer-friendly, focusing on scientific management of stray cattle through better shelters, effective tracking, and sustainable fodder systems. Simultaneously, public awareness campaigns can promote responsible cattle ownership and community participation.

Only by integrating policy reforms, technological interventions, and social cooperation can India hope to manage the stray cattle problem effectively. This balance is essential to protect animal rights while ensuring that farmers can cultivate their land without fear of loss or damage. Ultimately, solving this issue is crucial not only for the survival of farmers but also for the health of India's agricultural economy and rural society.

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The Power Within Plants: How Growth Regulators Drive Yield, Resilience, and Quality in Crops



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Introduction

Plant Growth Regulators (PGRs), also known as phytohormones, are organic compounds that profoundly influence plant growth, development, and responses to environmental stress, even when present in very small quantities. Classical PGRs such as auxins, cytokinins, gibberellins, abscisic acid, and ethylene regulate vital physiological processes including cell division, elongation, flowering, fruit set, and dormancy. In recent years, modern agriculture has expanded the use of new-generation regulators such as brassinosteroids, jasmonates, salicylic acid, polyamines, strigolactones, peptides, and triacontanol. These compounds strengthen plant defence mechanisms by enhancing antioxidant activity, osmotic adjustment, and stress tolerance under adverse conditions such as drought, salinity, and temperature extremes. Altogether, PGRs have become essential tools in climate-smart agriculture, improving yield, crop quality, and resilience.

Plant Hormones and Plant Growth Regulators

Plant hormones are naturally synthesized within plant tissues and perform highly specific regulatory roles in physiological processes such as germination, differentiation, and fruit ripening. Plant growth regulators include both natural and synthetic substances that mimic or modify hormonal activity when applied externally. While hormones act internally in specific sites, PGRs enable external manipulation of plant functions such as rooting, height control, and synchronized fruit ripening. Thus, all plant hormones function as PGRs, but not all PGRs are hormones.

Classification and Significance

PGRs can be classified by their origin and function. Natural regulators include auxins, gibberellins, and cytokinins, while synthetic ones include NAA, 2,4-D, and paclobutrazol. Functionally, they may act as growth promoters or inhibitors. Additional compounds such as jasmonates, salicylic acid, and polyamines play a major role in stress regulation. Through hormonal balance, PGRs enhance germination, flowering, nutrient efficiency, and overall plant productivity, making them vital components of sustainable and climate-resilient agriculture.

What Are Plant Growth Regulators?

Plant Growth Regulators (PGRs), often referred to as phytohormones, are the “chemical messengers” that control almost every aspect of a plant’s life from seed germination to flowering, fruiting, and aging. The classic PGRs include auxins, gibberellins, cytokinins, abscisic



Figure 1: Role of plant growth regulators in changing cropping scenario

acid, and ethylene. In recent years, new-generation compounds such as brassinosteroids, salicylic acid, jasmonates, polyamines, and seaweed-based biostimulants have added a new dimension to crop management.

Each of these regulators plays a specific role. Auxins stimulate root formation, gibberellins promote stem elongation and seed germination, and cytokinins encourage cell division and delay aging. Absciscic acid acts as a “stress hormone,” helping plants survive drought or cold, while ethylene regulates fruit ripening and leaf fall. Modern research also highlights the importance of jasmonates and salicylic acid in enhancing a plant’s resistance to stress and disease.

The Science Behind Growth Regulation

Plant growth regulation is a complex and dynamic process governed by biochemical, genetic, and environmental interactions. The coordination of these factors ensures that plants maintain proper growth, development, and adaptation throughout their life cycle. Central to this process are plant growth regulators (PGRs), which act as signalling molecules controlling cell division, elongation, and differentiation. The balance among these compounds determines plant architecture, yield potential, and stress tolerance.

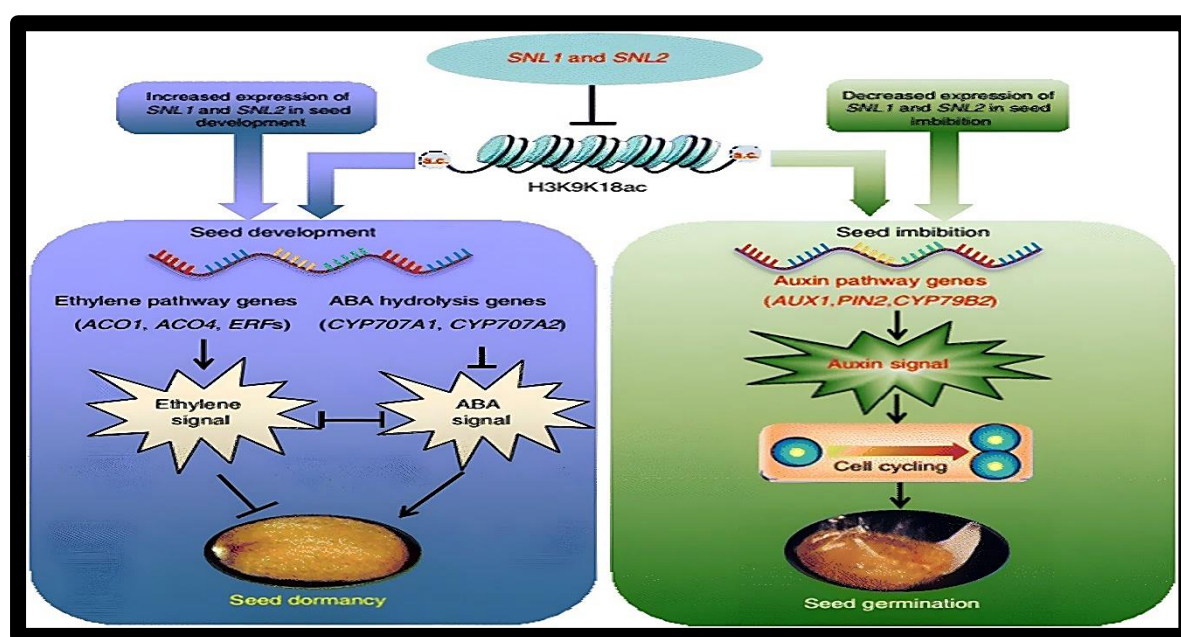
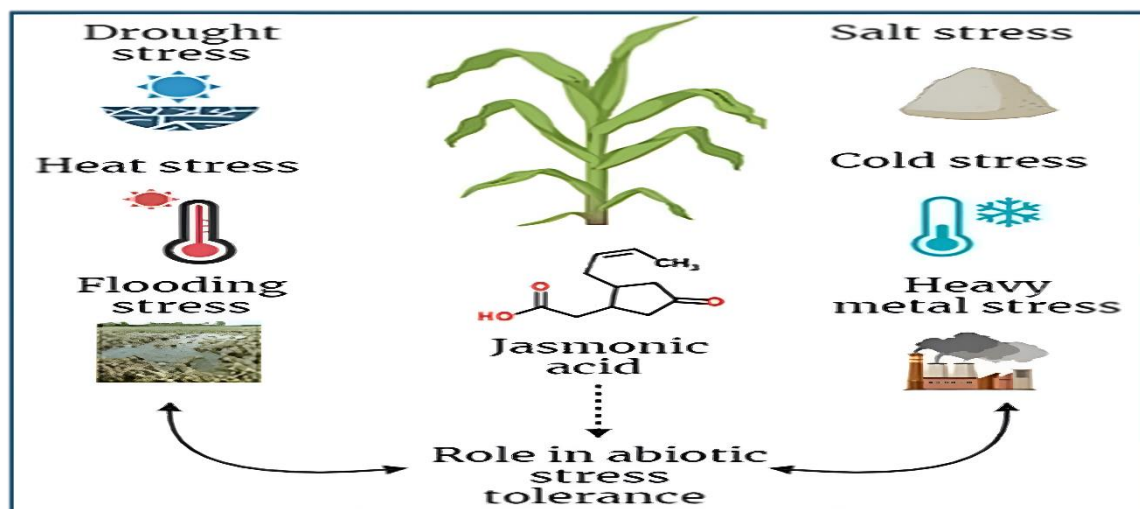


Fig 2: Role of auxin in seed germination and cell cycling

At the molecular level, PGRs influence plant growth by regulating enzyme activity and gene expression. Auxins stimulate proton pumps in cell membranes, causing acidification of the cell wall and enabling cell expansion. Gibberellins activate enzymes that modify the structure of cell walls, facilitating elongation during germination and stem growth. Cytokinin promotes cell division by stimulating DNA synthesis and protein production, especially in meristematic tissues. In contrast, abscisic acid and ethylene act as inhibitory regulators that induce dormancy, control leaf fall, and promote senescence. The interaction between these growth-promoting and growth-inhibiting compounds maintains equilibrium and ensures that growth occurs in a balanced and timely manner.

Growth regulation also involves sophisticated molecular signaling systems. Each hormone binds to specific receptors, initiating a cascade of cellular events that activate or suppress genes responsible for growth and metabolism. For instance, gibberellins interact with GID1 receptors, resulting in the degradation of DELLA proteins that normally suppress growth-related genes. Similarly, auxin binds to the TIR1 receptor, leading to the breakdown of AUX/IAA repressor proteins and the activation of genes promoting elongation. These molecular mechanisms illustrate how plants translate hormonal signals into physiological responses (Wakeel *et al.*, 2018). Environmental conditions such as light, temperature, water, and nutrient availability further influence hormonal pathways. Photoreceptors like phytochromes and cryptochromes interact with hormones to regulate seed

germination, phototropism, and flowering. Under stress conditions, regulators such as abscisic acid, jasmonic acid, and salicylic acid activate protective genes that enhance antioxidant activity, osmotic balance, and membrane stability (Rehman *et al*,2023).



In modern agriculture, understanding the science of growth regulation enables the strategic use of PGRs to improve productivity and quality. Farmers can manipulate these regulators to control plant height, promote uniform flowering, delay senescence, and increase resilience to stress. Through this integrated control of hormonal and environmental factors, PGRs contribute significantly to sustainable, efficient, and climate-smart crop production.

PGRs act as molecular switches, turning genes on or off depending on environmental and developmental cues. For instance, in rice and wheat, they help regulate flowering time and grain filling. In legumes like lentil and urbean, they enhance protein and amino acid synthesis. At the biochemical level, PGRs modify enzyme activity, improve photosynthetic efficiency, and optimize nutrient use all of which translate to better yields and improved crop quality.

Economic and Environmental Benefits

PGRs not only enhance crop productivity but also deliver tangible economic gains to farmers. Higher yields, improved quality, and better stress tolerance translate to increased income and lower input costs. Many studies report that PGR-treated crops fetch better market prices due to uniformity, improved taste, and longer shelf life. For example, Bt cotton farmers in Karnataka achieved higher net returns when using GA₃ and NAA sprays compared to untreated controls (Hiremath *et al*,2021).

From an environmental perspective, PGRs promote sustainability by reducing the dependency on chemical fertilizers and pesticides by enhancing nutrient uptake and photosynthetic efficiency, they allow farmers to achieve more with less is an essential feature of climate-smart agriculture. Moreover, many modern PGRs are biodegradable and eco-friendly, leaving minimal residues in soil and water

Challenges and the Way Forward

Despite their advantages, the adoption of PGRs in India and other developing countries faces several hurdles. The quality of locally produced PGRs varies widely, with impurities reducing their effectiveness. There are also regulatory challenges, as many products take years to gain approval. Additionally, farmers often lack proper knowledge about the right dosages, timing, and combinations for different crops.

To overcome these issues, experts recommend establishing certified quality testing labs, streamlining regulatory frameworks, and investing in new-generation molecules such as bio-based and nano-formulated PGRs. Farmer training and digital advisory systems can also play a pivotal role in promoting safe and effective use. India, with its strong chemical manufacturing base and diverse agricultural zones, is well positioned to become a global leader in the PGR sector.

The Future of Crop Regulation

As agriculture moves toward precision and sustainability, PGRs will play a defining role in balancing productivity with environmental responsibility. Integrating PGRs with modern tools such as AI-driven nutrient management, drone-based spraying, and Internet-of-Things (IoT) monitoring could revolutionize farming practices. These technologies can ensure that PGRs are applied at the right time, in the right dose, and in the right place maximizing benefits while minimizing waste.

The future lies not just in producing more food, but in producing it better with higher nutritional value, improved resilience, and reduced ecological footprint. In that vision, plant growth regulators are not optional inputs; they are essential allies in building a sustainable and productive agricultural future.

Conclusion

From paddy fields in India to wheat farms in Europe and sugarcane plantations in Southeast Asia, plant growth regulators have proven their worth as powerful tools for enhancing productivity and quality. They bridge the gap between traditional farming wisdom and modern scientific innovation, offering a path toward resilient, sustainable, and profitable agriculture. As we step into a future of climate uncertainties, embracing the science of PGRs is not just a choice it is an agricultural necessity.

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“Phosphorus Is Not ‘Deficient’ — It Is ‘Trapped’”



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Introduction:

Phosphorus (P) is widely recognized as one of the most critical nutrients limiting crop productivity after nitrogen. In conventional agronomic thinking, poor crop growth or low yield is often directly attributed to phosphorus deficiency, leading to a routine recommendation of higher doses of phosphatic fertilizers. This belief—“*low yield equals low phosphorus*”—has shaped fertilizer management strategies for decades. However, growing evidence from long-term field experiments across Indian agro-ecosystems challenges this simplistic assumption and reveals a striking paradox in phosphorus nutrition.

In many Indian soils, particularly those under intensive cropping, the total phosphorus content is not inherently low. On the contrary, decades of continuous fertilizer application have resulted in substantial accumulation of phosphorus in soils. Yet, crop response to added phosphorus remains inconsistent or marginal in many cases. This disconnect between soil phosphorus reserves and plant uptake raises a fundamental question: if phosphorus is present in soil, why are crops unable to access it effectively?

The answer lies not in phosphorus deficiency but in phosphorus fixation. Once applied to soil, phosphorus does not remain freely available in the soil solution. Instead, it is rapidly adsorbed onto soil minerals such as iron and aluminium oxides or precipitated with calcium compounds, forming tightly bound complexes. These processes reduce the concentration of plant-available phosphorus, even when total soil phosphorus is high.

Thus, phosphorus availability is governed by two opposing but interconnected processes—adsorption, which immobilizes phosphorus on soil surfaces, and desorption, which governs its release back into the soil solution for plant uptake. Understanding the balance between these hidden processes is essential for resolving the phosphorus paradox and developing more efficient, sustainable phosphorus management strategies.

What Happens to Phosphorus After Application?

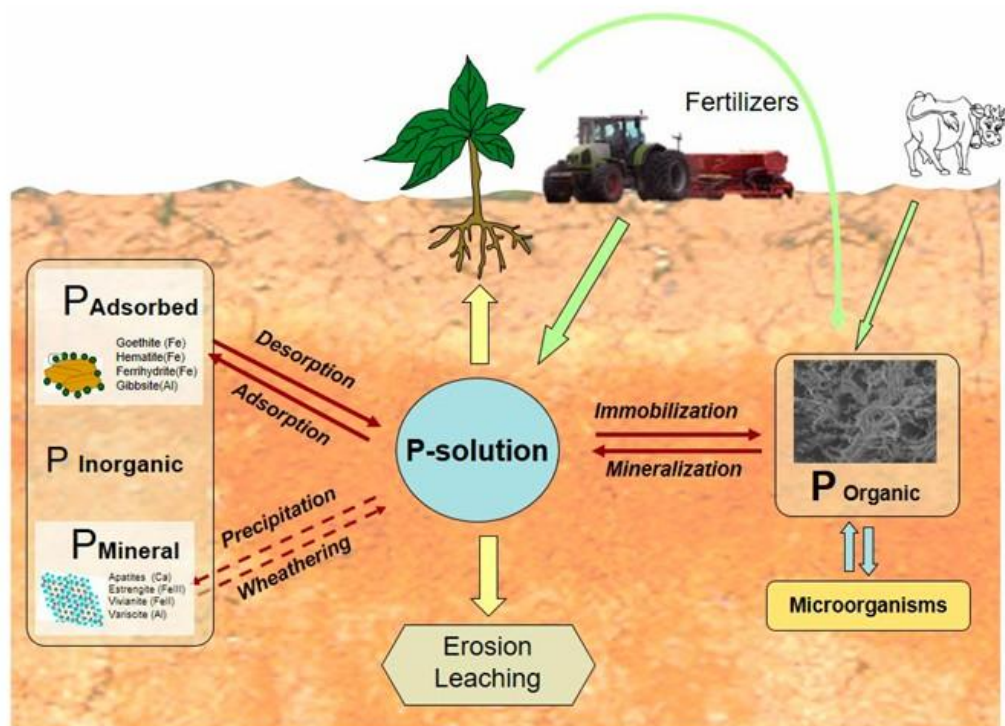
When phosphorus fertilizer is applied to soil, it does not remain freely available to crops for long. Immediately after application, soluble phosphate dissolves in soil moisture and briefly enters the soil solution, where it becomes accessible to plant roots. However, this phase is short-lived. Within hours to days, a large proportion of the dissolved phosphorus undergoes rapid adsorption onto soil particles. This adsorption occurs primarily on the surfaces of clay minerals and iron, aluminium, or calcium compounds, depending on soil type and pH.

Over time, the adsorbed phosphorus undergoes further transformations. Initially weakly held phosphate ions may gradually migrate into more stable and tightly bound forms through processes such as surface precipitation, occlusion within mineral structures, or conversion into less soluble compounds. These slow transformations progressively reduce phosphorus availability, even though the total phosphorus content of the soil continues to increase. Thus, a significant portion of applied phosphorus becomes chemically present but biologically inaccessible to crops.

Adsorption vs. Desorption: The Hidden Control Mechanism

Adsorption refers to the process by which soil particles hold phosphorus on their surfaces, effectively removing it from the soil solution. While adsorption helps prevent phosphorus losses through leaching or runoff, excessive adsorption restricts nutrient availability. In contrast, desorption is the reverse process, whereby adsorbed phosphorus is released back into the soil solution.

Crop roots rely almost entirely on desorption for their phosphorus nutrition. Plants absorb phosphorus only from the soil solution, and as roots deplete this solution, fresh phosphorus must be supplied through desorption. Therefore, soils that strongly adsorb phosphorus but release it slowly often exhibit poor crop response, even when soil phosphorus levels appear adequate. Understanding this adsorption–desorption balance is central to improving phosphorus use efficiency in agricultural systems.



Why Indian Soils “Trap” Phosphorus

Role of Soil Minerals

One of the primary reasons Indian soils strongly “trap” phosphorus lies in their mineralogical composition. Many agricultural soils are rich in iron and aluminium oxides, particularly in tropical and subtropical regions where intense weathering prevails. These oxides possess highly reactive surfaces with strong positive charges that readily attract negatively charged phosphate ions. Once adsorbed, phosphorus forms inner-sphere complexes with iron and aluminium oxides, making it difficult to release back into the soil solution.

In neutral to alkaline soils, which are widespread across the Indo-Gangetic plains and central India, calcium compounds dominate phosphorus reactions. Phosphate ions react with calcium to form sparingly soluble calcium phosphates that further reduce phosphorus availability. Both iron–aluminium oxides and calcium compounds exhibit high bonding energy, meaning the phosphorus held on these surfaces is tightly bound and resists desorption. As a result, even soils with adequate total phosphorus may supply insufficient phosphorus to crops.

Effect of Long-Term Cropping

Long-term intensive cropping systems further aggravate phosphorus trapping. Continuous removal of phosphorus by crops gradually depletes the readily available phosphorus pool, leaving behind a soil matrix dominated by high-energy, unsatisfied adsorption sites. These vacant sites exhibit a strong affinity for newly added phosphorus, leading to rapid and often irreversible fixation.

Over time, repeated fertilizer applications to such soils increase the soil’s phosphorus fixation capacity rather than improving availability. This creates a paradox where more phosphorus is applied, yet crop response declines. Thus, the combined influence of reactive soil minerals and long-term cropping intensification transforms Indian soils into efficient phosphorus sinks, underscoring the need to manage phosphorus dynamics rather than simply increasing fertilizer inputs.

When No Phosphorus Is Applied: The Soil Becomes More Aggressive

Soils receiving little or no phosphorus over long periods gradually become chemically “P-hungry.” Continuous crop uptake depletes readily available phosphorus pools, leaving behind a large number of vacant, high-energy adsorption sites on soil minerals. These unsatisfied sites develop a strong affinity for phosphate ions, making the soil increasingly aggressive toward any newly added phosphorus.

This phenomenon explains why control plots consistently exhibit the highest phosphorus adsorption capacity. Even small additions of phosphorus are rapidly adsorbed onto reactive mineral surfaces, preventing its accumulation in the soil solution. Consequently, such soils behave as phosphorus sinks rather than nutrient sources for crops.

Control plots also show the highest desorption index (DI), indicating that once phosphorus is adsorbed, it is released very slowly. High DI values reflect the dominance of irreversible fixation processes, where phosphate ions form strong inner-sphere complexes with iron, aluminium, or calcium compounds and may eventually become occluded within mineral structures. Thus, prolonged phosphorus omission does not conserve soil fertility but instead enhances the soil's capacity to lock phosphorus, creating long-term constraints on crop nutrition.

Residual Phosphorus: Friend or Foe?

Residual phosphorus—the portion of applied phosphorus remaining in soil after crop uptake—plays a dual role in soil fertility. In the short to medium term, residual phosphorus can be beneficial by partially saturating high-energy adsorption sites, thereby reducing the soil's capacity to fix newly applied phosphorus. This often explains the declining crop response to phosphorus fertilizers observed after several years of continuous application.

However, excessive reliance on residual phosphorus creates new challenges. Repeated fertilizer inputs lead to phosphorus accumulation in surface soil layers, resulting in stratification that limits root access to deeper reserves and reduces nutrient use efficiency. Moreover, much of the accumulated phosphorus exists in chemically stable or occluded forms that contribute little to immediate crop nutrition despite inflating total soil phosphorus levels.

When adsorption sites approach saturation, soils lose their buffering capacity, increasing the risk of phosphorus loss through runoff and erosion. These losses pose environmental concerns, particularly eutrophication of surface waters. Thus, fertilizer-only phosphorus management suppresses fixation only temporarily and fails to address the underlying adsorption-desorption imbalance that governs long-term phosphorus availability.

Decoding Soil's P-Holding Power: Key Scientific Indicators

Understanding soil response to phosphorus application requires indicators that describe how strongly soils hold and buffer phosphorus rather than relying solely on available phosphorus values. Three key parameters—maximum phosphorus adsorption capacity (b), affinity constant (k), and maximum phosphorus buffering capacity (MPBC)—offer critical insight into soil phosphorus dynamics.

Maximum Phosphorus Adsorption Capacity (b)

The parameter b represents the total number of adsorption sites available for phosphorus fixation. Soils with high b values can immobilize large quantities of applied phosphorus, limiting its availability to crops. While this reduces losses, it results in poor fertilizer response even under adequate application.

Affinity Constant (k)

The affinity constant k reflects the strength with which phosphorus is bound to soil particles. High k values indicate strong bonding energy, meaning phosphorus is tightly held and resists desorption, effectively locking it away from plant uptake.

Maximum Phosphorus Buffering Capacity (MPBC)

MPBC, derived from $b \times k$, indicates a soil's resistance to changes in soil solution phosphorus. High MPBC soils require greater fertilizer inputs to achieve marginal increases in available phosphorus, making MPBC a hidden fertilizer demand index critical for efficient phosphorus management.

Desorption Index (DI)

The Farmer-Relevant Indicator While adsorption parameters explain how strongly soils retain phosphorus, the Desorption Index (DI) provides a more practical measure of phosphorus availability to crops. DI reflects the reversibility of phosphorus fixation and the soil's capacity to release adsorbed phosphorus back into the soil solution. A high DI value (>1) indicates dominance of adsorption over desorption, meaning phosphorus is strongly fixed and released slowly, resulting in poor crop access. Conversely, a low DI value (<1) suggests improved reversibility, ensuring a steady phosphorus supply as roots deplete soil solution phosphorus. High DI values are typical of soils receiving no phosphorus for extended periods, where unsatisfied adsorption sites promote

irreversible fixation. Integrated phosphorus management, particularly with organic amendments, lowers DI by reducing bonding energy and improving desorption. From a practical standpoint, DI translates complex soil chemistry into field-level implications, indicating whether productivity can be sustained with lower fertilizer inputs.

Field Evidence from KVK Bhatapara: When Reduced P Gives Higher Yield

The conceptual framework of phosphorus being “trapped rather than deficient” finds strong validation in an on-farm experimental trial conducted at Krishi Vigyan Kendra (KVK), Bhatapara, Chhattisgarh, under real farmers’ field conditions. The trial evaluated whether rationalization of phosphorus fertilizer, when combined with optimized nitrogen management, could sustain or improve rice productivity by mobilizing native and residual soil phosphorus pools. In this experiment, the conventional recommended fertilizer dose (RDF: 100:60:40 kg N:P₂O₅:K₂O ha⁻¹) was compared with a readjusted RDF involving 25% reduction in phosphorus (45 kg P₂O₅ ha⁻¹) and enhanced nitrogen (125% of RDF). Despite a substantial reduction in applied phosphorus, the readjusted treatment consistently outperformed the conventional practice across ten farmers’ fields.

Grain yield increased from 39.8 to 41.9 q ha⁻¹, accompanied by significant improvements in tiller density, panicle number, grains per panicle, and test weight. This yield enhancement occurred not because more phosphorus was applied, but because rice plants were able to effectively utilize native and residual soil phosphorus under submerged conditions. Flooded rice soils promote reductive dissolution of iron-bound phosphorus, thereby enhancing desorption and replenishment of soil solution P—exactly the process emphasized in adsorption–desorption theory.

Treatment	Panicles m ⁻²	Grains panicle ⁻¹	Test weight (g)	Grain yield (q ha ⁻¹)	Straw yield (q ha ⁻¹)
T ₁ – RDF	272	118	23.6	39.8	46.2
T ₂ – Readjusted RDF	304	132	24.9	41.9	51.0
SEm ±	6.9	3.2	0.41	0.52	0.84
CD (P = 0.05)	15.4	7.1	0.91	1.16	1.87

From a phosphorus dynamics perspective, the findings strongly suggest that long-term fertilizer use had already saturated high-energy adsorption sites in these soils. Additional phosphorus application therefore contributed little to crop uptake but increased residual accumulation. By reducing phosphorus input, the system relied more on desorption-driven P supply, confirming that soil P availability is governed by release kinetics rather than total P content.

Economically, the readjusted RDF reduced fertilizer cost while increasing net returns and benefit–cost ratio (2.03 vs. 1.78). This outcome directly supports the argument that high MPBC and high DI soils respond poorly to blanket phosphorus application, and that rationalization improves both agronomic and economic efficiency.

Treatment	P ₂ O ₅ applied (kg ha ⁻¹)	P fertilizer saving (%)	Cost of cultivation (₹ ha ⁻¹)	Net returns (₹ ha ⁻¹)	B:C ratio
T ₁ – RDF	60	–	45,000	35,000	1.78
T ₂ – Readjusted RDF	45	25.0	43,500	45,000	2.03

Thus, phosphorus fertilization should aim to weaken fixation and enhance release, not merely increase input rates. It demonstrates that managing soil behaviour—through nutrient balance and system understanding—can outperform conventional fertilizer-heavy strategies, offering a scalable pathway for sustainable phosphorus management in rice-based systems.



Rethinking Soil Test Interpretation

Conventional soil testing primarily relies on measurements of available phosphorus to guide fertilizer recommendations. While useful, this single parameter provides only a partial picture of soil phosphorus behaviour. Available phosphorus reflects a momentary concentration in the soil solution, but it does not indicate how strongly phosphorus is held by the soil or how readily it can be replenished through desorption. As demonstrated by adsorption–desorption studies, soils with similar available phosphorus levels can differ markedly in their capacity to supply phosphorus to crops.

To overcome this limitation, soil test interpretation must incorporate indicators that describe phosphorus dynamics, such as adsorption capacity, buffering capacity, and desorption index. These parameters provide insight into the soil's phosphorus holding strength and release potential, enabling more precise and efficient fertilizer recommendations. Future soil health cards should evolve beyond static nutrient values and include functional indicators that reflect nutrient availability over time, particularly in intensively cultivated systems.

Environmental Dimension: Preventing Phosphorus Loss and Pollution

Reducing phosphorus fixation does not inherently increase the risk of phosphorus loss. Instead, integrated phosphorus management promotes controlled and synchronized phosphorus release aligned with crop demand. By lowering adsorption strength and buffering capacity through organic amendments, phosphorus remains more available to crops while avoiding excessive accumulation in vulnerable pools. This controlled nutrient cycling minimizes runoff and erosion losses, thereby reducing the risk of eutrophication. Thus, improving phosphorus efficiency through integrated management supports both agricultural productivity and environmental sustainability.

Conclusion:

The persistent challenge of low phosphorus use efficiency in Indian agriculture is not primarily a problem of insufficient phosphorus supply, but a consequence of how soils chemically and biologically regulate phosphorus availability. This article demonstrates that in many intensively cultivated soils, phosphorus is abundant yet inaccessible, trapped by strong adsorption processes that limit its release to crops. Simply increasing fertilizer application fails to overcome this constraint and often aggravates inefficiency and environmental risk.

By examining adsorption–desorption dynamics, buffering capacity, and the desorption index, it becomes evident that effective phosphorus management must focus on modifying soil behaviour rather than fertilizer dose alone. High adsorption capacity, strong bonding energy, and elevated buffering capacity collectively explain why soils with adequate total phosphorus often show poor crop response. Organic amendments, particularly poultry manure, play a decisive role in weakening phosphorus fixation by masking adsorption sites, chelating fixing cations, and improving the reversibility of phosphorus reactions.

Integrated phosphorus management—combining sub-optimal inorganic phosphorus with organic inputs—emerges as a scientifically sound and agronomically viable strategy. It enhances phosphorus availability, improves fertilizer efficiency, strengthens soil health, and reduces environmental losses. Ultimately, sustainable phosphorus nutrition requires a paradigm shift: not supplying more phosphorus to soils, but enabling soils to release the phosphorus they already hold.

Alternative Protein Sources for Sustainable Aquafeeds



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Abstract

The growing demand for aquaculture production has increased the need for sustainable and cost-effective feed ingredients. Traditionally, fishmeal and fish oil have been the primary protein sources in aquafeeds; however, their limited availability, high cost, and environmental concerns have driven the search for alternative protein sources. Various ingredients such as plant-based proteins (soybean meal, groundnut cake, and corn gluten), animal by-products (poultry by-product meal, blood meal), microbial proteins (single-cell proteins, algae, and yeast), and insect meals have shown great potential to partially or completely replace fishmeal without compromising growth and health performance of fish and shrimp. These alternatives not only reduce dependence on wild-caught fish but also enhance feed sustainability and circular bioeconomy. The successful utilization of these novel protein sources requires careful evaluation of their nutritional value, digestibility, anti-nutritional factors, and processing methods. Overall, integrating alternative protein ingredients in aquafeeds can play a key role in ensuring sustainable and eco-friendly aquaculture production in the future.

Key words: Insect meal, novel protein sources, digestibility, eco-friendly, sustainability.

Introduction

Aquaculture is currently one of the most rapidly expanding food production sectors worldwide, contributing significantly to global food security and nutrition (FAO, 2022). As the industry grows, the need for nutritionally balanced and environmentally sustainable feeds has become increasingly important. Fishmeal has long been considered the gold standard protein source in aquafeeds because of its high digestibility, balanced amino acid profile, and palatability (Tacon and Metian, 2015). However, the rising cost, fluctuating supply, and ecological impact associated with fishmeal production have raised concerns regarding its continued dependence (Naylor et al., 2021). Potential alternatives include plant-based proteins such as soybean meal, groundnut cake, and rapeseed meal; animal by-products like poultry by-product meal and blood meal; microbial and algal proteins; and insect meals derived from species such as *Hermetia illucens* (black soldier fly) and *Tenebrio molitor* (mealworm) (Henry et al., 2015; Olsen et al., 2020). Each of these alternatives varies in nutrient composition, digestibility, and the presence of anti-nutritional factors, which must be carefully considered during feed formulation and processing. Moreover, the utilization of such alternative ingredients aligns with the principles of circular bioeconomy by transforming low-value or waste materials into high-quality feed resources, thereby minimizing environmental footprints and improving resource efficiency (Gatlin et al., 2017). Therefore, the development and optimization of sustainable protein sources for aquafeeds are essential to maintain productivity, economic viability, and environmental responsibility in modern aquaculture.

Different types of alternative protein sources

1. Plant-Based Protein Sources

Plant-derived proteins are among the most accessible and widely explored fishmeal alternatives because they are cost-effective, renewable, and globally available. However, each plant ingredient varies in nutrient composition, amino acid balance, and the presence of anti-nutritional factors (ANFs). Commonly used plant ingredients include soybean meal, groundnut cake, sunflower meal, cottonseed meal, corn gluten meal, and rapeseed meal. Among these, soybean meal is the most preferred because it provides around 40–48% crude protein with a balanced amino acid composition, especially lysine, although it is deficient in methionine (Tacon et al., 2020). However, one of the main limitations of plant proteins is the presence of anti-nutritional factors (ANFs) such as trypsin inhibitors, tannins, saponins, lectins, and phytic acid. These compounds interfere with digestion, nutrient absorption, and

enzyme activity, ultimately reducing feed efficiency and growth performance (Francis et al., 2001). For instance, phytic acid binds to minerals like phosphorus and zinc, making them unavailable to fish.

Soybean Meal (SBM)

Soybean meal is considered the benchmark among plant proteins for aquafeeds. It contains around 44–48% crude protein, with a balanced amino acid profile, particularly rich in lysine (Tacon et al., 2020). It also provides good levels of phosphorus and essential fatty acids. The main drawbacks are its deficiency in methionine and the presence of anti-nutritional compounds like trypsin inhibitors, oligosaccharides, and phytic acid, which can reduce nutrient digestibility and mineral absorption (Francis et al., 2001).

Through heat treatment, solvent extraction, or fermentation, these ANFs can be reduced, making SBM suitable for partial or total fishmeal replacement in omnivorous and herbivorous species such as tilapia, carp, and catfish. In carnivorous species, inclusion beyond 40% may cause enteritis, so proper formulation balance is essential (Krogdahl et al., 2010).

Groundnut Oil Cake (GNC)

Groundnut or peanut oil cake is another widely used plant protein source in aquaculture. It contains around 45–50% crude protein and is rich in arginine and glutamic acid but deficient in lysine and methionine (Akinleye et al., 2019). GNC has good palatability and digestibility but may contain aflatoxins if stored improperly. Additionally, it provides essential minerals like calcium, phosphorus, magnesium, and potassium crucial for metabolic and skeletal development. Detoxification methods such as chemical treatment or microbial fermentation can minimize these risks. When properly processed, GNC can replace 25–50% of fishmeal in diets for species like carp and catfish without adverse effects.

Sunflower Meal

Sunflower meal is an innovative and cost-effective plant protein source increasingly used in fish nutrition as a partial or substantial replacement for fish meal and soybean meal. Unlike traditional plant proteins, sunflower meal is derived from the residue after oil extraction from sunflower seeds, providing a balanced profile of protein and fiber, along with a good range of amino acids. It contains about 35–42% crude protein and is rich in sulfur-containing amino acids such as methionine and cysteine (Cheng & Hardy, 2004). However, it is deficient in lysine and contains high fiber content, which can reduce digestibility, particularly in carnivorous species. Dehulling and enzyme supplementation can help improve nutrient utilization. Its inclusion up to 20–30% in carp and tilapia diets has shown positive growth responses.

Rapeseed (Mustard) Meal

Rapeseed or mustard meal contains around 35–40% crude protein and provides a balanced amino acid composition with a good amount of methionine. However, the presence of glucosinolates and erucic acid limits its inclusion level, as these compounds can affect thyroid function and reduce feed intake (Kumar et al., 2011). Low-glucosinolate varieties such as canola meal have become more favorable alternatives and can safely replace up to 50% of fishmeal in many aquafeeds when heat-treated.

Corn Gluten Meal (CGM)

Corn gluten meal is a by-product of the corn starch industry, containing 55–65% crude protein and rich in methionine but low in lysine (Li et al., 2019). It has high digestibility and acts as a good attractant in feeds due to its natural yellow pigment (xanthophylls), which enhances fish coloration. It is suitable for replacing 20–40% of fishmeal in diets for many freshwater species. CGM is highly digestible for most finfish species and has a unique profile: it contains minimal fiber and is relatively free from compounds that interfere with nutrient absorption, such as phytates or tannins. CGM also contains a moderate amount of lipids (2–4%), fibre, and phosphorus. Its carotenoid pigments (xanthophylls), particularly lutein and zeaxanthin, are responsible for its bright yellow color and serve as natural color enhancers in ornamental fish and crustaceans, improving body pigmentation and visual appeal. However, its palatability is lower than that of fishmeal due to a lack of certain attractants like nucleotides and free amino acids. Still, when used in combination with marine protein or flavor enhancers, it serves as an effective plant-based protein alternative.

2. Animal By-Product Meals

Animal by-products are valuable protein sources obtained from the processing of poultry, meat, and other livestock. These ingredients are highly digestible and nutritionally rich, but quality varies depending on processing methods. Animal by-products such as poultry by-product meal, meat and bone meal, blood meal, and feather meal are valuable alternatives because they are rich in high-quality protein and essential amino acids that closely resemble those in fishmeal. While animal by-products are nutritionally rich, variability in composition, risk of microbial contamination, and potential consumer concerns regarding feed safety require strict quality control, hygienic rendering processes, and traceability. When properly processed, these by-products significantly reduce the pressure on fishmeal resources and promote sustainable aquafeed development.

Poultry By-Product Meal (PBM)

PBM is one of the most promising animal-derived ingredients, containing 55–65% crude protein, moderate lipid content, and an amino acid composition comparable to fishmeal (Stevenson et al., 2017). It is particularly rich in glycine and proline. PBM has shown successful inclusion up to 75% replacement of fishmeal in diets of tilapia and catfish without compromising growth. However, quality assurance and hygienic processing are essential to prevent microbial contamination. Mineral content is also considerable especially phosphorus, calcium, and trace elements, which contribute to bone development and metabolic functions in fish. Its digestibility is high, and it introduces valuable nutrients such as phospholipids, cholesterol, and minerals, important for fish health and reproductive performance. The nutritional value of PBM largely depends on processing methods such as temperature, pressure, and time during rendering. Overheating or improper rendering can denature proteins and reduce digestibility. High-quality PBM is characterized by low ash content (<15%), minimal feather residues, and high digestibility.

Meat and Bone Meal (MBM)

MBM is obtained from the rendering of animal carcasses and bones. It provides 45–55% protein and is a good source of calcium and phosphorus, which are essential for skeletal development (Olsen et al., 2020), 8–12% lipid, and a significant mineral fraction. (However, the protein digestibility can vary depending on processing temperature. Excessive heating may reduce amino acid availability. Meat and bone meal are produced through rendering, a process involving heating, defatting, and drying of animal by-products. The rendering temperature and time directly influence the nutrient availability and digestibility of the final product. In aquaculture, MBM has been widely evaluated as a fishmeal replacement.

Blood Meal

Blood meal is a highly concentrated protein source with 80–90% crude protein, rich in lysine but deficient in isoleucine and methionine (Tacon & Metian, 2015). Additionally, blood meal contains high levels of iron, beneficial for preventing anemia and supporting erythropoiesis (red blood cell production) in fish. Although it supports rapid growth, poor palatability and dark coloration limit its inclusion in large amounts. Combining blood meal with other protein sources or adding flavor enhancers can improve feed acceptance.

Feather Meal

Hydrolyzed feather meal contains 70–80% protein, primarily keratin, which is poorly digestible unless properly hydrolyzed. It is rich in cysteine and other sulfur-containing amino acids but lacks lysine and methionine (Hertrampf and Piedad-Pascual, 2000). When included in small quantities (5–10%), it can serve as a cost-effective supplement.

3. Microbial and Algal Proteins

Microbial and algal proteins, often called single-cell proteins (SCPs), are gaining global attention as next-generation ingredients in aquaculture feeds. SCPs include protein biomass produced from yeast (e.g., *Saccharomyces cerevisiae*), bacteria (e.g., *Methylococcus capsulatus*), fungi, and microalgae (e.g., *Chlorella vulgaris*, *Spirulina platensis*). These organisms can grow on inexpensive carbon sources such as agricultural waste, molasses, methane, or carbon dioxide, converting them into high-quality protein biomass (Rossi et al., 2021).

Microbial and algal proteins provide an excellent balance of amino acids, vitamins, essential fatty acids, and antioxidants. For example, microalgae such as *Spirulina* and *Chlorella* are rich in proteins (55–70%), carotenoids,

and polyunsaturated fatty acids that enhance pigmentation, immunity, and antioxidant status in fish (Rahman et al., 2022). Yeast and bacterial proteins can also improve gut health by promoting beneficial microbiota and modulating immune responses. A major advantage of SCP production is its low environmental footprint, as it requires minimal land and water compared to conventional crops. Furthermore, it can utilize industrial by-products such as methane or glycerol, contributing to waste reduction. However, the high production cost and need for drying or processing technologies currently limit its widespread application in commercial aquafeeds. Continued advancements in bioreactor efficiency, fermentation technology, and cost-effective biomass recovery are expected to make SCPs more economically feasible in the future.

Yeast Protein

Yeast, particularly *Saccharomyces cerevisiae*, provides 45–55% crude protein along with B-complex vitamins and β -glucans that act as immunostimulants (Rahman et al., 2022). Yeast biomass can enhance gut health, disease resistance, and feed efficiency when used at 2–5% of diet formulations.

Bacterial Protein (*Methylococcus capsulatus*)

Bacterial proteins, such as those derived from *Methylococcus capsulatus*, are produced using methane as a carbon source and contain about 70% crude protein (Rossi et al., 2021). They exhibit high digestibility and a favorable amino acid profile. Large-scale bacterial protein production is emerging as a sustainable option for aquafeeds, reducing dependency on agricultural crops.

Microalgae

Microalgae like *Chlorella vulgaris* and *Spirulina platensis* provide 55–70% crude protein and are rich in essential amino acids, carotenoids, and polyunsaturated fatty acids (Rahman et al., 2022). *Spirulina* is especially valued for its antioxidant and immunostimulatory properties, improving fish coloration and stress tolerance. Although production costs remain high, integrating algae with wastewater treatment or CO₂ capture can make it more economical and eco-friendlier.

4. Insect Meal

Among all alternative protein sources, insect meal has emerged as the most sustainable and nutritionally balanced option for aquaculture. Insects are part of the natural diet of many fish species and possess an excellent amino acid profile, high digestibility, and beneficial functional compounds (Henry et al., 2015). The most commonly used species in feed production are black soldier fly (*Hermetia illucens*), mealworm (*Tenebrio molitor*), and housefly (*Musca domestica*). Black soldier fly larvae (BSFL) meal typically contains 40–60% crude protein, 10–20% fat, and a good balance of essential amino acids. It also provides antimicrobial peptides and chitin, which can enhance gut health and disease resistance (Makkar et al., 2014). Moreover, insects can be grown on organic waste, converting low-value materials like food scraps, manure, or crop residues into high-quality biomass within a short life cycle. This makes insect farming environmentally friendly and resource-efficient, with a much smaller carbon footprint compared to soybean or fishmeal production.

Several studies have reported successful partial replacement of fishmeal with BSFL meal in diets of tilapia, trout, and catfish without adverse effects on growth or feed conversion ratio. However, large-scale application is still limited by regulatory frameworks, production cost, and the need for standardized processing technologies. As insect production becomes more industrialized, it is expected to play a crucial role in sustainable and circular aquaculture feed systems.

Black Soldier Fly Larvae (BSFL)

The black soldier fly (*Hermetia illucens*) is the most researched insect species for aquafeed. BSFL meal contains 40–60% protein and 10–20% fat, with a balanced amino acid profile rich in lysine and methionine (Henry et al., 2015). It also contains chitin and antimicrobial peptides that enhance gut health and immunity (Makkar et al., 2014). BSFL can be reared on organic waste, converting it into valuable biomass efficiently. In addition to high protein content, BSFL contain various bioactive components such as chitin, lauric acid, and antimicrobial peptides, which provide functional benefits beyond basic nutrition. These compounds enhance gut health, modulate intestinal microbiota, improve immune responses, and reduce pathogen load in cultured species (Makkar et al., 2014). Feeding trials in species like tilapia, rainbow trout, catfish, and carp have demonstrated

good digestibility and palatability, with partial or full fishmeal replacement showing no negative impact on growth performance or feed conversion ratios.

One of the strongest advantages of BSFL is their role in environmental sustainability. The larvae can be mass-produced on organic waste streams—including agro-industrial by-products, food waste, and manure—converting low-value substrates into high-value protein efficiently (Wang & Shelomi, 2017). This bioconversion process reduces landfill waste, lowers greenhouse gas emissions, and supports circular economy principles in aquaculture. Therefore, BSFL represent a nutritionally robust, environmentally friendly, and economically viable ingredient for next-generation aquafeeds.

Mealworm (*Tenebrio molitor*)

Mealworm larvae meal provides around 45–55% crude protein and high lipid content (25–30%) with beneficial unsaturated fatty acids (Iaconisi et al., 2017). It has shown good digestibility and palatability in several fish species, such as rainbow trout and tilapia. Beyond their basic nutrient profile, mealworms provide functional advantages that support fish health and performance. Their proteins are highly digestible, and fish such as gilthead seabream, rainbow trout, and tilapia have shown excellent palatability and feed acceptance when mealworm meal is included in their diets (Gasco et al., 2016). In feeding trials, partial replacement of fishmeal with mealworm meal has resulted in maintained or improved growth rates, feed conversion ratios, and fillet quality, demonstrating the suitability of *T. Molitor* for commercial aquaculture applications (Iaconisi et al., 2017). From a sustainability perspective, mealworms offer a low-impact, efficient solution for alternative protein production. They require limited land and water, possess a short life cycle, and can be reared on a variety of organic by-products, significantly reducing feed production costs and environmental footprint (van Huis, 2013). As the aquafeed industry seeks environmentally responsible ingredients to replace fishmeal and fish oil, mealworm larvae stand out as an economically viable, nutritionally valuable, and scalable option for future fish nutrition.

Housefly Larvae (*Musca domestica*)

Housefly larvae (*M. Domestica*), commonly known as maggots, are increasingly recognized as a sustainable and cost-effective protein source for aquaculture feeds. Due to their rapid growth, ability to thrive on organic wastes, and high nutritional value, they offer a promising substitute for fishmeal in commercial aquafeeds.

Housefly larvae meal contains 40–60% crude protein and can replace 25–50% of fishmeal in aquafeeds (Wang & Shelomi, 2017). The larvae can be produced on organic wastes, supporting environmental sustainability and waste recycling. Essential amino acids: Good levels of lysine, threonine, and valine, minerals: Calcium, phosphorus, iron, and trace elements, chitin: A structural polysaccharide that may enhance gut health when fed at moderate levels. Protein digestibility generally ranges from 70–90% depending on species and processing method. Also, can effectively replace 25–50% of fishmeal without negative effects (Wang & Shelomi, 2017).

Conclusion

Alternative protein sources are becoming essential for making aquafeeds more sustainable and affordable. Ingredients like insect meals, plant proteins, algae, and microbial proteins provide good nutrition for fish while reducing pressure on wild fish stocks and lowering environmental impacts. Using these resources also helps recycle waste and supports a more circular, eco-friendly aquaculture system. As technology and research continue to improve, these alternative proteins will play a major role in producing healthier, greener, and more cost-effective aquafeeds in the future.

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Can Insects Eat Plastic? Nature's Tiny Allies Against Plastic Pollution



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Abstract

Plastic pollution has emerged as a silent but serious threat to Indian agriculture, affecting soil health, crop productivity, livestock and rural ecosystems. Agricultural plastics such as mulch films, fertilizer bags, irrigation pipes and packaging materials persist in the environment for decades. Recent scientific studies have revealed an unexpected natural solution, certain insects are capable of consuming and biologically degrading plastics. This article highlights the role of plastic-degrading insects, their gut microbes and enzymes and explores their potential application in eco-friendly plastic waste management for Indian agriculture. While insects alone cannot solve the plastic crisis, their biological machinery offers promising opportunities for sustainable and innovative waste management strategies.

Introduction

India generates nearly **3.5 million tonnes of plastic waste every year**, a significant portion of which originates from agriculture, food packaging and rural households. Plastic mulch films, seed packets, pesticide containers and irrigation materials have become indispensable in modern farming but their improper disposal has created long-term environmental problems. Plastics clog soils, reduce water infiltration, harm soil microorganisms and pose risks to grazing animals (Wang *et al.*, 2022).

Traditional disposal methods such as burning plastics in fields, dumping in landfills or partial recycling are neither safe nor sustainable. In this context, scientists are increasingly looking towards **nature-based solutions**, including insects, to mitigate plastic pollution.

Plastic-Degrading Insects: Nature's Unexpected Recyclers

Insects are known for their ability to digest tough natural materials such as wood, wax and plant fibers. These substances share chemical similarities with synthetic plastics. Based on this idea, scientists discovered that certain insects, mainly in their larval stages can consume and partially degrade plastics (Yang *et al.*, 2014).

Plastic-Eating Insects Identified So Far

- Waxworms (*Galleria mellonella*) - degrade polyethylene
- Mealworms (*Tenebrio molitor*) - degrade polystyrene, polyethylene, polypropylene and even PVC
- Rice moth larvae (*Corcyra cephalonica*) - degrade low-density polyethylene
- Flour beetles (*Tribolium spp.*) - degrade polystyrene and polyethylene foam
- Superworms (*Zophobas atratus*) - degrade Styrofoam and other polymers

These insects don't just chew plastic, they **biologically transform it**.

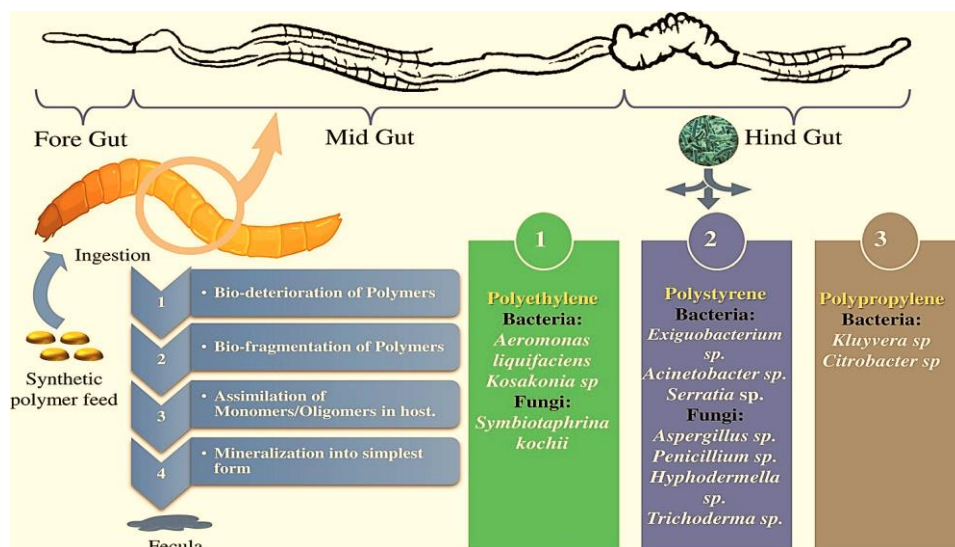
How do insects degrade plastic?

Plastic degradation by insects is not merely due to chewing. The process involves a synergistic action of insect digestive enzymes and gut microorganisms.

Three Key Steps

1. **Mechanical Breakdown:** Insects chew plastic into small fragments using strong mandibles.
2. **Microbial Action:** Gut bacteria and fungi colonize the plastic surface and weaken its structure (Engel & Moran, 2013).
3. **Enzymatic Degradation:** Enzymes such as oxidases, esterases, hydrolases and peroxidases break long plastic chains into smaller molecules that can be further metabolized (Ren *et al.*, 2019).

Studies have identified plastic-degrading bacteria such as *Enterobacter*, *Pseudomonas*, *Exiguobacterium* and *Klebsiella* from insect guts.



Waxworm Saliva: A breakthrough in plastic biodegradation

One of the most remarkable discoveries came from research on waxworms. Scientists found that waxworm saliva alone can oxidize and depolymerize polyethylene at room temperature within hours (Sanluis *et al.*, 2022).

Two enzymes named, **Demetra** and **Ceres** belonging to the phenol oxidase family were identified as the key agents. These are the first animal-derived enzymes shown to directly break carbon-carbon bonds in polyethylene, a major bottleneck in plastic biodegradation.

This discovery opens new possibilities for enzyme-based plastic recycling technologies.

Can insects live on plastic alone?

Although insects can survive on plastic diets, studies show that plastic is not an efficient energy source. Larvae feeding exclusively on plastic often show:

- Reduced body weight
- Slower growth
- Lower survival compared to normal diets

For example, confused flour beetle larvae feeding on polystyrene and polyethylene survived but lost significant body mass (Abdulhay, 2020). This indicates that insects are unlikely to become plastic-dependent pests, reducing ecological risk.

Relevance to Indian Agriculture

Plastic-degrading insects offer several indirect benefits for Indian farming:

- Identification of plastic-degrading enzymes
- Isolation of beneficial gut microbes
- Development of bio-based recycling units
- Reduction of plastic residues in rural areas

Rather than releasing insects into the environment, scientists emphasize using their enzymes and microbial systems in controlled waste-treatment facilities (Filippis *et al.*, 2023).

Challenges and Limitations

- Slow degradation rates
- Limited plastic specificity
- Difficulty in large-scale application
- Need for controlled conditions

Therefore, insect-based plastic degradation should be viewed as a supportive technology, not a standalone solution.

A Small Creature, A Big Solution

Once regarded only as pests, insects are now emerging as valuable allies in the fight against plastic pollution. By decoding their digestive systems and microbial partnerships, science is learning how nature tackles even the toughest materials.

In the future, solutions to plastic pollution may not come from machines alone but from the smallest recyclers nature has ever designed.

Conclusion

Plastic pollution poses a serious threat to Indian agriculture and the environment. Recent studies showing the ability of certain insects to degrade plastics offer a promising, eco-friendly approach to plastic waste management. Although insects alone cannot solve the plastic crisis, their gut microbes and enzymes provide valuable tools for developing bio-based recycling technologies. With continued research and responsible application, insect-mediated plastic degradation can support sustainable agriculture and contribute to a cleaner rural environment.

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Quality Management Strategies for Vegetable Crop Seeds



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Seed quality management is a critical component of successful vegetable crop production, as seed serves as the primary input determining crop establishment, uniformity, yield, and quality. Vegetables are highly sensitive to variations in seed quality due to their short growth cycles, high economic value, and strict market standards. Effective seed quality management encompasses genetic purity, physical purity, physiological vigour, and seed health, all of which collectively influence crop performance and profitability.

Importance of Seed Quality in Vegetable Crops

High-quality seeds ensure rapid and uniform germination, vigorous seedling growth, and better adaptability to field conditions. Poor-quality seeds result in uneven plant stands, increased susceptibility to pests and diseases, and reduced yield. Since many vegetable crops are grown under intensive cultivation systems and protected environments, even minor reductions in seed quality can lead to significant economic losses. Therefore, maintaining seed quality from production to sowing is essential for sustainable vegetable cultivation.

Components of Seed Quality

Seed quality is a multidimensional trait comprising the following key components:

Genetic purity: The trueness of the seed to its variety or hybrid. It is particularly important in vegetables where hybrid seeds dominate commercial cultivation. Genetic contamination leads to variability in plant growth, fruit shape, size, and maturity.

Physical purity: It involves the absence of inert matter, weed seeds, and seeds of other crops. Physically pure seed ensures accurate seed rate application and prevents the introduction of weeds into cultivated fields.

Physiological quality: Includes germination percentage, seed vigour, and seed longevity. High physiological quality enables seeds to germinate rapidly and uniformly even under suboptimal environmental conditions.

Seed health: It denotes freedom from seed-borne pathogens such as fungi, bacteria, viruses, and nematodes. Seed-borne diseases in vegetables often act as primary inoculum sources, causing severe losses during early crop stages.

Seed Production and Pre-Harvest Management

Seed quality management begins at the seed production stage. Selection of suitable agro-climatic conditions, isolation distances, and proper rouging are essential to maintain genetic purity. Regular field inspections during vegetative, flowering, and fruiting stages help in eliminating off-types and diseased plants.

Balanced nutrient management and adequate irrigation improve seed filling and physiological maturity. Timely harvesting is crucial, as immature seeds have low vigour, while over-mature seeds may suffer mechanical damage and field deterioration. In fleshy vegetables like tomato, brinjal, and cucumber, proper fruit maturity and controlled fermentation during seed extraction are important to maintain seed viability and health.

Post-Harvest Handling and Processing

Post-harvest operations significantly influence seed quality. Drying seeds to safe moisture levels is essential to prevent microbial growth and deterioration. For most vegetable seeds, moisture content should be reduced to 6–8 per cent before storage. Drying should be carried out under shade or controlled conditions to avoid thermal injury.

Seed processing operations such as cleaning, grading, and sizing improve physical purity and uniformity. Removal of undersized, shrivelled, and damaged seeds enhances overall seed lot performance. Mechanical injury during processing must be minimized, especially in delicate seeds like onion and carrot.

Seed Treatment and Seed Health Management

Seed treatment is a vital practice for managing seed-borne pathogens and improving seedling establishment. Chemical seed treatments using fungicides help control diseases such as damping-off, seed rot, and seedling blight. However, increasing concerns about environmental safety have encouraged the use of biological and eco-friendly seed treatments.

Biological agents such as *Trichoderma*, *Pseudomonas fluorescens*, and *Bacillus* species are widely used for vegetable seed treatment. These bioagents suppress pathogenic microorganisms, enhance seedling vigour, and promote early root growth. Botanical extracts and natural products are also gaining importance in sustainable seed health management.

Seed Storage and Packaging

Proper storage is essential to preserve seed viability and vigour until sowing. Vegetable seeds are generally short-lived and highly sensitive to temperature and humidity. Storage under cool and dry conditions significantly extends seed longevity. The use of moisture-proof containers such as aluminium foil pouches and laminated packets helps prevent moisture absorption.

The principle of low moisture content and low temperature is fundamental to maintaining seed quality. Regular monitoring of seed viability during storage helps in timely utilization of seed lots before deterioration occurs.

Seed Testing and Quality Assurance

Seed testing provides a scientific basis for assessing seed quality. Standard seed tests include germination, physical purity, moisture content, and seed health testing. Vigour tests such as accelerated ageing and electrical conductivity are particularly useful for predicting field performance of vegetable seeds.

Certification and quality control systems ensure that seeds supplied to farmers meet prescribed standards. Adherence to national seed standards and quality assurance protocols enhances farmer confidence and adoption of improved vegetable varieties.

Role of Integrated Seed Quality Management

Integrated seed quality management combines improved seed production practices, eco-friendly seed treatments, proper storage, and rigorous testing. This holistic approach reduces dependence on chemical inputs, improves crop establishment, and contributes to sustainable vegetable production systems. The integration of biological seed treatments with good agronomic practices strengthens plant resilience and enhances productivity.

Conclusion

Seed quality management is a cornerstone of profitable and sustainable vegetable crop production. Ensuring high genetic purity, physiological vigour, physical cleanliness, and seed health requires coordinated efforts at production, processing, storage, and distribution stages. With increasing emphasis on sustainable agriculture, integrated and biologically based seed quality management practices are gaining prominence. Adoption of scientific seed management strategies not only improves crop performance but also supports long-term agricultural sustainability and food security.

Role of Seaweed Extracts in Enhancing Growth and Productivity of Vegetable Crops



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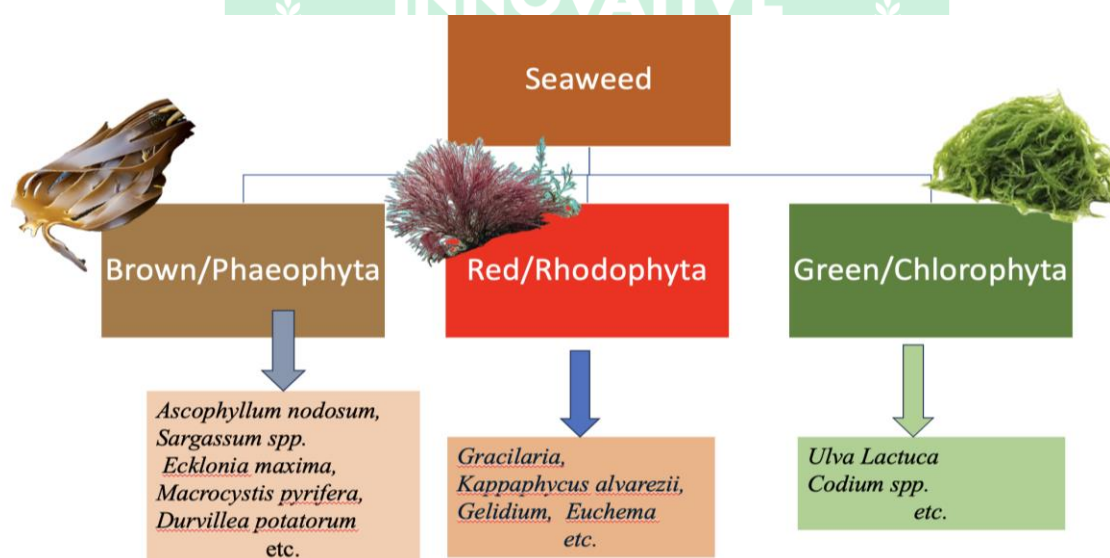
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Abstract

Seaweeds are marine macroalgae rich in plant nutrients, growth regulators, and bioactive compounds. In recent years, seaweed and seaweed-based products have gained importance in vegetable production due to their ability to enhance plant growth, yield, and quality in an eco-friendly manner. Seaweed extracts act as natural biostimulants, improving nutrient uptake, root development, stress tolerance, and overall crop performance. This article highlights the role of seaweed in promoting growth and productivity of vegetable crops.

Introduction

Seaweeds are large, multicellular marine algae found in oceans and coastal regions. They are broadly classified into **brown (Phaeophyceae)**, **red (Rhodophyceae)**, and **green (Chlorophyceae)** algae. Commonly used seaweeds in agriculture include *Ascophyllum nodosum*, *Sargassum*, *Laminaria*, *Kappaphycus*, and *Gracilaria*. Traditionally used as organic manure in coastal farming systems, seaweed is now widely processed into **liquid seaweed extracts (LSEs)** and granular formulations. These products are increasingly applied in vegetable crops due to their growth-promoting, soil-improving, and stress-mitigating properties.



Nutrient Composition of Seaweed

Seaweeds contain a wide range of essential nutrients required for plant growth:

- ❖ **Macronutrients:** Nitrogen (N), Phosphorus (P), Potassium (K), Calcium (Ca), Magnesium (Mg), Sulphur (S)
- ❖ **Micronutrients:** Iron (Fe), Zinc (Zn), Copper (Cu), Manganese (Mn), Boron (B), Molybdenum (Mo)
- ❖ **Organic compounds:** Amino acids, vitamins, carbohydrates, and polysaccharides

Though nutrient concentrations are moderate, their availability and synergistic action enhance nutrient uptake efficiency in vegetable crops.

Presence of Plant Growth Regulators

One of the most important roles of seaweed is the presence of natural **plant growth hormones**, such as:

1. **Auxins:** Promote root initiation and elongation
2. **Cytokinins:** Stimulate cell division, delay leaf senescence, and enhance photosynthesis
3. **Gibberellins:** Encourage stem elongation and leaf expansion
4. **Betaines:** Improve stress tolerance and chlorophyll stability

These growth regulators play a crucial role in improving early seedling vigor and overall vegetative growth in vegetables.

Effect on Root Growth and Nutrient Uptake

Application of seaweed extracts significantly improves **root architecture**, including root length, root volume, and lateral root formation. A well-developed root system enhances water and nutrient absorption, leading to better plant growth. Enhanced microbial activity in the rhizosphere further improves nutrient availability.

Influence on Vegetative Growth

Seaweed application increases plant height, leaf number, leaf area, and chlorophyll content in vegetable crops such as tomato, chilli, cabbage, brinjal, cucumber, and onion. Improved photosynthetic efficiency results in higher biomass accumulation and vigorous crop growth.

Role in Flowering, Yield, and Quality

Seaweed extracts positively influence reproductive growth by:

- ❖ Enhancing flowering and fruit set
- ❖ Reducing flower drop
- ❖ Increasing fruit size, weight, and uniformity
- ❖ Improving quality attributes such as color, taste, vitamin content, and shelf life

Vegetable crops treated with seaweed products often show increased marketable yield.

Stress Tolerance and Plant Health

Seaweed helps vegetable crops withstand **abiotic stresses** such as drought, salinity, heat, and nutrient stress. Bioactive compounds present in seaweed activate plant defense mechanisms, enhance antioxidant activity, and improve tolerance to environmental stress conditions.

Improvement of Soil Health

When applied to soil, seaweed improves soil structure, water-holding capacity, and microbial population. Polysaccharides present in seaweed act as natural soil conditioners, enhancing soil fertility and sustainability.

Methods of Application in Vegetable Crops

Seaweed products can be applied through:

- ❖ **Seed treatment:** Improves germination and early vigor
- ❖ **Foliar spray:** Common method for rapid absorption and growth stimulation
- ❖ **Soil application or fertigation:** Enhances root growth and soil health

Recommended concentrations generally range from **2–5 ml per liter of water** for liquid seaweed extracts, depending on the crop and product.

Environmental and Sustainable Benefits

Seaweed is biodegradable, non-toxic, and environmentally safe. Its use reduces dependence on chemical fertilizers, lowers production costs, and supports sustainable vegetable production systems.

Conclusion

Seaweed plays a significant role in enhancing growth, yield, quality, and stress tolerance of vegetable crops. Acting as a natural biostimulant, seaweed improves root development, nutrient uptake, and physiological processes in plants. Due to its eco-friendly nature and multifunctional benefits, seaweed-based products are increasingly becoming an integral component of sustainable vegetable cultivation.

Role of CLIMWAT Software in Climate-Based Agricultural Water Management



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Abstract

Efficient irrigation planning and sustainable water resource management depend heavily on accurate climatic information. CLIMWAT, developed by the Food and Agriculture Organization (FAO), is a global climatic database software designed to provide long-term average climate data required for estimating crop water requirements and irrigation scheduling. The software contains standardized datasets from thousands of meteorological stations worldwide, including temperature, rainfall, humidity, wind speed, and sunshine duration, which are essential for calculating reference evapotranspiration. CLIMWAT is widely used in combination with the CROPWAT model to support irrigation design, water allocation planning, and climate impact assessment. Its accessibility, global coverage, and compatibility with decision-support tools make it particularly valuable for developing regions where real-time climate data is limited. This article highlights the features, applications, and significance of CLIMWAT in promoting climate-smart agriculture and improving water use efficiency.

Keywords: CLIMWAT, Crop Water Requirement, Irrigation Scheduling, Climate Smart Agriculture

Overview of CLIMWAT Software

CLIMWAT is a database application designed to store and provide monthly average climatic data from thousands of meteorological stations worldwide. The software works in close integration with FAO's CROPWAT model, which estimates crop water requirements and irrigation scheduling. The database includes key climatic parameters such as minimum and maximum temperature, relative humidity, wind speed, sunshine duration, and rainfall. These parameters are essential for calculating reference evapotranspiration (ET_o), a core variable used in irrigation planning and crop water requirement estimation.

Key Features and Capabilities

One of the major strengths of CLIMWAT is its global coverage, containing climate records from more than 5,000 stations representing diverse agro-climatic zones. This wide coverage allows users to analyse climatic conditions even in regions with limited local weather station data. CLIMWAT offers standardized and quality-controlled datasets, ensuring compatibility with irrigation design tools.

The user-friendly interface allows quick selection of stations and direct export of data into CROPWAT software. Another important feature is the availability of long-term climatic averages, which are useful for strategic planning, feasibility studies, and irrigation project design.

Role in Irrigation Planning and Design

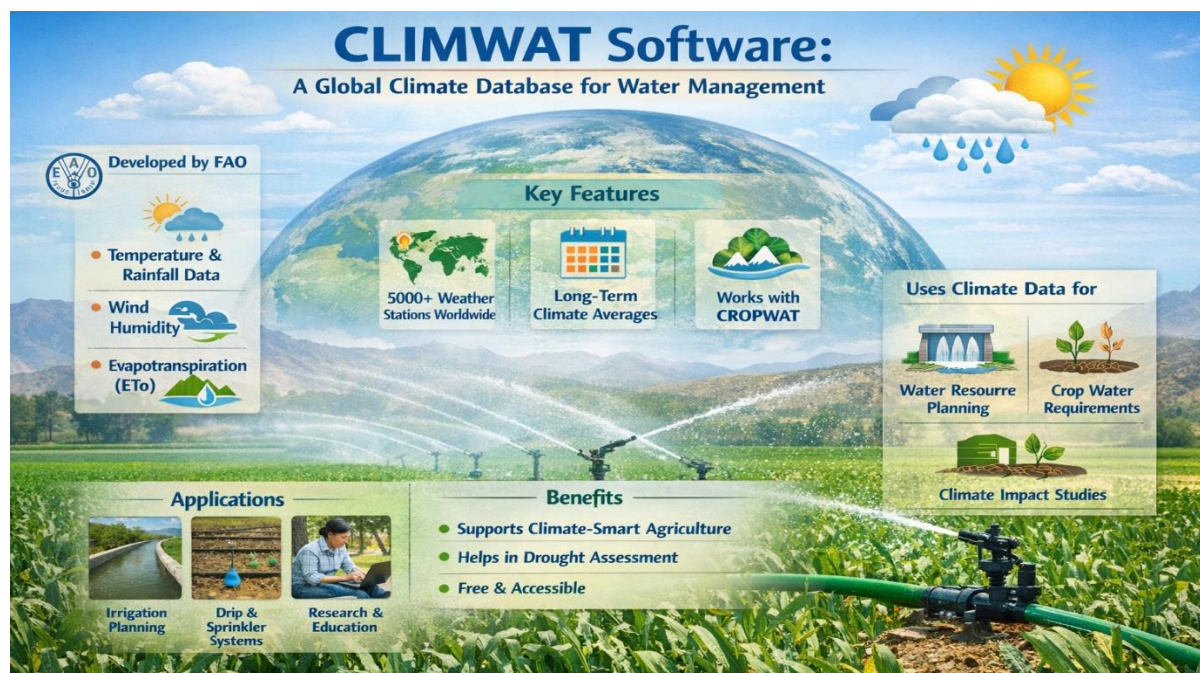
CLIMWAT plays a significant role in estimating irrigation water demand. By providing climatic inputs required to calculate evapotranspiration, the software supports accurate assessment of crop water needs.

In large-scale irrigation projects, CLIMWAT data is used to estimate seasonal water requirements for canal design, reservoir capacity planning, and water allocation strategies. For micro-irrigation systems such as drip and sprinkler irrigation, the software helps optimize irrigation schedules, reduce water losses, and improve water use efficiency.

Contribution to Climate-Smart Agriculture

Climate variability and rising temperatures have increased uncertainty in agricultural production systems. CLIMWAT contributes to **climate-smart agriculture** by enabling long-term analysis of climatic trends and their impact on crop water demand.

The software helps identify drought-prone areas, evaluate cropping patterns, and design irrigation strategies that improve resilience to climate stress. This makes CLIMWAT particularly useful for sustainable agricultural development in water-scarce regions.



Applications in Research and Education

CLIMWAT is widely used in academic institutions for teaching irrigation engineering, agricultural meteorology, and water resource management. Students use the software to understand the relationship between climate variables and crop water requirements.

Researchers apply CLIMWAT data for irrigation modelling, climate impact studies, watershed management, and agricultural planning projects. Government agencies also use the software for preparing irrigation master plans and national water development programs.

Benefits for Developing Countries

In many developing countries, limited access to high-quality meteorological data restricts irrigation planning efforts. CLIMWAT provides a reliable secondary data source that supports infrastructure development in data-scarce regions.

The software is freely available and requires minimal computing resources, making it accessible to extension agencies, NGOs, and rural development organizations.

Limitations and Future Scope

Although CLIMWAT provides valuable long-term average climate data, it is not designed for real-time weather forecasting or daily irrigation scheduling. The software is best suited for planning, design, and strategic assessment purposes.

Future improvements could include integration with satellite-based climate datasets, automatic database updates, and linkage with real-time weather monitoring systems.

Conclusion

CLIMWAT software has emerged as a vital tool for improving irrigation efficiency and promoting sustainable water management. By bridging climate data with irrigation planning models, it supports informed decision-making at farm, project, and policy levels. As climate challenges continue to intensify, the importance of reliable climate-based planning tools like CLIMWAT will continue to grow.

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The Broken Bridge: Why the Extension Worker is the Architect of India's Second Green Revolution



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For nearly eight decades, India's agricultural narrative has been celebrated through the lens of macro-successes: The Green Revolution, the attainment of food self-sufficiency, and our rise as a leading global exporter. Yet, beneath these statistics lies a profound micro-failure. There exists a staggering "Extension Gap"—a chasm between the cutting-edge breakthroughs of agricultural scientists and the practical reality of the smallholder farmer. While our satellites and labs operate in the 21st century, the "last mile" delivery mechanism remains paralyzed by bureaucratic inertia.

The failure to develop a professional, ubiquitous, and technically competent extension mechanism to cover every village across the length and breadth of the country is the single greatest administrative tragedy of post-independence India. Without a human bridge to carry science to the soil, the farmer is left to navigate an increasingly volatile climate using nothing more than traditional intuition and the biased advice of commercial interests.

The Vacuum of Authority and the Pesticide Trap

In the absence of a government extension worker, a dangerous vacuum is created. Agriculture is a time-sensitive, biological science that requires constant technical oversight. When a farmer observes yellowing leaves or a sudden pest infestation, they cannot afford to wait for a distant government agency to respond. In this void, the local input dealer becomes the "de facto" scientist.

This creates a catastrophic conflict of interest. The dealer, whose primary motive is to sell volume, often prescribes expensive and unnecessary chemical "cocktails." For millions of farmers, this lack of professional guidance leads directly into a debt trap. They spend a significant portion of their potential profit on inputs that degrade the soil, poison the groundwater, and fail to address the root cause of crop failure. We have traded the technical authority of the state for the commercial interests of the salesman.

The Necessity of Hyper-Local Agrometeorological Advisories

The most pressing argument for a revitalized extension service is the need for hyper-local agrometeorological advisories. In an era of climate change, broad regional weather forecasts are virtually useless to the individual farmer. A rainstorm in one village does not guarantee water for the next; a heatwave may devastate a wheat crop in one production system while a nearby horticultural farm remains unaffected.

Currently, farmers lack the technical support to translate weather data into specific farm-level actions. We need extension workers capable of providing tailored advice that accounts for the specific crop variety, the stage of growth, and the unique production system of each farm. Whether it is adjusting the irrigation schedule for a high-intensity dairy farm or shifting the sowing window for a rain-fed cereal crop, these decisions must be based on micro-climatic data. A human expert must be present to interpret these signals, ensuring that the farmer reacts to the atmosphere with precision rather than panic.

The Mirage of Digital-Only Extension

In a bid to bypass the logistical challenge of staffing the last mile, recent governance has pivoted heavily toward "Digital Agriculture." While apps and SMS alerts are impressive in boardrooms, they are a poor substitute for a human interface on the ground. Agriculture is intensely localized. A centralized digital blast cannot feel the moisture in a specific patch of silt or identify a localized fungal strain unique to a specific micro-climate. Digital tools are force-multipliers, not the force itself. A farmer needs a trusted professional who can integrate digital data with the physical reality of the field.

The Structural Decay of the Last Mile

The collapse of the extension mechanism is the result of decades of systemic neglect. In most Indian states, technical cadres at the village level have been allowed to wither away. Large percentages of sanctioned posts for Agriculture Extension Officers remain vacant, while those employed are frequently diverted to administrative chores like election duties or subsidy census management. This has led to a "Paper-Pushing" culture where success is measured by the number of Soil Health Cards printed rather than actual improvements in soil quality or farmer income. A card is a dead piece of paper if there is no extension officer to sit with the farmer and explain how to adjust fertilizer applications based on that data.

Conclusion: The Knowledge-Sovereign Future

To scale the Indian economy and achieve true food security, the nation must treat the extension worker as the most critical infrastructure in the country. We require a mandate where every cluster of villages is served by a dedicated professional who is part of a specialized service. This mechanism must move away from the "Welfare Model," where the extension worker is merely a distributor of doles, toward a "Wealth Creation Model."

The glory of our agricultural achievement must shift from the volume of grain in our godowns to the depth of knowledge in our fields. Developing a professional extension army to cover every acre of the country is not an administrative burden; it is the highest-return investment the state can make. Until the scientist's lab is connected to the farmer's land by a permanent, human bridge, India's Green Revolution will remain unfinished.



Sustainable Agriculture: A Pathway to Food Security and Environmental Protection



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Introduction

Agriculture remains the backbone of the Indian economy, supporting nearly half of the population directly or indirectly. However, modern agricultural practices have increasingly relied on excessive chemical fertilizers, pesticides, and intensive farming methods, leading to soil degradation, environmental pollution, and declining productivity. In this context, **sustainable agriculture** has emerged as a vital approach to ensure long-term food security while conserving natural resources.

Concept of Sustainable Agriculture

Sustainable agriculture refers to farming systems that are **economically viable, environmentally sound, and socially acceptable**. It focuses on maintaining soil fertility, conserving water, reducing chemical inputs, and promoting biodiversity, without compromising crop yield and farmer income.

The key principles of sustainable agriculture include:

- Efficient use of natural resources
- Conservation of soil and water
- Reduced dependence on synthetic agrochemicals
- Enhancement of ecological balance
- Long-term productivity and profitability

Importance of Sustainable Agriculture

Sustainable farming plays a crucial role in addressing the major challenges faced by present-day agriculture:

1. **Soil Health Improvement**
Continuous use of chemical fertilizers depletes soil organic matter. Sustainable practices such as crop rotation, green manuring, and compost application improve soil structure, fertility, and microbial activity.
2. **Environmental Protection**
Reduced pesticide and fertilizer usage minimizes air, soil, and water pollution. Sustainable agriculture helps in lowering greenhouse gas emissions and mitigating climate change impacts.
3. **Water Conservation**
Techniques like drip irrigation, mulching, and rainwater harvesting enhance water-use efficiency and reduce wastage, which is essential in water-scarce regions.
4. **Economic Stability for Farmers**
Lower input costs, diversified cropping systems, and premium prices for sustainably produced crops improve farmers' income and reduce financial risks.

Major Sustainable Agricultural Practices

Several practices have proven effective in promoting sustainability in agriculture:

- **Integrated Nutrient Management (INM):** Combines organic manures, biofertilizers, and chemical fertilizers for balanced nutrition.
- **Integrated Pest Management (IPM):** Utilizes biological control, resistant varieties, and cultural practices to manage pests with minimal pesticide use.
- **Organic Farming:** Avoids synthetic inputs and relies on natural processes for crop production.
- **Conservation Agriculture:** Emphasizes minimum tillage, crop residue retention, and crop diversification.

- **Use of Resistant Varieties:** Cultivation of pest- and disease-resistant crop varieties reduces crop losses and chemical dependence.

Role of Sustainable Agriculture in Food Security

With the global population increasing rapidly, ensuring sufficient food production is a major challenge. Sustainable agriculture enhances productivity while preserving resources for future generations. It ensures consistent crop yields, improves nutritional quality, and supports resilient farming systems capable of withstanding climate variability.

Challenges in Adoption

Despite its benefits, adoption of sustainable agriculture faces challenges such as lack of awareness, limited access to resources, initial transition costs, and inadequate technical support. Strengthening extension services, farmer training programs, and government incentives can help overcome these barriers.

Conclusion

Sustainable agriculture is not merely an alternative farming approach but a necessity for the future of food production. By integrating traditional knowledge with modern scientific innovations, sustainable practices can protect the environment, improve farmer livelihoods, and ensure food security. Widespread adoption of sustainable agriculture will play a decisive role in building a resilient and environmentally responsible agricultural system.



“Born in the Rainforests, Crowned in Kingdoms: The Botanical Legend of Black Pepper”



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ABSTRACT:

Black pepper (*Piper nigrum* L.), belonging to the family Piperaceae, is among the most widely traded spices in the world and is prized for its pungent flavour, which comes from the compound piperine. It is a perennial climbing vine grown mainly for its berries, widely used both as a spice and for medicinal purposes. India plays a major role as a producer, consumer and exporter of black pepper, with cultivation largely concentrated in Kerala, Karnataka, and Tamil Nadu. The crop grows best under humid tropical conditions with high rainfall, warm temperatures and well-drained soils rich in organic matter. From a botanical perspective, the vine produces different types of shoots that aid climbing, spreading and fruiting, and it is commonly propagated through vegetative methods such as runner shoot cuttings and serpentine layering. Balanced nutrient management, including recommended NPK application and the use of microbial consortia, supports healthy growth and yield. Harvesting at the proper stage of maturity and adopting appropriate post-harvest practices are crucial for maintaining quality and overall value.

Key words: Black pepper, *Piper nigrum*; piperaceae; humid tropics; vegetative propagation; nutrient management; postharvest practices

Introduction

Black pepper (*Piper nigrum* L.), a member of the family Piperaceae, is one of the most widely traded spices in the world, valued for its sharp and pungent flavour derived from the natural compound piperine. It is a perennial climbing vine cultivated for its berries, which are widely used as a spice and also for medicinal purposes. India stands as a major producer, consumer, and exporter of black pepper globally. The spice is mainly cultivated in Kerala, Karnataka, and Tamil Nadu, with smaller growing areas in Maharashtra, the northeastern states, and the Andaman and Nicobar Islands. Among these, Kerala and Karnataka contribute the largest share of black pepper production in the country.

Botany

The pepper plant is classified as a climbing and spreading perennial vine. It develops underground roots that absorb nutrients from the soil, while the aerial roots act as adhesive structures that help the plant cling to supports. The stem is robust and can reach heights of up to 10 m. The leaves are glossy, with a dark green upper surface and a lighter green underside. They are oval in shape with pointed tips, measuring approximately 10 cm in length. In black pepper, five portions are identified.

- Main stem: It originates from the seed or from a cutting.
- Runner shoots: It's produced from the basal portion of the main stem.
- Fruiting branches (Plagiotropes): produced from the nodes of the main stem.
- Topshoots (Orthotropes)
- Hanging shoots (Geotropes)

Climate and Soil

Black pepper is a crop of the humid tropics and requires high rainfall along with high humidity for optimal growth. It is successfully cultivated between 20° north and south latitudes and at elevations of up to 1,500 m above sea level. The crop performs best within a temperature range of 23–32°C, with an optimum temperature of around 28°C. An ideal relative humidity of 75–80% is considered favourable for its growth and development.

Black pepper thrives in a wide range of soils, from heavy clay to light sandy clay, provided they are rich in humus, friable in nature, and well-drained while retaining adequate moisture. Soils with a neutral pH, high organic matter content, and good base saturation, particularly with calcium and magnesium, enhance crop productivity.

Morphology

Black pepper vines produce three distinct types of shoots. The primary climbing shoots have long internodes and develop adventitious roots at the nodes, enabling them to cling to supporting structures. Runner shoots arise from the base of the vine, creep along the ground, possess long internodes, and form roots at each internode. In addition, the vine produces lateral shoots, which are responsible for bearing fruit. Propagating cuttings are mainly obtained from runner shoots, although terminal shoots may also be used.

Propagation

Black pepper is mainly propagated by cuttings taken from runner shoots. Runner shoots selected from healthy, high-yielding vines are gently coiled on wooden pegs placed at the base of the vine. This prevents the shoots from coming into direct contact with the soil and forming roots. During February and March, the runner shoots are detached from the vine and, after trimming the leaves, cuttings consisting of two to three nodes are prepared. These cuttings are then planted either in nursery beds or in polythene bags filled with potting mixture.

Serpentine Layering

Serpentine layering is a simple, farmer-friendly technique that enables the production of multiple plants from a single vine and is widely practised. Compared to seed propagation, it is a more efficient method for black pepper. In this method, healthy runner shoots are bent, and several of their nodes are buried in the soil, allowing each buried node to develop roots and produce new shoots.

Planting

With the onset of the monsoon, pits of 50 × 50 × 50 cm are prepared at a distance of about 30 cm from the base of the supporting tree, preferably on the north, east, or northeastern side. These pits are filled with a mixture of topsoil and farmyard manure at the rate of 5 kg per pit, along with 50 g of rock phosphate.

Chemical Content of Black Pepper

Black pepper contains a wide range of chemical constituents, including piperine, saponins, flavonoids, essential oils, and chavicine. The relative proportions of these compounds vary considerably, mainly depending on varietal differences and the quality of black pepper.

Nutrient Application

The recommended blanket nutrient application for black pepper vines aged three years and above is NPK at 50:50:150 g per vine per year. During the establishment phase, only one-third of this dose is applied in the first year, which is increased to two-thirds in the second year. From the third year onwards, the full recommended dose is applied annually to support optimum growth and yield.

Microbial consortium:

A talc-based formulation containing a consortium of plant growth-promoting rhizobacteria (*Micrococcus luteus*, *Enterobacter aerogenes* and *Micrococcus* sp) is used in black pepper both in the nursery and in the main field to improve plant growth and yield. For application, 20 g of the talc formulation is mixed in one litre of water and applied at the rate of 250 ml per vine in the field and 100 ml per bag in the nursery. As an alternative method, 1 kg of the talc formulation may be thoroughly mixed with 100 kg of farmyard manure before application.

Pests and diseases of black pepper:

Pollu beetle: (*Longitarsus nigripennis*)

The adult insects feed on the growing tips, leaves, tender spikes, and berries. The grubs tunnel into the berries, turning them black and causing them to crumble easily when pressed.

Top shoot borer: (*Cydia hemidox*)

The caterpillars bore into the tender shoots, causing them to turn black and dry up.

Leaf gall thrips: (*Liothrips karnyi*)

Thrips live in groups inside the tubular galls they induce along the leaf margins. As a result, the affected leaves become thickened, distorted, and crinkled.

Scale insects: (*Lepidosaphes piperis*)

Drying of the infested portion of the vine.

Disease of the black pepper:

Quick wilt: (*Phytophthora capsici*)

The pathogen attacks the leaves and spikes, and collar infections can lead to the sudden collapse of the vine. Other signs include yellowing of leaves and leaf drop. Excess soil moisture and high humidity during the monsoon promote the infection and its spread.

Pollu disease:

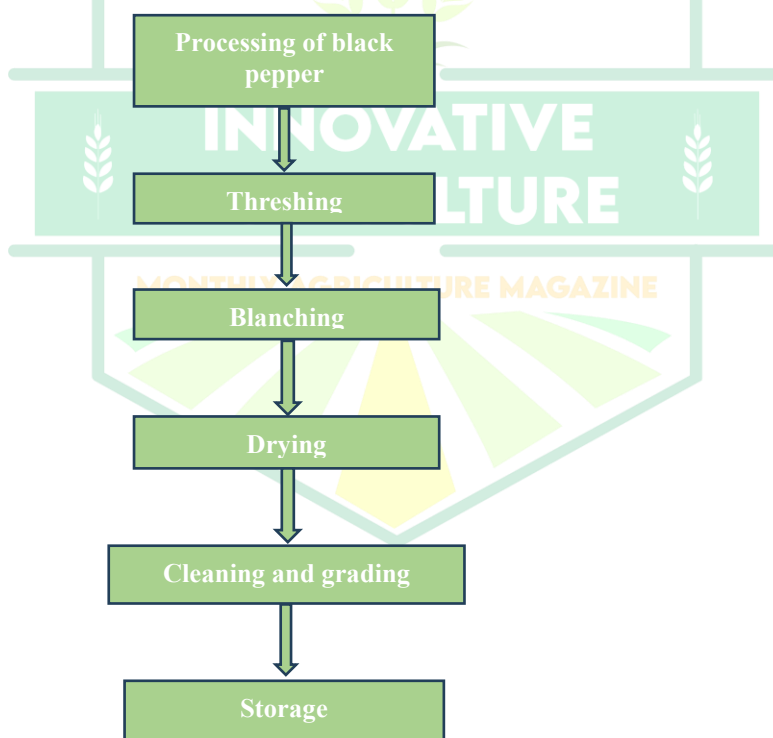
Young berries develop brown, sunken patches that eventually form distinctive cross-splits, turn black, and dry out.

Harvesting

Black pepper requires about seven to eight months after flowering to attain full maturity. In India, harvesting is usually carried out from December to January in the plains, while in the high ranges it extends from January to April. Harvesting begins when one or two berries on the spike start turning yellow, indicating the appropriate stage of maturity.

The spikes are hand-picked by nipping them off and collected in bags. Harvested spikes are generally gathered in clean gunny bags. Spikes that fall on the ground are collected separately, cleaned thoroughly, and then mixed with the main lot. The stage of maturity at harvest is important, as it determines suitability for processing into different black pepper products.

Post-Harvest Processing of Black Pepper



Threshing

Traditionally, despiking is carried out by trampling with the feet. However, this method is crude and labour-intensive and poses a high risk of contamination with extraneous matter such as soil particles and other impurities. To facilitate easier separation of berries from the spikes, the harvested spikes are sometimes heaped and left for one or two days before threshing.

Blanching

The quality of black pepper can be enhanced through a simple pre-drying treatment. Mature berries placed in a perforated container are dipped in boiling water for about one minute before drying, which helps improve the overall quality of the final product.

Drying

Drying is the most critical processing step for black pepper. At harvest, pepper berries contain about 60–70% moisture, which must be reduced to safe levels through proper drying. During the drying process, enzymatic browning occurs, in which phenolic compounds are oxidised by atmospheric oxygen under the catalytic action of the enzyme phenolase, ultimately causing the berries to turn black.

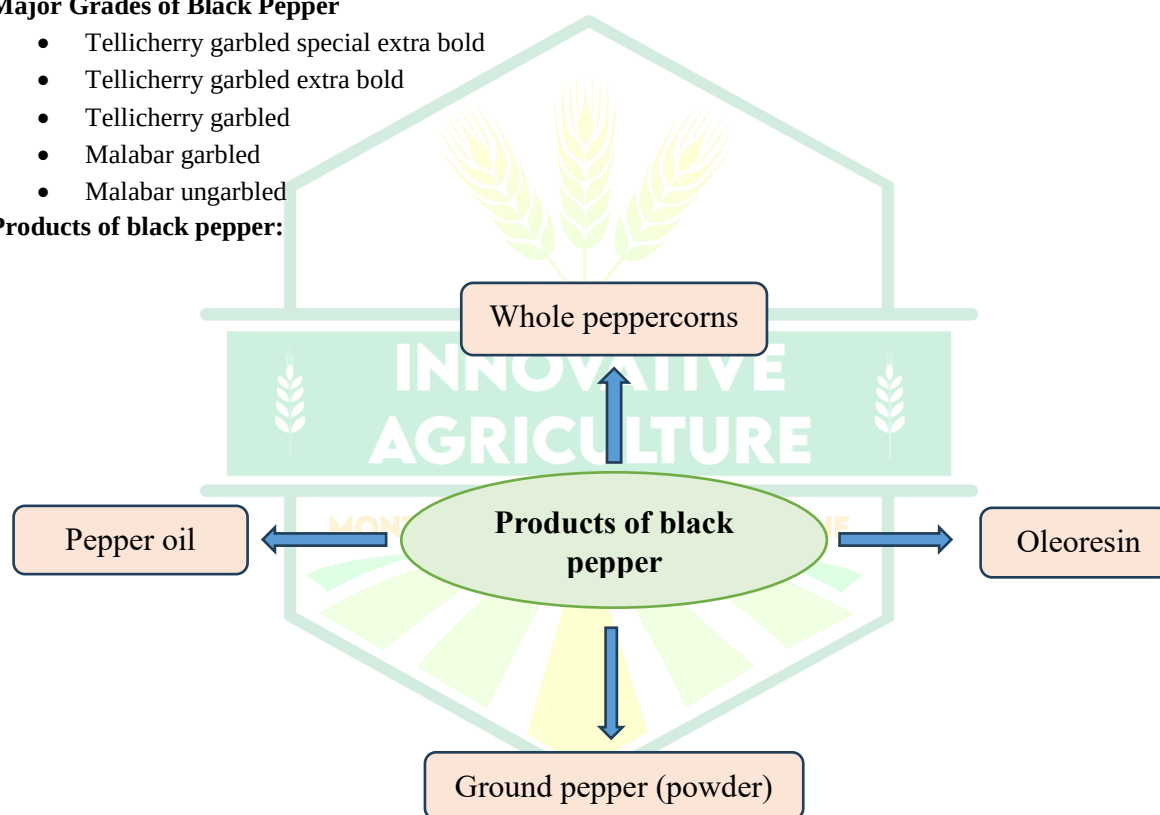
Cleaning and Grading

Threshed and dried black pepper often contains extraneous materials such as spent spikes, pinheads, stones, and soil particles. Cleaning and grading are therefore essential operations, as they improve the quality of the produce, enhance its market value, and enable higher economic returns.

Major Grades of Black Pepper

- Tellicherry garbled special extra bold
- Tellicherry garbled extra bold
- Tellicherry garbled
- Malabar garbled
- Malabar ungarbled

Products of black pepper:



Storage:

Black pepper readily absorbs moisture from the surrounding air. During the rainy season, when humidity levels are high, this can lead to the development of mould and increased insect infestation. To prevent such problems, the produce should be dried to a moisture level below 10 per cent before storage. After grading, the pepper is bulk-packed separately in multilayer paper bags or woven polypropylene bags fitted with food-grade liners.

Conclusion:

Black pepper is an important spice crop with high agricultural and economic value. Its cultivation depends on humid tropical climatic conditions and well drained, organic matter rich soils. The botanical characteristics of the vine influence its growth climbing habit and fruit production. Vegetative propagation methods ensure uniform and efficient plant establishment. Balanced nutrient management supports healthy growth and sustainable yield. Harvesting at the correct stage of maturity is essential for quality produce. Proper postharvest help maintain the value of black pepper from field to market.

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Remote Sensing and GIS-Based Soil Texture Mapping for Precision Land Management



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Abstract

Soil texture is one of the most fundamental properties controlling soil behaviour, influencing water retention, infiltration, aeration, nutrient availability, root penetration, and overall land productivity. Traditional soil texture mapping based on field sampling and laboratory analysis, although accurate, is time-consuming, labour-intensive, and often impractical for large and heterogeneous landscapes. With the rapid advancement of geospatial technologies, Remote Sensing (RS) and Geographic Information Systems (GIS) have emerged as powerful tools for spatially explicit soil texture mapping at multiple scales. These technologies enable the integration of satellite imagery, digital elevation models, climate data, and field observations to generate high-resolution, cost-effective, and repeatable soil texture maps. Such maps are essential for precision land management, which seeks to optimize land use, agricultural inputs, and conservation practices according to site-specific conditions. This article discusses the principles of soil texture mapping, the role of remote sensing and GIS, commonly used data sources and analytical techniques, integration with machine learning, validation approaches, applications in precision land management, challenges, and future prospects. The article aims to provide a comprehensive yet accessible overview for researchers, practitioners, students, and policymakers interested in applying geospatial technologies for sustainable soil and land management.

1. Introduction

Soil is a dynamic natural resource that forms the foundation of terrestrial ecosystems and agricultural production. Among the various soil properties, soil texture defined as the relative proportion of sand, silt, and clay particles plays a central role in determining soil physical, chemical, and biological behaviour. Texture influences water holding capacity, drainage, erosion susceptibility, nutrient retention, and the response of soils to management practices. Consequently, accurate knowledge of soil texture distribution across landscapes is critical for effective land use planning, crop selection, irrigation scheduling, fertilizer management, and soil conservation.

Historically, soil texture information has been derived from conventional soil surveys based on extensive field sampling, profile description, and laboratory analysis. While these methods provide high accuracy at sampled locations, they are costly, time-consuming, and often limited in spatial coverage. Moreover, traditional soil maps may not capture fine-scale spatial variability that is crucial for precision land management.

The emergence of Remote Sensing (RS) and Geographic Information Systems (GIS) has revolutionized the way soil properties are mapped and monitored. Satellite and airborne sensors provide continuous, synoptic, and multi-spectral observations of the Earth's surface, while GIS offers a framework for managing, analysing, and visualizing spatial data. When combined with digital soil mapping techniques, RS and GIS enable the prediction of soil texture across large areas with improved spatial resolution and efficiency.

Precision land management is an approach that tailors management practices to spatial variability within fields and landscapes. It relies heavily on accurate, high-resolution spatial information on soil and terrain attributes. Soil texture maps generated using RS and GIS form a critical input for this approach, supporting data-driven decision-making aimed at enhancing productivity, reducing environmental impacts, and promoting sustainability.

This article explores how remote sensing and GIS technologies are used for soil texture mapping and how the resulting information contributes to precision land management. It also highlights recent methodological advancements, practical applications, and future directions in this rapidly evolving field.

2. Understanding Soil Texture and Its Importance

Soil texture refers to the relative proportions of sand (2.0–0.05 mm), silt (0.05–0.002 mm), and clay (<0.002 mm) particles in a soil. These proportions are typically represented using a soil texture triangle, which classifies soils into textural classes such as sandy loam, clay loam, silty clay, and loamy sand.

The importance of soil texture stems from its strong influence on soil functions:

- **Water dynamics:** Coarse-textured soils (sandy) drain rapidly and hold less water, while fine-textured soils (clayey) retain more water but may have poor drainage.
- **Nutrient availability:** Clay and silt particles have higher surface area and cation exchange capacity, allowing greater nutrient retention compared to sand.
- **Root growth and aeration:** Medium-textured soils (loams) provide a favourable balance between aeration and water availability.
- **Erosion susceptibility:** Fine-textured soils are more prone to compaction, whereas sandy soils are more vulnerable to wind erosion.

Because soil texture is relatively stable over time compared to other soil properties, it serves as a foundational layer for many soil and land management decisions. However, texture can vary significantly within short distances due to differences in parent material, topography, and depositional processes. Capturing this variability requires spatially detailed mapping approaches, which is where RS and GIS play a transformative role.

3. Remote Sensing for Soil Texture Mapping

Remote sensing involves acquiring information about the Earth's surface without direct contact, typically using sensors mounted on satellites, aircraft, or unmanned aerial vehicles (UAVs). For soil texture mapping, remote sensing data provide indirect indicators related to soil reflectance, surface roughness, moisture, and vegetation cover.

3.1 Spectral Characteristics of Soils

Soil particles of different sizes and mineral compositions exhibit distinct spectral reflectance patterns in the visible, near-infrared (NIR), and shortwave infrared (SWIR) regions. For example:

- Sandy soils generally show higher reflectance due to larger particle size and lower organic matter content.
- Clay-rich soils often exhibit absorption features associated with clay minerals and bound water.
- Organic matter and moisture reduce overall reflectance.

By analysing these spectral signatures, it is possible to infer soil texture or develop predictive models linking spectral data to measured texture fractions.

3.2 Satellite and Airborne Data Sources

Commonly used remote sensing platforms include:

- **Landsat series:** Moderate spatial resolution and long historical record.
- **Sentinel-2:** High spatial and temporal resolution with multiple spectral bands.
- **MODIS:** Useful for regional-scale studies.
- **Hyperspectral sensors:** Provide hundreds of narrow bands, enabling detailed mineralogical analysis.

Airborne and UAV-based sensors offer even higher spatial resolution, making them suitable for field-scale precision mapping.

3.3 Vegetation as an Indicator

In many landscapes, soil is partially or fully covered by vegetation. Vegetation patterns reflect underlying soil properties, including texture. For instance, differences in crop vigor, canopy density, or stress may indicate variations in soil water holding capacity related to texture. Vegetation indices such as NDVI can thus serve as indirect predictors.

4. Role of GIS in Soil Texture Mapping

Geographic Information Systems provide the analytical backbone for integrating diverse spatial datasets and performing digital soil mapping.

4.1 Spatial Data Integration

GIS allows the combination of:

- Remote sensing imagery
- Digital elevation models (DEMs)
- Climate data
- Land use/land cover maps
- Field soil sample locations

This integration supports comprehensive spatial analysis and modelling.

4.2 Terrain Analysis

Topography strongly influences soil formation processes. Derived terrain attributes such as slope, aspect, curvature, and topographic wetness index are commonly used as predictors in soil texture models.

4.3 Spatial Interpolation and Modelling

GIS provides tools for spatial interpolation (e.g., kriging, inverse distance weighting) and supports advanced modelling approaches, including machine learning, to predict soil texture across unsampled locations.

5. Digital Soil Mapping and Machine Learning

Digital Soil Mapping (DSM) combines soil observations with environmental covariates to produce continuous soil property maps.

5.1 Conceptual Framework

DSM is based on the idea that soil properties are a function of soil-forming factors: climate, organisms, relief, parent material, and time.

5.2 Machine Learning Algorithms

Popular algorithms include:

- Random Forest
- Support Vector Machines
- Artificial Neural Networks
- Gradient Boosting

These methods can capture complex, non-linear relationships between predictors and soil texture.

5.3 Model Training and Validation

Field soil samples are split into training and validation datasets. Model performance is evaluated using metrics such as R^2 , RMSE, and MAE.

6. Validation and Accuracy Assessment

Accuracy assessment is critical to ensure reliability of soil texture maps.

- Cross-validation techniques
- Independent validation datasets
- Uncertainty mapping

These approaches help identify areas of high and low confidence.

7. Applications in Precision Land Management

Soil texture maps support numerous precision land management practices.

7.1 Precision Agriculture

- Variable-rate irrigation
- Site-specific fertilizer application
- Crop suitability analysis

7.2 Water Resource Management

Texture maps guide irrigation design, drainage planning, and groundwater recharge assessment.

7.3 Soil Conservation

Identifying erosion-prone areas and planning conservation structures.

7.4 Land Use Planning

Supporting zoning, infrastructure development, and environmental impact assessment.

8. Challenges and Limitations

- Influence of soil moisture and vegetation cover
- Limited availability of field data
- Model transferability
- Computational and technical requirements

9. Future Perspectives

Emerging technologies such as hyperspectral imaging, cloud computing, artificial intelligence, and digital twins will further enhance soil texture mapping capabilities. Integration with Internet of Things (IoT) sensors and participatory data collection is expected to improve model accuracy and usability.

10. Conclusion

Remote sensing and GIS-based soil texture mapping represents a transformative approach for generating spatially detailed, cost-effective, and timely soil information. By integrating spectral data, terrain attributes, and field observations within digital soil mapping frameworks, it is possible to capture the inherent spatial variability of soil texture across landscapes. Such information is indispensable for precision land management, enabling site-specific decisions that enhance productivity, optimize resource use, and reduce environmental impacts.

While challenges related to data quality, model uncertainty, and technical capacity remain, continuous advancements in sensor technology, machine learning, and cloud-based platforms are steadily addressing these limitations. As these technologies become more accessible, RS- and GIS-based soil texture mapping is poised to become a standard component of sustainable land management strategies, supporting global efforts toward food security, climate resilience, and environmental conservation.



Challenges, Opportunities, and Future Directions in Marine Ornamental Fish Breeding and Culture



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Abstract

Broodstock management plays a key role in the successful breeding of marine ornamental fish. Healthy and well-maintained broodstock help produce quality eggs and larvae, which are vital for sustainable fish farming. Good nutrition, proper tank design, and suitable environmental conditions support natural spawning and reduce stress in fish. When natural breeding fails, hormone treatments can be used to improve reproduction. Disease prevention through quarantine and biosecurity is also essential to protect both broodstock and their offspring. By improving broodstock care, water quality, and larval feeding methods, farmers can increase survival rates and reduce the need to collect fish from the wild. This approach supports both profitable aquaculture and marine conservation.

Introduction:

The ornamental fish trade includes many aquatic species, with freshwater and marine fish being the most valuable. Around 1,800 marine species are traded globally. Although marine ornamentals form less than 10% of total trade, their high value adds greatly to revenue. About 90% of freshwater ornamentals are bred in captivity, but 90–95% of marine species are still collected from the wild. This overreliance on wild stocks causes coral reef damage, mortality from chemicals, and ecosystem decline.

Coral reefs also face threats from human activities and climate change, calling for urgent conservation. Captive breeding is a key solution, though research on larval rearing and species requirements remains limited. Despite these challenges, marine ornamental aquaculture is vital for both economic growth and reef protection. However, large-scale farming faces biological and technical barriers. Many species lack visible sex differences and have complex breeding patterns. Larval rearing is difficult due to the need for specific pelagic conditions and suitable live feed. Limited knowledge of species biology makes sustainable marine ornamental fish culture complex and resource-demanding.



Breeding technique for Damsel fish developed by CMFRI

Broodstock Conditioning and Reproductive Regulation

Ornamental fish aquaculture faces the critical challenge of managing the wide variability in reproductive strategies among species to meet increasing market demands. The reproductive development of broodstock encompasses three primary phases: gonadal development (including gonadogenesis and gametogenesis), final oocyte maturation, and gamete release—ovulation and spawning in females, and milt expulsion in males. Effective broodstock conditioning is fundamental for ensuring the production of viable, high-quality gametes within captive breeding systems. Achieving this objective requires the integration of several key components, such as optimized tank design, the application of behavioral or hormonal stimuli to enhance reproductive activity, and the systematic selection and maintenance of broodfish. Broodstock management must account for physical attributes like body size, age, and morphology, as well as complex biological determinants, including social

dynamics, potential for sex differentiation or reversal, gamete quality at morphological and biochemical levels, disease resilience, and conservation of genetic variability. These principles, well established in food fish hatcheries, are equally crucial for the successful propagation of marine ornamental species, facilitating sustainable production, broodstock welfare, improved larval survival, and overall hatchery efficiency

Broodstock Husbandry and Applied Reproductive Techniques

Once breeders acquire their broodstock, creating the ideal mix of nutrition and environmental stability is key to supporting sexual development and encouraging natural spawning. Many ornamental fish species, though beautiful, sometimes struggle to breed in captivity, which makes technical interventions necessary for successful egg and larval production. When fish do not spawn reliably on their own, specialists use assisted methods such as hormone treatments or careful, manual collection of eggs and milt. While these practices are somewhat invasive, they're often crucial for maintaining healthy stock and ensuring hatchery productivity. Good results come from balancing careful daily care with scientific reproductive assistance—because the health and quality of fish eggs depend on both.

RAS units for Anthias broodstock rearing and spawning



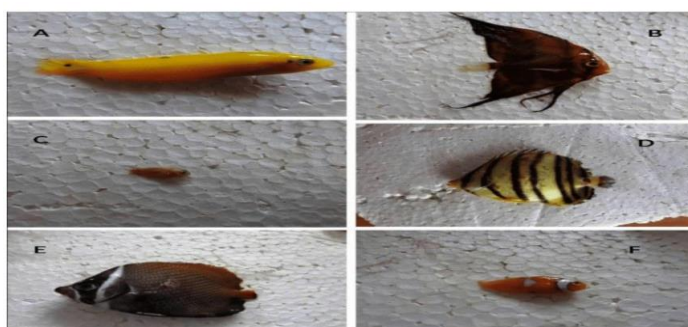
Ornamental marine species also show remarkable—and sometimes hard to imitate—breeding behaviors. That means hatcheries rely on strategies like adjusting water temperature and daylight hours, giving special feeds, using hormone cues, and, if needed, manually extracting eggs. Bringing these approaches together helps improve spawning reliability and larval survival, supporting a robust and sustainable aquarium trade.

Disease Management and Biosecurity in Marine Ornamental Fish Hatcheries

Disease control is a cornerstone of successful hatchery operations, with broodstock management playing a pivotal role in preventing the introduction and transmission of infectious agents. Pathogens such as bacteria, fungi, parasites, and particularly viruses can be transmitted vertically from infected broodstock to their offspring through gametes. Marine ornamental fish are susceptible to a range of pathogens including bacterial species like *Mycobacterium*, *Vibrio*, *Aeromonas*, *Pseudomonas*, and *Myxobacteria*, as well as parasites such as *Cryptocaryon*, *Amyloodinium*, *Uronema*, and monogenean trematodes. The initial and most critical step in disease prevention is the selection of healthy, pathogen-free broodstock. Although specific pathogen-free (SPF) broodstock programs have been successful in commercial species such as shrimp and food fish, their use in marine ornamental fish remains limited due to the frequent reliance on wild-caught broodstock, which are exposed to endemic pathogens and may acquire additional infections during capture or transport.

Different types of diseases associated with the aquarium fish in the Hatchery

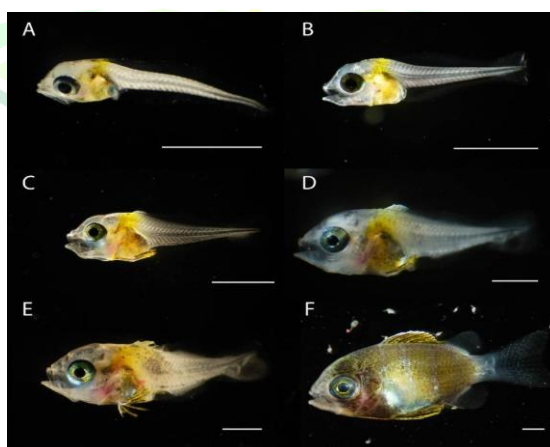
Given the difficulties in sourcing SPF broodstock, hatcheries must implement vigilant disease surveillance and early diagnostic procedures, alongside robust biosecurity protocols to minimize pathogen entry, prevent vertical transmission, and control disease outbreaks effectively. These protocols include strict quarantine of new broodstock, routine health monitoring, and adherence to best practices in hygiene and water quality management. As the ornamental fish industry grows, increased research into disease profiles and health management tailored to marine ornamentals is essential. Concurrently, the use of probiotics, immunostimulants, and other preventive measures should be incorporated into an integrated health management strategy to enhance biosecurity and support sustainable production.



Gamete Physiology, Embryonic Development, and Larval Morphology at Hatch

Developing effective captive breeding protocols for marine ornamental aquaculture depends on a thorough understanding of gamete physiology, embryological stages, and early larval morphology. Foundational research in these areas is essential for optimizing broodstock management and enhancing larval rearing techniques. Species-specific indicators such as gamete quality, embryonic developmental milestones, and larval features at hatch are critical for evaluating reproductive status and predicting offspring viability before beginning larval culture. Key parameters include the size and structure of gametes, the timing and progression of embryogenesis, larval size and morphology at hatch, yolk reserve levels, and the development of functional traits like mouth opening, swimming capability, and sensory organ formation.

Environmental and biological factors during egg incubation significantly influence embryogenesis, affecting both hatching success and the quality of larvae. Variables such as temperature, salinity, oxygen concentration, and light conditions play critical roles in determining embryonic survival and developmental rates. As such, understanding the ontogenetic processes of marine ornamental species helps identify how environmental conditions shape larval fitness and survival outcomes. Although some baseline data exist for select ornamental marine species, further research is needed to characterize species-specific developmental patterns. This includes studies on physiological and immunological tolerances, energy utilization during embryogenesis, and morphological milestones relevant to first feeding and metamorphosis. Advancing this knowledge base is essential for designing species-adapted rearing systems, improving hatchery efficiency, and enhancing the overall sustainability of marine ornamental fish production.



Larval development of laboratory-reared *A. saxatilis* at: A) 1 dph, B) 5 dph, C) 9 dph, D) 11 dph, E) 14 dph, and F) 22 dph

Larval Rearing Challenges in Marine Ornamental Aquaculture

Larval rearing represents a major challenge in advancing marine ornamental aquaculture, as successfully nurturing larvae through their vulnerable early stages is essential for commercial sustainability. Despite progress in larval culture techniques for food fish and freshwater ornamentals, marine ornamental species still lag behind in research and technology. Unlike some species, marine ornamental fish typically do not provide parental care post-

spawning. Their larvae enter a planktonic phase soon after hatching, making them highly prone to predation, including from other plankton feeders or even their own parents if they remain nearby. This lack of protection combined with the delicate nature of planktonic larvae results in high mortality rates in captivity, posing significant obstacles to reliable larval rearing.



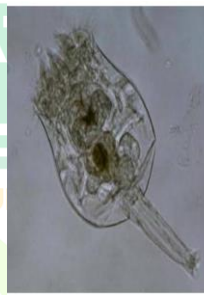
Multi-tank RAS unit for clownfish rearing and spawning

Larval Nutrition in Marine Ornamental Fish

Larval nutrition is vital for fish survival, growth, and development in hatcheries. Important feed features include particle size, movement, and nutrient content like proteins and essential fatty acids. Live feeds such as rotifers and *Artemia* nauplii are commonly used but don't fully match the diversity of natural diets. Early larvae have immature digestive systems, making appropriate feed composition and timing crucial. Including high-quality proteins, fatty acids, vitamins, and minerals supports larval health, immunity, and pigmentation. Tailoring diets to larval digestive capacity improves survival and growth in marine ornamental aquaculture.



Artemia



Rotifer

Water Quality and System Design in Marine Ornamental Fish Hatcheries

Effective water quality management and system design are essential for the success of marine ornamental fish hatcheries. Since species have varying tolerances and preferences for water conditions at different developmental stages, mimicking their natural environments is a proven strategy. Marine ornamental fish, often from nutrient-poor reef habitats, are especially sensitive to pollutants such as ammonia, nitrite, and nitrate, which commonly accumulate in dense aquaculture systems. Maintaining clean, stable water parameters through proper filtration, aeration, and monitoring is critical to ensuring healthy fish development and hatchery productivity.

Conclusion

Marine ornamental aquaculture remains in its early stages of development, facing several persistent challenges and knowledge gaps particularly in species-specific biology, larval rearing, and sustainable breeding techniques. As global demand for ornamental marine species grows, focused research and innovation across critical areas such as broodstock management, larval nutrition, disease control, and system design will be essential for overcoming current bottlenecks and improving production efficiency. Continued advancements in these domains hold the potential not only to establish a commercially viable and environmentally responsible industry but also to contribute meaningfully to coral reef conservation and marine ecosystem management. By bridging the gap between scientific research and practical aquaculture application, the marine ornamental sector can support both biodiversity preservation and sustainable economic growth.

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ANTI NUTRITIONAL FACTORS IN SORGHUM



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Introduction

Sorghum is a major food and nutritional security crop to most of Asian and African countries. It is a staple food crop on which the lives of billions of people depend. It is a good source of energy, proteins, carbohydrates, vitamins and minerals including the trace elements, particularly iron and zinc. Sorghum grain also contains minerals such as phosphorus, calcium, potassium and magnesium in varying quantities. To be used for human consumption sorghum is processed into a variety of traditional foods including fermented and non-fermented products such as unleavened bread, porridges, cookies, cakes, cereal extracts, malted alcoholic and non-alcoholic beverages. However, sorghum-based foods have continued to be nutritionally deficient and organoleptically inferior. This is largely due to the presence of anti-nutritional factors (ANF) such as tannin, phytic acid, oxalate, polyphenol and trypsin inhibitors.

Many plant components have the potential to precipitate adverse effects on the productivity of farm livestock (D'Mello, 2000). These compounds are present in the food, foliage and/or seeds of virtually every plant that is used in practical feeding. These compounds are often called anti-nutritional factors. Anti-nutritional factors are also those generated in natural feedstuff by the normal metabolism of the specie from original materials and by different mechanisms exert effects contrary to optimum nutrition (Chubb, 1982). Anti-nutritional factors may be grouped according to their mode of action as follows.

- Substances depressing digestion or metabolic utilisation of protein e.g. protease inhibitors, lectins (haemagglutinins), saponins and polyphenolic compounds.
- Substances reducing or interfering with the utilisation of mineral elements e.g. Phytic acid, oxalic acids, glucosinolates and gossypol
- Substances inactivating or increasing the requirements of certain vitamins e.g. Anti-vitamins A, D, E and K, anti-thiamine, nicotinic acid, pyridoxine and cyanocobalamin.

Some anti-nutritional factors may however exhibit more than one mode of activity. Sorghum (*Sorghum bicolor* (L) Moench) is widely grown in the semi-arid and arid regions. It benefits from an ability to tolerate drought, soil toxicities and temperature extremes effectively than other cereals. Sorghum grains contain about 92.50% dry matter, 3270.00kcal/kg metabolizable energy for poultry, 9.50% crude protein, 2.55% ether extract, 2.70% crude fibre, 1.25% ash and 76.60% nitrogen free extract (NFE). Its protein is slightly higher than maize but as with most cereals deficient in lysine and tryptophan. More importantly, some varieties of sorghum grain have been reported to contain anti-nutritional factors chiefly tannin which binds proteins and impair digestion (Aduku, 2004 and Etuk and Ukaejiofo, 2007).

Sorghum contains key anti-nutritional factors (ANFs) like tannins, phytic acid, and trypsin inhibitors, which bind nutrients, reducing mineral/protein absorption and digestibility; also present are dhuririn (cyanogenic glycoside, toxic in sprouts/shoots). These compounds decrease nutrient bioavailability, but processing like malting, fermentation, soaking, and germination effectively reduces them, improving sorghum's nutritional value for human and animal consumption.

Sorghum basically contains two major anti-nutritional factors; tannin, a polyphenolic compound located in

the grain and, dhurrin a cyanogenic glucoside located mainly in the aerial shoot and sprouted seeds. Tannins are high in sorghum with brown pericarp and no testa and very low in unpigmented grains. The main anti-nutritional effects of tannins are: reduction in voluntary feed intake due to reduced palatability, diminished digestibility and utilisation of nutrients, adverse effects upon metabolism and toxicity. The level of tannins present in sorghum seems to be the predominant factor that influences its nutritional value.

Drying, soaking, grinding and pelleting appear to reduce tannin content in feedstuffs while diet supplementation with methyl group donors like choline and methionine reduce the problems associated with tannins in livestock. Dhurrin, on enzyme action readily yields hydrogen cyanide (HCN). The quantity of HCN in sorghum varies with cultivar and the growth condition but diminishes with age. Excess cyanide ion can quickly produce anoxia of the central nervous system through inactivating the cytochrome oxidase system and death can result within a few seconds. Making fodder into hay or silage however, destroys the poison.

Major Antinutritional Factors in Sorghum:

1. **Tannins (Polyphenols):** Found in the grain's outer layer, they bind to proteins and digestive enzymes, reducing protein digestibility, palatability, and nutrient utilization, and can cause toxicity.
2. **Phytic Acid (Phytate):** Forms complexes with minerals (iron, zinc, calcium, magnesium), making them unavailable for absorption, lowering mineral bioavailability.
3. **Trypsin Inhibitors:** Block the action of trypsin, a crucial enzyme for protein digestion, hindering protein utilization.
4. **Dhurrin:** A cyanogenic glucoside in shoots and sprouted seeds, it releases toxic hydrogen cyanide (HCN) when digested, potentially causing poisoning, especially in livestock.

Effects on Nutrition:

1. **Reduced Mineral Absorption:** Tannins and phytates bind essential minerals like iron, zinc, calcium, and magnesium, decreasing their uptake.
2. **Decreased Protein Utilization:** Tannins and trypsin inhibitors interfere with protein digestion and absorption.
3. **Lower Feed Intake & Digestibility:** Tannins reduce palatability and create astringent tastes, leading to less consumption and poorer digestion.

Reduction Methods:

Antinutrients are phenolic compounds in crops that have a capability of binding essential nutrients into complexes and making them unavailable in both human and animal diets. Phenolic compounds, mainly phytic acid, condensed tannins, oxalate and trypsin inhibitors are common antinutrients in sorghum. Malting and Fermentation are an effective and potential biochemical process for the reduction of anti-nutritional factors in sorghum flour to safe level. Considerable amounts of phytate, condensed tannin, and oxalate and trypsin inhibitor from sorghum flour were significantly reduced as germination period elongated. The decreased antinutrients in sorghum have contributed to leaching of water soluble phenolic compounds and activated enzyme activities during malting. Reduction of tannins, oxalate, trypsin inhibitor and phytic acid content in sorghum increased with an increase in fermentation time. The reduction is as a result of exogenous and endogenous enzymes, microbial degradation and optimum pH conditions formed during fermentation. Consequently, Malted and fermented sorghum flour resulted in improved nutritive value and sensory characteristics of sorghum flour.

1. **Germination/Malting:** It will increase enzyme activity, breaking down phytates and tannins, and leaching water-soluble phenolics.
2. **Fermentation:** During fermentation microbial action and pH changes further degrade Anti Nutritional Factors, improving nutrient availability.
3. **Soaking and Grinding:** It helps in leaching out of several anti-nutrients.
4. **Processing (Hay/Silage):** It is the best method to destroy dhurrin in forage sorghum.
5. **Variety Selection:** It is the best approach and utilization of low-tannin sorghum varieties improves nutritional quality.

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Marine Protected Areas – as a tool for resource conservation



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Introduction

Marine ecosystems are vital for global biodiversity, food security, and the livelihoods of coastal communities. However, overfishing, habitat destruction, pollution, and climate change have severely degraded marine resources, causing declines in fish stocks and disrupting marine food chains. These threats highlight the urgent need for effective management measures to protect marine ecosystems for future generations. Marine Protected Areas (MPAs) are recognized as an important tool for marine conservation. They help protect critical habitats, conserve biodiversity, and support the recovery of overexploited fish populations by regulating human activities. MPAs enhance habitat diversity, safeguard threatened species, preserve genetic resources, and support fisheries through fish spillover and larval dispersal. They also serve as scientific reference sites to assess human impacts. Overall, MPAs play a key role in marine resource conservation and sustainable fisheries management.

Marine Protected Areas

Marine Protected Areas (MPAs) are defined in several ways, but in general they refer to ocean regions that receive a certain degree of special protection for conservation. These areas can vary from temporary or seasonal closures of spawning grounds to zones permanently closed to fishing, and also include marine parks with multiple zoning systems that permit different activities in different areas.

According to the IUCN, Marine Protected Area is defined as a geographic region that are legally or effectively managed to achieve long term protection of natural resources, ecosystem services and cultural values.

Categories of Marine Protected Areas as per IUCN

Category 1a

Strictly protected areas are created mainly to conserve biodiversity and important geological features. Human access and activities are highly restricted or carefully managed to protect these values. They also serve as important sites for scientific research and long-term environmental monitoring.

Category 1b

These areas are large regions that are mostly unaltered, or only minimally modified, retaining their natural features and ecological processes. They have little or no permanent human settlement and are managed to conserve their natural state.

Category 2

These are large natural or near-natural areas set aside to conserve ecological processes, species, and ecosystems. They also allow for culturally and environmentally appropriate activities like spiritual practices, research, education, and recreation. Managed mostly as “no-take” zones, extraction is generally prohibited, with limited use allowed for scientific research, invasive species control, or sustainable use by indigenous communities following traditional practices.

Category 3

These areas protect specific natural monuments, such as landforms, seamounts, caves, geological features, or unique living elements like coral formations. They are usually small but attract many visitors because of their distinctive features.

Category 4

These areas focus on conserving specific species or habitats. They often need active management to support the target species or habitats, though not all areas require intervention.

Category 5

These areas are shaped by long-term interactions between humans and nature, giving them unique ecological, cultural, and scenic value. Preserving this relationship is essential to maintain their conservation and other benefits.

Category 6

These areas protect ecosystems and habitats while preserving cultural values and traditional resource management. They are usually large, mostly natural, with some parts managed for sustainable, low-intensity, non-industrial use that supports conservation goals.

Benefits of Marine Protected Areas

Marine Protected Areas can aid fisheries management and can promote sustainable benefits which includes

1. Controlling fish mortality of sedentary species in data-poor situations

MPAs are an effective management tool for fisheries targeting small, sedentary fish or invertebrate populations. Unlike methods such as Total Allowable Catches, MPAs do not require precise stock estimates, making them suitable for data-poor fisheries and areas with limited management capacity. However, their success still depends on strong enforcement and sufficient knowledge of species distribution, population density, and habitat needs.

2. Assisting management of multispecies fisheries

Managing multispecies fisheries is difficult when many species-specific rules are needed and information is limited. In such cases, MPAs can protect groups of species associated with particular habitats. Combining species-specific measures with multi-species MPAs provides an effective fisheries management approach.

3. Minimizing bycatch

Bycatch usually occurs in predictable areas and seasons, and experienced fishers are often aware of these patterns. Fishers generally try to reduce bycatch because it is wasteful and increases sorting effort, though high bycatch levels may sometimes be accepted as unavoidable. MPAs can effectively reduce bycatch when they are established in locations and seasons where bycatch and discards are highest.

4. Buffering against uncertainty

MPAs can be combined with other fisheries management measures to reduce uncertainty and improve overall management. When traditional approaches fail, such as due to stock assessment errors, MPAs can act as a safeguard by limiting damage. However, their effectiveness depends on proper design and the biological traits of the target species. While understanding these traits is important, processes like larval dispersal are often poorly understood.

5. Delegating management responsibilities or tasks

In many areas, co-management allows fisheries management responsibilities to be shared between government authorities and local communities. MPAs provide clear spatial boundaries where such shared management can occur. Local communities may take part in patrolling, monitoring, maintenance of infrastructure, rule enforcement, research, and awareness programs. Co-management increases stakeholder participation, empowers local users through shared decision-making, and reduces the management burden on government agencies.

6. Protecting traditional and cultural use rights and practices

Although MPAs are sometimes viewed as conflicting with indigenous rights, they can also help recognize and protect traditional fishing grounds, cultural sites, and customary practices. In some cases, indigenous communities need support to safeguard these areas from external threats. The Convention on Biological Diversity encourages protected areas that respect and preserve indigenous knowledge, and policies by IUCN, WCPA, and WWF support protecting indigenous interests and customary use. When indigenous communities aim to sustain their traditional livelihoods, MPAs can protect customary rights while supporting fisheries management and biodiversity conservation. Active involvement of indigenous peoples in planning and managing MPAs is essential for success.

7. Protecting and enhancing local livelihoods

MPAs are often seen as harming coastal livelihoods, but in some cases, they protect small-scale fishing grounds by reserving coastal zones for artisanal fishers. As resources recover within MPAs, fish stocks increase, leading to higher catches inside and around protected areas, which can improve local livelihoods.

Although MPAs are most effective when based on sound scientific planning, they are not a standalone solution for marine conservation. While they play a key role in protecting biodiversity, MPAs remain vulnerable to threats such as pollution and climate change. Therefore, they must be integrated with broader ecosystem-based management across the wider marine environment.

Future of Marine Protected Areas

Marine Protected Areas (MPAs) are increasingly recognized as effective tools for improving fisheries management and conserving biodiversity. At the same time, globalization has highlighted the importance of decentralized governance, allowing affected stakeholders to play a greater role in decision-making. In this context, MPAs offer additional opportunities in an increasingly interconnected world

1. Integrated marine spatial management

Marine Protected Areas (MPAs), when used as tools for fisheries management and biodiversity conservation, need to be incorporated into wider spatial management frameworks in order to balance multiple environmental and social values and demands. When carefully designed and effectively implemented, MPAs offer a valuable opportunity to promote cross-sectoral strategies and to connect the objectives of fisheries management with those of biodiversity conservation.

2. Decentralization policies and co-management

Ongoing trends toward decentralizing authority to local governments and communities—such as through fisheries and ecosystem co-management arrangements encourage active stakeholder participation in the planning and implementation of Marine Protected Areas (MPAs). This represents a significant development from which MPAs can both gain and to which they can contribute, as lessons learned from MPA management can help shape policies related to decentralization and shared governance responsibilities.

3. MPA Networks

The shift from establishing individual Marine Protected Areas (MPAs) to developing interconnected MPA networks offers greater flexibility in management approaches. However, similar to single MPAs, the success of MPA networks depends on thorough, holistic, integrated, and participatory planning processes.

4. Sustainability of MPAs

The long-term sustainability of Marine Protected Areas (MPAs) depends on effective management that achieves stated objectives and maintains continuous communication and engagement with stakeholders to build political commitment and support, as well as to secure sustainable financing. The growing recognition of the importance of the environment and ecosystem services provides an opportunity to explore innovative financing mechanisms, including Payment for Ecosystem Services (PES) schemes.

5. Research and new technologies

Although much has been learned about how marine ecosystems respond to MPAs, long-term monitoring and well-designed research are still needed to better assess their effectiveness. This is especially important at larger scales, including fisheries, ecosystem processes, and social and economic impacts. New technologies such as VMS, GIS, and information-sharing platforms offer valuable tools to improve MPA planning and implementation.

Challenges confronting Marine Protected Areas in an evolving context

The management of marine resources and MPAs is influenced by ongoing changes such as globalization, shifts in governance, and climate change. To respond effectively to these factors, MPAs must be planned with flexibility and adaptability to address emerging challenges.

1. Competition for resources

The increasing pressure on marine resources and space, including from expanding aquaculture and recreational fishing activities, highlights the need for urgent intersectoral coordination. MPAs function as spatial management

instruments, but they do not reduce resource demand. Instead, they aim to improve enhance the efficient use of existing resources and facilitate coordination among resource users.

2. Legal, institutional and policy frameworks

Effective implementation of MPAs for achieving multiple management goals and cross-sectoral benefits requires appropriate institutional support. However, these structures are often insufficient at present. To establish the necessary legal, institutional, and policy frameworks, coordination and cooperation among government bodies and stakeholders are essential.

3. Ocean governance

Increasing awareness of the importance of the marine environment has brought greater focus on ocean governance. Future ocean governance must be fair by balancing ecological needs with socio-economic requirements and by ensuring that costs and benefits are shared equitably among social groups. These challenges must be carefully addressed when planning and implementing MPAs.

4. High seas management

Changes in ocean governance increasingly involve international waters and the high seas. Establishing MPAs in these areas for fisheries management and biodiversity conservation introduces new management challenges and may call for innovative legal and institutional approaches. Existing Regional Fisheries Bodies (RFBs) already have an important role, which may need to be strengthened, adapted, or expanded.

5. Food security and poverty reduction

When MPAs may cause short-term negative effects on food security, livelihoods, and poverty, alternative or supplementary livelihood options must be developed. This is especially difficult in communities that depend heavily on marine resources. Active participation of affected users and relevant government agencies is essential to ensure sustainable livelihoods. MPA design should also balance scientific goals with social and economic needs.

6. Climate change

Climate change significantly affects the effectiveness of Marine Protected Areas (MPAs) by influencing species distributions, habitats, and biodiversity. As climatic conditions change, species may shift their ranges, causing MPAs designed using past distribution patterns to become less effective. To address this, networks of MPAs that provide protection across different environments and changing biological conditions are likely to be more effective than single MPAs. However, since long-term environmental changes are difficult to predict, adaptive management and flexible implementation of MPAs are essential.

Conclusion

Marine Protected Areas (MPAs) play a crucial role in conserving marine biodiversity across diverse ecosystems and regions. Scientific evidence demonstrates that well-managed MPAs, particularly no-take zones and community-based areas, enhance biodiversity, support fish stock recovery, increase ecosystem resilience, and protect coral reef habitats. However, their effectiveness is often constrained by challenges such as inadequate planning and enforcement, insufficient funding, inappropriate size, and increasing pressures from climate change, including ocean warming and acidification. Strengthening adaptive management through community involvement, effective governance, and strict enforcement is essential to improve conservation outcomes. When carefully designed and properly implemented, MPAs remain a key strategy for sustaining the long-term health and resilience of marine ecosystems.

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Vertical Farming Systems



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Abstract

Rapid urbanization, climate variability and declining arable land have intensified the demand for alternative food production systems capable of delivering high yields in limited spaces. Vertical farming addresses these challenges by enabling crop cultivation in stacked layers under precisely controlled environmental conditions. However, the long-term success of such systems depends not only on technological inputs but also on biological adaptation. The abstract highlights the central role of plant breeding in optimizing crop performance for controlled environment agriculture. Breeding priorities shift from stress tolerance to traits such as compact architecture, rapid and uniform growth, synchronized development, efficient photosynthesis under artificial lighting and improved root adaptation to soilless systems. These traits enhance resource-use efficiency, reduce production costs and improve crop quality and market value. Controlled environments also enable faster breeding cycles and more precise selection. Purpose-driven breeding is therefore essential for improving productivity, sustainability and economic viability, positioning vertical farming as a key component of future urban food systems.

1. Introduction

Rapid urbanization, climate variability, shrinking arable land and rising food demand have placed unprecedented strain on conventional agricultural systems. With the global population projected to reach nearly 9.7 billion by 2050, innovative approaches capable of producing food sustainably within urban environments are urgently required. Vertical farming has emerged as a promising alternative, enabling crop production in stacked layers under fully controlled environmental conditions.

Vertical farming systems rely on precise regulation of light, temperature, humidity, carbon dioxide concentration and nutrient supply, often through hydroponic, aeroponic, or aquaponic methods. These systems offer year-round production, high land-use efficiency, reduced water consumption and minimal pesticide use. However, despite significant technological advances, the long-term success and scalability of vertical farming depend heavily on biological optimization. Most crops grown indoors are still varieties bred for open-field conditions, which are not ideally suited to controlled environments. In this context, plant breeding plays a decisive role in determining the productivity, efficiency and sustainability of vertical farming systems.

2. Redefining Breeding Objectives for Controlled Environments

Conventional plant breeding has focused on developing varieties capable of tolerating environmental stresses such as drought, heat, pests, diseases and soil variability. In vertical farming, many of these stresses are largely eliminated through environmental control. Consequently, breeding objectives must shift toward traits that maximize performance under stable, resource-optimized conditions.

Compact plant architecture is a primary requirement for vertical farming. Traits such as reduced plant height, shorter internodes, upright leaf orientation and limited lateral spread enable higher planting density and more efficient use of vertical space. Rapid and uniform growth is equally important, as faster crop cycles increase the number of harvests per year and improve infrastructure utilization. Uniformity in growth and maturity also facilitates automation, reducing labour requirements and operational complexity.

Synchronization of developmental stages further enhances efficiency in indoor systems. Crops that reach harvest maturity simultaneously simplify scheduling, mechanized harvesting and post-harvest handling, which is particularly important in high-cost urban farming environments.

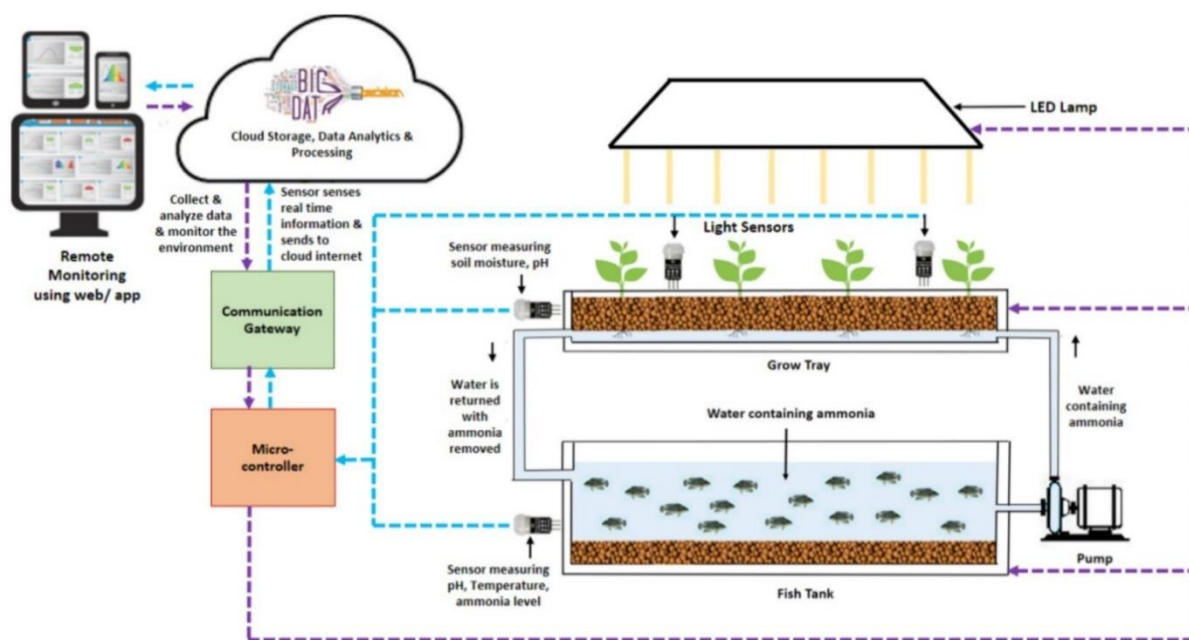


Figure 1: System of Vertical Farming

3. Energy Efficiency and Photosynthetic Performance

Energy consumption, especially for artificial lighting, remains one of the major constraints in vertical farming. Electricity costs significantly influence production economics, making energy efficiency a central concern. Plant breeding can contribute directly to this challenge by improving photosynthetic efficiency under artificial light conditions.

Plants differ in their response to light quality, intensity and photoperiod. Breeding crops that efficiently utilize energy-efficient LED spectra can reduce lighting requirements without compromising yield. Traits related to chlorophyll concentration, leaf morphology and photoreceptor sensitivity influence how effectively plants convert light energy into biomass. Faster growth rates further reduce energy costs by shortening production cycles, thereby lowering cumulative energy use per crop.

Through the development of photosynthetically optimized cultivars, breeding can complement technological innovations to improve the overall energy efficiency and economic viability of vertical farming systems.

4. Resource-Use Efficiency and Root Adaptation

Vertical farming is often highlighted for its efficient use of land and water. However, realizing these benefits at scale requires crops that are biologically adapted to soilless cultivation systems. Root traits are particularly important in hydroponic and aeroponic environments, where nutrient uptake occurs directly from solution rather than soil.

Efficient root systems that maintain stable architecture under constant moisture, tolerate high oxygen availability and maximize nutrient absorption contribute to improved nutrient-use efficiency and reduced fertilizer losses. Although water scarcity is less critical in closed indoor systems, varieties with lower transpiration rates still enhance system efficiency by reducing the energy required for humidity and climate control.

Breeding crops with root and physiological traits suited to controlled environments strengthens the sustainability claims of vertical farming by minimizing resource inputs while maintaining high productivity.

5. Enhancing Crop Quality and Market Value

In addition to yield and efficiency, vertical farming offers unique opportunities to enhance crop quality. Controlled environments allow consistent expression of genetically determined traits related to nutrition, flavour, colour and texture. Plant breeding can exploit these conditions to develop high-value crops tailored to urban and premium markets.

Breeding for enhanced nutritional content, including higher levels of vitamins, antioxidants and bioactive compounds, aligns with growing consumer demand for healthy and functional foods. Flavour and aroma traits, governed by secondary metabolism, can also be optimized under stable indoor conditions. Visual appeal, including uniformity, leaf shape and colour intensity, further increases market value and consumer acceptance.

Such quality-oriented breeding strategies enable vertical farming enterprises to differentiate their products and improve profitability.

4. Accelerated Breeding and Economic Implications

Controlled environments also offer advantages for the breeding process itself. Year-round cultivation allows multiple generations to be grown annually, significantly shortening breeding cycles. Speed-breeding approaches benefit from optimized light and temperature regimes, enabling rapid flowering and seed production. Reduced environmental variability improves phenotypic accuracy, enhancing selection efficiency.

From an economic perspective, crops bred specifically for vertical farming reduce production costs through faster growth, higher yields, uniformity and compatibility with automation. Strategically, dedicated breeding programs for indoor agriculture ensure long-term competitiveness and reduce dependence on field-bred varieties that may limit system performance.

5. Conclusion

Vertical farming represents a viable pathway toward sustainable urban food production, but its success extends beyond technological innovation alone. Plant breeding is fundamental to unlocking the full potential of controlled environment agriculture. By redefining breeding objectives to emphasize compact architecture, rapid growth, energy efficiency, resource-use optimization and enhanced quality, crops can be better aligned with the unique demands of indoor farming systems.

As vertical farming continues to expand, close integration between breeding programs and production environments will be essential. Purpose-built cultivars will play a critical role in improving efficiency, sustainability and economic viability, positioning vertical farming as a meaningful component of future global food systems.

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Seeds of Sustainability: Climate Law and the Future of Agriculture



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1. Climate Change and the Shattered Rhythm of Farming

Climate change has quietly but decisively altered the rhythm of agriculture. What was once governed by relatively stable seasons and local ecological knowledge is now marked by unpredictability and risk. Erratic rainfall, prolonged droughts, intensifying heat stress, declining soil fertility, salinization, and extreme weather events viz., cyclones, floods, heat waves, and unseasonal frosts have transformed farming from a dependable livelihood into a precarious enterprise. For millions of small and marginal farmers across the world, particularly in the Global South, this ecological instability directly threatens food security, income stability, and social cohesion.

Agriculture remains deeply embedded in rural cultures and economies. In countries like India, agriculture is not merely an economic sector but a way of life that sustains communities, traditions, and intergenerational knowledge. Climate-induced disruptions therefore ripple far beyond crop losses. They intensify rural indebtedness, accelerate distress migration, widen gender inequalities, and strain already fragile social safety nets. Against this backdrop, climate law has emerged as a critical though often underappreciated instrument for shaping the future of sustainable agriculture and resilient rural livelihoods.

2. Agriculture at the Climate Crossroads

Agriculture occupies a paradoxical position in global climate discourse. On one hand, it is among the sectors most vulnerable to climate change. On the other, it is a significant contributor to greenhouse gas emissions through livestock methane, fertiliser-related nitrous oxide, deforestation, residue burning, and energy-intensive irrigation. This dual identity complicates regulatory approaches and demands nuanced legal frameworks. Climate law must therefore navigate a delicate balance: reducing agriculture's environmental footprint while safeguarding livelihoods and food systems. Unlike industrial sectors, agriculture is dominated by smallholders in many developing countries, whose capacity to absorb regulatory costs is limited. A rigid, compliance-heavy approach risks pushing vulnerable farmers further into poverty.

Modern climate governance frameworks increasingly acknowledge this complexity. The Paris Agreement explicitly recognises food security and the vulnerability of food production systems to climate change. The Sustainable Development Goals (SDGs), particularly Goals 2 (Zero Hunger), 12 (Responsible Consumption and Production), and 13 (Climate Action), place agriculture at the heart of sustainable development. Nationally Determined Contributions (NDCs) submitted by countries frequently identify agriculture as a priority sector for both mitigation and adaptation. Yet translating these global commitments into farmer-centric outcomes remains a profound legal and governance challenge. Policy intent often falters at the point of implementation, where institutional capacity, coordination, and local realities collide.

3. The Role of Climate Law in Agricultural Transformation

Climate law provides the normative, institutional, and procedural foundation for transforming agriculture in a warming world. Its influence extends across adaptation, mitigation, rights protection, and governance reform.

3.1. Enabling Climate Adaptation on the Ground

Adaptation is the most immediate priority for farmers facing climate stress. Climate laws can mandate the integration of climate risk assessments into agricultural planning, ensuring that cropping patterns, irrigation investments, and extension services are aligned with emerging climate realities. Legal provisions supporting climate-resilient agriculture may include:

- Promotion of drought- and heat-tolerant crop varieties
- Legal backing for water conservation, micro-irrigation, and watershed management
- Institutionalization of agro-meteorological advisory services
- Mandatory early-warning systems for extreme weather events

When embedded in law, such measures move beyond pilot projects and become enforceable state responsibilities. Importantly, climate law can ensure that adaptation finance reaches the last mile, preventing elite capture and regional imbalances.

3.2. Supporting Mitigation through Incentives

Mitigation in agriculture must be incentive-driven rather than punitive. Climate law can facilitate this shift by creating enabling frameworks for:

- Renewable energy adoption on farms (solar pumps, biogas plants)
- Agroforestry and carbon-sequestering land-use practices
- Sustainable soil and nutrient management
- Reduced residue burning through alternative technologies

Carbon markets, green finance instruments, and climate-linked subsidies depend heavily on legal clarity, transparency, and regulatory oversight. Without robust legal architecture, such mechanisms risk becoming exclusionary or ineffective.

4. Climate Law as a Tool for Rights and Justice

Beyond environmental regulation, climate law plays a crucial rights-protective role. Farmers, indigenous communities, pastoralists, and agricultural workers depend directly on land, water, biodiversity, and ecosystems for survival. Climate change exacerbates existing inequalities in access to these resources.

Well-designed climate laws can:

- Strengthen land tenure security and prevent climate-induced dispossession
- Protect water rights amid increasing scarcity
- Safeguard farmers' access to seeds and traditional genetic resources
- Ensure equitable benefit-sharing from climate finance and carbon initiatives

By embedding principles such as equity, participation, intergenerational justice, and common but differentiated responsibilities, climate law can correct historical imbalances. It can ensure that those least responsible for climate change are not made to bear disproportionate burdens of transition.

5. Sustainable Livelihoods at the Core

A climate-resilient agricultural future cannot be built without placing livelihoods at the centre. Sustainable livelihoods go beyond income; they encompass food security, dignity, resilience, and the ability to adapt across generations. Climate law must therefore move beyond technocratic regulation to embrace social transformation. Legal frameworks should support:

- Farmer cooperatives and collective bargaining mechanisms
- Gender-responsive agricultural and climate policies
- Access to climate information and digital advisory platforms
- Social protection systems linked to climate risk

Women farmers, tenant cultivators, and indigenous communities are often excluded from formal land titles, credit, and insurance, despite being central to agricultural production. Climate law that ignores these structural inequalities risks reinforcing vulnerability rather than reducing it.

6. Implementation Gaps and Structural Challenges

Despite progressive frameworks, implementation gaps remain the Achilles' heel of climate law. Weak enforcement, fragmented institutional mandates, limited fiscal space, and inadequate local capacity undermine legal intent. Farmers often struggle to navigate complex bureaucratic procedures to access climate schemes. Market pressures further complicate the picture. Global supply chains and export-driven agriculture may incentivize monocropping and chemical-intensive practices, even where climate laws advocate sustainability. Another critical challenge lies in reconciling traditional knowledge with formal regulation. Indigenous and local

farming practices often embody deep climate wisdom, crop diversity, mixed farming and ecosystem-based management - yet legal systems frequently fail to recognize or integrate them meaningfully.

7. The Road Ahead: From Law to Living Framework

The future of agriculture depends on how effectively climate law bridges environmental responsibility and human development. This requires moving beyond symbolic commitments toward ground-level legal empowerment where farmers are not passive recipients of policy but active participants in climate governance. Climate law must evolve as a living framework: adaptive, inclusive, and responsive to local realities. Participatory lawmaking, decentralised governance, and continuous feedback mechanisms are essential to keep climate regulation relevant and effective.

As climate pressures intensify, agriculture can no longer be treated as a peripheral sector in climate policy. When law nurtures the seeds of sustainability, agriculture can become not only climate-resilient but climate-positive restoring ecosystems, sequestering carbon, and sustaining livelihoods. The challenge is clear and urgent to ensure that the law protects both the land and those who live by it. In doing so, climate law can help secure a future where farming remains a viable livelihood, ecosystems are restored, and food systems are resilient in an increasingly uncertain world,



Fish Pigmentation: A Hidden Driver of Value Addition in Aquaculture



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Abstract:

Aquaculture is increasingly shifting from quantity-based production to quality-driven value creation, where appearance, health, and consumer preference play a decisive role. Fish pigmentation, though often overlooked, is a key factor influencing the market value of farmed species. Natural pigments such as carotenoids and melanin contribute not only to attractive coloration but also indicate fish health, stress response, and nutritional status. In food fish and ornamental aquaculture alike, enhanced pigmentation improves consumer acceptance, export potential, and price realization. Recent advances in feed formulation and the use of natural pigment sources have enabled farmers to manage coloration effectively while supporting sustainable aquaculture practices. Moreover, pigmentation patterns can serve as practical indicators of environmental conditions and management efficiency in culture systems. This article highlights fish pigmentation as a strategic tool for value addition in aquaculture, emphasizing its role in improving product quality, farmer profitability, and alignment with modern, innovation-oriented aquaculture systems.

Keywords: Aquaculture value addition, Carotenoids, Aquafeeds, Fish health indicators, Sustainable aquaculture

Introduction:

Aquaculture has emerged as one of the fastest-growing food production sectors, contributing significantly to global food security, employment, and rural livelihoods. Traditionally, aquaculture success was measured mainly by production volume and growth rate. However, modern aquaculture is rapidly shifting toward **quality-oriented and market-driven production systems**, where visual appeal, nutritional value, and consumer preference determine profitability. Among these quality parameters, **fish pigmentation** plays a crucial yet often underestimated role in value addition.

Fish coloration is not merely an aesthetic trait; it is closely linked to nutrition, health, environmental conditions, and consumer acceptance. Effective management of pigmentation can significantly enhance the economic value of cultured fish, making it an important focus area for innovative aquaculture practices.

Understanding Fish Pigmentation:

Fish coloration is governed by specialized pigment-containing cells called **chromatophores**, which are located primarily in the skin and scales. These cells are responsible for producing and dispersing pigments that give fish their characteristic colors and patterns. The major types of chromatophores include **melanophores**, which impart black or brown coloration; **xanthophores**, responsible for yellow hues; **erythrophores**, which produce red coloration; and **iridophores**, which create silvery or iridescent effects by reflecting light. The arrangement, density, and physiological activity of these chromatophores collectively determine the intensity and uniformity of fish coloration.

Pigments in fish may be:

- **Endogenous**, such as melanin synthesized within the body
- **Diet-derived**, such as carotenoids, which must be obtained through feed

Pigments in fish originate from two main sources. **Endogenous pigments**, such as melanin, are synthesized within the fish body and play a role in camouflage, protection from ultraviolet radiation, and stress response. In contrast, **diet-derived pigments**, particularly carotenoids, cannot be synthesized by fish and must be obtained through feed. Carotenoids are essential for red, orange, and yellow coloration and also contribute to antioxidant defense and immune function.

Because many commercially valuable pigments depend on dietary intake, **nutrition becomes a key factor in pigmentation management**. Balanced feeds enriched with natural pigment sources can significantly enhance coloration, improve fish health, and increase the overall market value of aquaculture products.

Importance of Pigmentation in Aquaculture Markets:

Color is one of the first attributes noticed by consumers while purchasing fish. Bright, uniform, and species-specific coloration is often associated with freshness, quality, and health.

- In **food fish**, pigmentation affects market preference and price, especially in premium species.
- In **ornamental fish culture**, color intensity and pattern directly determine economic value and export demand.
- Poor pigmentation can reduce consumer trust and result in economic losses, even if growth performance is satisfactory.

Thus, pigmentation acts as a **silent quality marker** influencing purchasing decisions and branding of aquaculture products.

Role of Pigments in Fish Health and Performance:

Fish pigments, particularly **carotenoids**, play a significant role in physiological functioning beyond their contribution to external coloration. These pigments act as **powerful antioxidants**, protecting fish cells from oxidative damage caused by environmental stress, metabolic activity, and poor water quality. By neutralizing harmful free radicals, carotenoids help maintain cellular integrity, leading to improved growth performance and overall vitality.

In addition to their antioxidant properties, pigments serve as **immunomodulators**. Adequate carotenoid levels in the diet have been associated with enhanced immune responses, increased resistance to diseases, and improved survival rates, especially under intensive culture conditions. Fish with optimal pigmentation are often better equipped to cope with pathogenic challenges, reducing dependency on chemical treatments and antibiotics. Pigmentation also functions as a **visible indicator of stress and environmental quality**. Fading, uneven, or dull coloration commonly reflects nutritional deficiencies, poor water conditions, high stocking density, or disease onset. Conversely, healthy and stable pigmentation is usually linked with proper feeding, good water management, and low stress levels. Thus, pigmentation serves as a practical, indirect indicator of farm management efficiency, helping farmers assess fish health and culture conditions at an early stage.

Nutritional Management of Pigmentation:

Nutrition plays a pivotal role in the effective management of fish pigmentation, making feed formulation one of the most practical and reliable tools for enhancing coloration in aquaculture. Since many important pigments, particularly carotenoids, cannot be synthesized by fish, their adequate supply through diet is essential. Modern aquaculture feeds increasingly incorporate **natural pigment sources** such as microalgae, crustacean shell waste, plant-derived extracts, and microbial products. These sources not only improve pigmentation but also contribute additional nutritional and functional benefits.

The inclusion of pigment-rich ingredients in aquafeeds leads to **improved color development**, resulting in brighter, more uniform, and species-specific coloration. Such visual enhancement directly influences consumer perception and market value. Pigment-enriched diets are also known to **enhance immune responses and stress tolerance**, enabling fish to better withstand environmental fluctuations and disease challenges common in intensive culture systems.

Another major advantage is **increased consumer acceptance**, as natural pigmentation is often associated with product quality, freshness, and safety. Moreover, the use of natural pigments reduces reliance on synthetic additives, supporting **eco-friendly and sustainable aquaculture practices**. This approach aligns well with current consumer demand for responsibly produced, safe, and environmentally conscious aquaculture products, ultimately contributing to long-term profitability and sustainability of the sector.

Pigmentation as an Indicator of Environmental Quality:

Fish pigmentation is highly sensitive to changes in the surrounding environment, making it a valuable visual indicator of culture conditions in aquaculture systems. Alterations in color intensity, uniformity, or pattern often occur as a response to **environmental stressors** such as poor water quality, inadequate nutrition, high stocking

density, and disease outbreaks. Under stressful conditions, physiological processes affecting chromatophores activity are disrupted, leading to color fading, darkening, or patchy pigmentation.

Poor water quality parameters—such as low dissolved oxygen, high ammonia levels, or sudden temperature fluctuations—commonly result in stress-induced pigmentation changes. Similarly, nutritional deficiencies, particularly of essential pigments and micronutrients, can lead to dull or uneven coloration. Overcrowding further exacerbates stress, increasing competition for feed and space, which is often reflected in altered pigmentation. In the early stages of disease, subtle changes in coloration may appear even before visible clinical symptoms develop.

Regular monitoring of pigmentation allows farmers to **identify stress at an early stage** and implement timely corrective measures, such as adjusting feed quality, improving water management, or reducing stocking density. Because it requires no specialized equipment, pigmentation assessment serves as a **practical, low-cost bioindicators**, helping improve fish survival, productivity, and overall farm management efficiency.

Value Addition and Economic Benefits:

Effective management of fish pigmentation directly contributes to **value addition and improved economic returns** in aquaculture. Well-pigmented fish are visually more appealing and are often perceived by consumers as healthier, fresher, and of superior quality. As a result, such fish command **higher market prices** compared to poorly pigmented counterparts, even when production costs remain similar.

Pigmentation also enables **better product differentiation** in competitive markets. Uniform and species-specific coloration helps farmers and producers establish a distinct identity for their products, supporting premium branding and improving market positioning. In export-oriented aquaculture, particularly for ornamental species and high-value food fish, consistent and attractive pigmentation is a key quality criterion, thereby **enhancing export potential** and access to international markets.

In **ornamental fish culture**, minor improvements in color intensity, brightness, or pattern can lead to substantial price variations, significantly increasing profit margins. Similarly, in **food fish aquaculture**, attractive pigmentation reinforces consumer trust and supports premium labeling, leading to increased demand and repeat purchases. Collectively, these benefits translate into **higher farmer income**, improved livelihood security, and greater sustainability of aquaculture enterprises.

Future Prospects and Innovations:

The role of fish pigmentation in aquaculture is gaining recognition not only as a quality trait but also as a **strategic tool for innovation and value addition**. Recent advances in aquaculture nutrition, biotechnology, and selective breeding are creating exciting opportunities to manage and enhance pigmentation more efficiently and sustainably. Research on **functional feeds**—enriched with natural carotenoids, antioxidants, and other bioactive compounds—is enabling farmers to improve fish coloration while simultaneously supporting growth, immunity, and stress tolerance.

Understanding **pigment bioavailability** and the metabolic pathways through which fish assimilate dietary pigments is also advancing, allowing more precise feed formulations that maximize coloration and overall health. On the genetic front, studies on the **regulation of chromatophores** and selective breeding strategies are opening the possibility of developing strains with naturally enhanced pigmentation, reducing reliance on high-cost feed additives and synthetic pigments.

By integrating pigmentation management into routine farming practices, this trait can shift from being **an overlooked aesthetic feature** to a **key economic and strategic asset**. Farmers can leverage enhanced coloration not only to boost market value and consumer appeal but also as a practical indicator of fish health and environmental management. Looking ahead, pigmentation-driven innovation promises to strengthen profitability, sustainability, and competitiveness in modern aquaculture systems, making it a central focus of research and commercial practice.

Conclusion

Fish pigmentation is far more than a cosmetic feature—it is a powerful driver of value addition in aquaculture. By influencing market appeal, health status, and consumer preference, pigmentation directly impacts profitability and sustainability. Recognizing and managing fish coloration through nutrition, environmental control, and

innovative practices can help aquaculture stakeholders move toward quality-driven, resilient, and market-oriented production systems. Embracing pigmentation as a management tool represents a significant step toward the future of modern aquaculture.

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RNA Interference (RNAi): Mechanisms, Types, and Applications



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1. Introduction

RNA interference (RNAi) is a natural process in eukaryotic cells that reduces gene expression after transcription. It uses small RNA molecules, typically 20–25 nucleotides long, to bind to complementary messenger RNA (mRNA), leading to its breakdown or preventing its translation. This sequence-specific regulation allows scientists to investigate the roles of genes in biological processes.

The phenomenon was first observed in *Caenorhabditis elegans* by Andrew Fire and Craig Mello in 1998, demonstrating that double-stranded RNA (dsRNA) can silence genes with remarkable precision. Their pioneering work earned them the 2006 Nobel Prize in Physiology or Medicine.

RNAi has since been harnessed for therapeutic purposes. As of January 2024, over 130 RNA-based therapies are in clinical trials, highlighting its growing relevance in modern medicine.

2. Core Components of the RNAi Pathway

The RNAi process relies on several molecular players:

a) Double-stranded RNA (dsRNA): The trigger for RNAi, originating from viruses, transposons, or artificially synthesized sources.

b) Dicer enzyme: An RNase III endonuclease that chops long dsRNA into small interfering RNAs (siRNAs) about 21–25 nucleotides in length.

c) RISC (RNA-Induced Silencing Complex): A multi-protein assembly that uses siRNA to locate and silence target mRNAs.

d) Argonaute proteins: The catalytic component within RISC responsible for cutting the target mRNA.

3. Types of RNAi

3.1 siRNA-Mediated Gene Silencing

Small interfering RNAs (siRNAs) are produced from longer dsRNA and guide RISC to target mRNA sequences with exact complementarity, resulting in precise mRNA cleavage.

Mechanism:

1. Synthetic siRNAs (or dsRNA processed into siRNAs by Dicer) are loaded into RISC.
2. Due to perfect complementarity, AGO2 is fully activated.
3. AGO2 cleaves the target mRNA at a specific site determined by the siRNA sequence.
4. The cleaved mRNA is rapidly degraded by cellular nucleases.
5. The siRNA can be recycled and direct multiple rounds of cleavage, amplifying the silencing effect.

Key Features:

- Highly specific for exact mRNA targets.
- Efficiently degrades mRNA regardless of its translation state.

3.2 miRNA-Mediated Gene Silencing

MicroRNAs (miRNAs) are endogenous small RNAs that regulate genes by binding partially complementary sequences in mRNAs, leading to translation inhibition or gradual mRNA decay.

Mechanism:

1. Primary miRNAs (pri-miRNAs) are transcribed in the nucleus and processed by Drosha into precursor miRNAs (pre-miRNAs).
2. Pre-miRNAs are exported to the cytoplasm and further processed by Dicer into mature miRNA duplexes.
3. One strand is loaded into RISC, which binds to partially complementary sequences in target mRNAs.
4. The binding suppresses translation or destabilizes the mRNA.

Key Features:

- Can target multiple genes due to partial complementarity.
- Produces subtle regulation rather than complete gene silencing.
- Plays essential roles in normal development and gene expression fine-tuning.

4. Applications of RNAi

a) Therapeutic Medicine: RNAi is being developed to treat genetic disorders, cancers, viral infections, and neurodegenerative diseases by silencing disease-causing genes.

b) Agriculture: By targeting vital genes in pests or pathogens, RNAi contributes to developing crops with improved resistance, reducing pesticide usage, and enhancing sustainability.

c) Functional Genomics: RNAi enables systematic gene knockdowns, helping researchers study gene function, uncover drug targets, and understand complex biological networks.

5. Challenges and Considerations

Off-target effects: siRNAs may inadvertently affect genes with similar sequences; careful design and screening reduce this risk.

Immunogenicity: Certain siRNA structures can trigger immune responses; chemical modifications help minimize these reactions.

Delivery and biodistribution: Ensuring that RNAi molecules reach the target tissues without degradation remains challenging.

Transient effects: siRNA silencing is usually temporary; vector-based approaches such as shRNA provide longer-term gene suppression.

6. Conclusion

RNA interference is a critical mechanism for gene regulation with wide-ranging applications in medicine, agriculture, and biology. Its precise, sequence-specific action has revolutionized functional genomics and enabled novel therapeutic strategies. Although challenges like off-target effects, immune activation, and delivery limitations exist, ongoing advancements in RNA design and delivery are expanding its potential. RNAi is set to play an increasingly vital role in precision medicine and sustainable biotechnology.

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When Flowers Feed Fins: Turning Floral Waste into Fish Color Magic



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Introduction: When beauty becomes waste

Flowers symbolize beauty, devotion and celebration. Every day, enormous quantities of flowers are used in temples, homes, weddings and markets. Once their purpose is fulfilled, these flowers are discarded as waste. Floral residues are commonly dumped into open spaces or water bodies, where they decompose rapidly and contribute to environmental pollution. Although flowers are biodegradable, their accumulation creates serious issues such as water contamination, foul smell and the spread of pathogens. Finding meaningful and sustainable uses for floral waste has therefore become an important environmental priority.

Floral waste as a valuable natural resource

Discarded flowers are often perceived as useless, but in reality they are rich in valuable natural compounds. Petals of flower crops such as marigold (*Tagetes* spp.), hibiscus (*Hibiscus rosa-sinensis*), rose (*Rosa* spp.), chrysanthemum (*Chrysanthemum morifolium*) and butterfly pea (*Clitoria ternatea*) contain high levels of natural pigments like carotenoids, flavonoids and anthocyanins. These pigments are responsible for the bright yellow, orange, red, blue and purple colors seen in flowers. Even after the flowers are discarded, these pigment compounds remain largely intact, making floral waste a promising raw material for reuse.



Importance of color in ornamental fish

Ornamental fish are reared primarily for their attractive appearance. Body coloration plays a crucial role in determining their aesthetic value and market price. In natural habitats, fish obtain color pigments from algae, plankton, and plant materials. However, under captive or aquarium conditions, these natural pigment sources are limited. As a result, ornamental fish often lose their natural brightness over time. This happens because most fish species cannot synthesize pigments such as carotenoids on their own and must depend entirely on dietary sources to maintain their coloration.



Natural pigments vs synthetic additives

Traditionally, synthetic pigments have been added to ornamental fish feed to improve coloration. While effective, synthetic colour enhancers are expensive and may raise concerns related to long-term safety and environmental impact. There is also increasing consumer demand for naturally produced and eco-friendly products. Natural pigment sources such as algae, crustacean shells, vegetables, and flowers have gained attention as safer and more sustainable alternatives. Among these, floral waste stands out due to its abundance, low cost, and rich pigment composition. Utilizing discarded flower petals not only reduces reliance on synthetic additives but also contributes to sustainable waste management.

Preparation of fish feed using floral waste

Recent research has shown that floral waste can be effectively converted into a natural color-enhancing ingredient for ornamental fish feed. Discarded flower petals collected from markets or places of worship are first cleaned and shade-dried to preserve their pigment content. The dried petals are then ground into a fine powder. This floral powder is mixed with a standard basal fish feed in suitable proportions and used as a dietary supplement for ornamental fish. The process is simple, economical, and does not require sophisticated equipment, making it suitable for small-scale adoption.

Effect of floral waste-based feed on fish coloration

Feeding ornamental fish with floral waste-supplemented diets has produced encouraging results. Fish receiving flower petal-enriched feed showed visibly brighter and more intense body coloration compared to fish fed with conventional feed alone. The improvement in color was gradual but consistent, indicating efficient absorption and utilization of natural pigments present in the floral waste. Research findings also revealed that even small quantities of flower petal powder were sufficient to enhance coloration, highlighting the effectiveness of floral pigments.

Mechanism of color enhancement in fish

The colour enhancement observed in ornamental fish fed with floral waste-based diets can be explained by the absorption and deposition of dietary pigments. Once ingested, carotenoids and other pigments are absorbed through the intestinal tract and transported via the bloodstream. These pigments are then deposited in chromatophores, specialized pigment-containing cells located in the skin, scales, and fins. Over time, the accumulation of pigments in chromatophores leads to intensified body coloration. Since the pigments are derived from natural floral sources, the resulting colour appears more natural and stable compared to artificially induced coloration.

Impact on growth and fish health

In addition to improving coloration, floral waste-based feed did not show any negative impact on fish health. Ornamental fish fed with such diets maintained normal growth, good survival, and healthy behavior throughout the feeding period. In some cases, better feed utilization and improved growth performance were observed, suggesting that floral waste may also contribute beneficial nutrients and antioxidants. This indicates that floral waste-based feed is not only effective but also safe for ornamental fish culture.

Environmental and economic significance

The utilization of floral waste in fish feed offers multiple environmental and economic advantages. Recycling flower residues reduces the burden on landfills and prevents the dumping of flowers into water bodies. From an economic perspective, natural pigments derived from floral waste provide a low-cost alternative to synthetic color enhancers, which are often expensive and inaccessible to small ornamental fish farmers. This approach supports the concept of

a circular economy, where waste from floriculture and flower markets is converted into a valuable input for aquaculture.

Future scope and wider applications

The successful use of floral waste in ornamental fish feed opens new possibilities for sustainable resource utilization. Different flower crops such as marigold, rose, chrysanthemum, tuberose, and gladiolus can be explored for their pigment potential. With further refinement, this technique can be scaled up for commercial feed production and extended to a wider range of ornamental fish species. The approach also offers opportunities for self-help groups and small entrepreneurs to engage in eco-friendly feed preparation.

Conclusion

Recycling floral waste for the preparation of ornamental fish feed is a simple yet powerful innovation that addresses environmental pollution while enhancing the aesthetic quality of ornamental fish. By utilizing pigment-rich flower residues, this method reduces dependence on synthetic additives and promotes sustainable aquaculture practices. Transforming discarded flowers into a valuable resource demonstrates how thoughtful integration of floriculture and fisheries can contribute to environmental protection and economic sustainability. What was once considered waste can thus become a source of color, value and ecological balance.



Value-Added Products from Banana: An Untapped Rural Enterprise



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Abstract

Banana is one of the most widely cultivated and consumed fruits in the tropical and subtropical regions of the world. In India, it is a major horticultural crop with significant production in states like Tamil Nadu, Maharashtra, Gujarat, West Bengal, and Andhra Pradesh. While fresh banana fruits are widely marketed, the value of banana cultivation can be substantially increased through processing and value addition. Value-added products derived from banana and its by-products not only contribute to higher returns for producers but also open avenues for rural entrepreneurship, employment generation, waste utilization, and nutritional security. This article explores the concept of value addition in banana, its economic and social implications, potential products and technologies, market opportunities, challenges, and strategies for implementation in rural contexts. The study highlights the untapped potential of banana value addition as a sustainable enterprise that can transform rural economies while minimizing post-harvest losses and improving farm livelihoods.

Introduction

Banana (*Musa spp.*) is a globally significant fruit crop, serving as a staple in many diets and a source of income for millions of small and marginal farmers. India is the world's largest producer of banana, contributing more than 25% of global output. Despite high production, a large proportion of bananas are sold as fresh fruit at farm gates or local markets, which exposes farmers to price volatility, seasonal gluts, and limited market access.

Value addition in agriculture refers to the transformation of raw produce into products with enhanced utility, shelf life, and market value. For banana, value addition can encompass processing into chips, powder, puree, wine, beverages, jams, and utilization of by-products such as peels for fiber, animal feed, and organic inputs. Value addition enhances the economic worth of banana, reduces seasonal price fluctuations, and addresses post-harvest losses that can reach up to 30–40% in perishables.

Value-added products from banana have both domestic and export potential. They cater to changing consumer preferences for convenience, nutrition, and functional foods. Moreover, banana waste streams such as peels and pseudostems can be converted into high-value by-products, contributing to circular economy models in agriculture.

Importance of Banana Value Addition

Economic Benefits to Farmers

The primary benefit of value addition is income enhancement. When bananas are processed into products like chips or flour, their market value increases manifold compared to their raw form. Small farmers can capture a larger share of the final consumer price by participating in processing, branding, and marketing rather than selling raw fruit at low wholesale prices. Value addition diversifies income sources and provides a buffer against farm income volatility.

Employment Generation in Rural Areas

Processing banana into value-added forms can create employment in rural areas, particularly for women and youth. Small-scale enterprises such as banana chip units, flour milling, jam and jelly production, and beverages can generate both direct and indirect jobs in processing, packaging, quality control, supply chain, and sales.

Reduction in Post-Harvest Losses

Banana is highly perishable, with a limited shelf life after harvest. Value addition extends shelf life by converting the fresh fruit into stable products. This reduces food loss and ensures that farmers receive value for their produce even during peak seasons when prices are low.

Nutritional and Market Advantages

Banana and its derivatives are rich in carbohydrates, dietary fiber, vitamins, and minerals. Products like banana flour and puree contribute to health foods and functional ingredients, attracting health-conscious consumers. Value-added banana products align with global trends in natural, wholesome, and nutritious foods.

Potential Value-Added Banana Products

Banana Chips and Crisps

Banana chips are among the most common value-added banana products. Made from raw or semi-ripe bananas, these chips are sliced, fried or baked, and often seasoned. They have a longer shelf life than fresh fruit and can be packaged for retail markets. With proper processing and quality controls, banana chips can meet both domestic and export standards.

Banana Powder and Flour

Banana powder and flour are emerging products in the health food sector. Made by drying and grinding bananas, these flours can replace or supplement wheat flour in bakery products, breakfast cereals, and gluten-free foods. Banana flour is also used as a thickener in sauces and soups, offering nutritional and functional benefits.

Banana Puree and Jam

Banana puree serves as a base for various products like jams, jellies, sauces, and baby foods. Puree retains the natural flavor and nutrients of banana and can be blended with other fruits to create innovative products. Banana jam and spreads have growing demand in urban markets.

Banana Wine and Beverages

Fermented banana beverages such as banana wine and kombucha-style drinks are gaining interest among niche consumers. These products offer unique flavors and can be marketed as artisanal or craft beverages.

Banana Fiber and By-Product Uses

Banana fiber, extracted from pseudostems, has applications in textiles, paper, mats, and handicrafts. Banana peels can be processed into animal feed, organic fertilizer, or bio-gas, contributing to zero-waste systems. Fiber extraction can provide additional income streams for rural artisans.

Processing Technologies and Methods

Selection and Pre-Treatment

Successful value addition starts with selecting high-quality bananas free from blemishes and disease. Pre-treatments such as washing, peeling, and blanching prepare the fruit for further processing. For chips, uniform slicing techniques ensure consistent quality and frying or baking efficiency.

Drying and Dehydration Techniques

Drying is a key process for products like banana chips and powder. Traditional sun drying can be combined with controlled dehydration using solar dryers or mechanical dryers to ensure uniform quality and reduce contamination. Controlled moisture removal extends shelf life and preserves nutrients.

Milling and Grinding for Flour

Banana flour production requires drying the fruit or plant parts to low moisture content followed by milling. The flour should be sieved to achieve a consistent particle size, which influences its functional properties in food applications.

Fermentation for Beverages

Fermentation processes for banana wine involve controlled inoculation with yeast, sugar adjustments, and monitoring of fermentation conditions such as pH and temperature. Quality control ensures a desirable product that meets safety standards.

Packaging and Storage

Appropriate packaging is crucial for value-added products. Materials that protect against moisture, oxygen, and light help preserve quality. Vacuum or modified-atmosphere packaging can further extend shelf life. Labeling should include nutritional information, production date, and storage instructions.

Market Opportunities and Consumer Trends

Growing Demand for Healthy Foods

Consumers are increasingly seeking nutritious, natural, and functional foods. Banana flour, puree-based snacks, and health beverage segments align with these trends. Products with high fiber, low gluten, or vegan labeling attract health-conscious buyers.

Domestic and Export Potential

Value-added banana products have strong domestic appeal in urban and semi-urban markets. Export opportunities exist in regions where banana chips and snacks are already popular, such as the Middle East, Europe, and Southeast Asia. Compliance with international food safety standards can unlock export markets.

E-Commerce and Direct Marketing

Digital marketplaces and direct-to-consumer models empower rural processors to reach broader markets. Social media, online stores, and community platforms allow small enterprises to build brands and sell regionally or nationally.

Economic and Social Impacts

Income Diversification for Farmers

Value addition helps farmers diversify income beyond seasonal raw sales. By processing bananas into multiple products, farmers can earn throughout the year and reduce dependency on fresh fruit markets.

Empowerment of Women and Youth

Processing units often employ women and youth, creating inclusive rural employment. Training and skill development in processing technologies can empower underserved groups to participate in value chain activities.

Local Enterprise Development

Village-level or cluster-based processing enterprises stimulate rural economies. Such enterprises attract ancillary services like transport, packaging suppliers, quality testing labs, and marketing agents, creating local business ecosystems.

Challenges and Constraints

Infrastructure and Technology Gaps

Many rural areas lack adequate processing infrastructure, cold storage, and reliable power. Limited access to modern dryers, millers, and fermentation equipment can constrain production capacity and product quality.

Quality Standards and Certification

Meeting food safety standards for packaged goods requires investment in quality control, hygiene practices, and certification. Small processors may struggle with compliance costs and technical expertise.

Market Linkages and Branding

While production is essential, establishing market linkages and brand recognition is equally important. Many rural producers lack access to distribution channels and struggle to compete with established brands in packaging and marketing.

Financial and Skill Barriers

Limited access to credit and business training hinders enterprise establishment. Small farmers may need support in business planning, financial management, and marketing strategies.

Strategies to Promote Banana Value Addition

Strengthening Rural Processing Clusters

Establishing processing clusters with shared infrastructure (dryers, packaging, storage) can reduce individual investment burdens and enhance economies of scale.

Capacity Building and Training

Training programs on processing methods, quality control, and business operations can equip rural producers with the skills needed for successful enterprises. Partnerships with agricultural universities and extension services are key.

Access to Finance and Incentives

Microfinance, cooperative credits, subsidized equipment loans, and government schemes for food processing can provide the financial backbone rural entrepreneurs need to start and scale value-addition businesses.

Market Linkages and Branding Support

Facilitating participation in fairs, expos, and digital marketplaces can build market access. Branding support through geographic indicators, organic labels, or regional specialties enhances product value.

Public–Private Partnerships

Collaborations between government, private sector, and NGOs can support infrastructure investment, quality standards compliance, and access to export markets.



Case Examples of Successful Enterprises

Village Chip Processing Units

In many banana-producing regions, small cooperatives have established banana chip units that process local produce and sell packaged chips in urban markets. With improved packaging and quality control, these units have expanded regionally.

Banana Flour Startups

Startups focusing on gluten-free banana flour have entered health food segments. By emphasizing nutritional benefits and sustainable sourcing, these brands connect rural producers to urban health food consumers.

Conclusion

Value-added products from banana represent an untapped rural enterprise with immense potential for economic, social, and environmental benefits. By transforming a perishable fruit into a range of stable, marketable products, rural producers can gain higher income, reduce post-harvest losses, and create sustainable livelihoods. Realizing this potential requires infrastructure development, training, market access, and supportive policies. With growing consumer demand for healthy and natural foods, value-added banana products are poised to thrive in domestic and global markets. For rural communities, capitalizing on this opportunity can be transformative — not only for farmers' incomes but for entire rural economies.

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The "Good Guys": Pollinators and Predators



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Introduction:

Pollinators are a diverse collection of animal species that transmit pollen from flowering plants. Insects, particularly Lepidoptera, are the most diverse and plentiful pollinators. There are over 140,000 insect species, with Coleoptera accounting for approximately 77,300 and Hymenoptera for over 70,000. Diptera and Thysanoptera have the lowest diversity among insect pollinators. Plant-pollinator interactions are important for agricultural food production and ecosystem function, contributing to global biodiversity. Approximately 87.5% of blooming plants rely on animal pollinators for reproduction. Animal pollination is essential for 87 of the world's top food crops and 35% of global crop production.

An organism is considered a predator if it catches and consumes other creatures to survive and procreate, benefiting the predator at the expense of the prey. Higher trophic levels in the food web are often occupied by predators, which feed on herbivores or lower-level carnivores that consume primary. They are essential in determining the composition and operation of ecosystems. The generalist predatory mite *Anystis baccarum* (L.), for example, was developed in Canada as a novel biocontrol agent and was released commercially in 2022.

The Economic Engine: Pollination and Food Security:

Pollination increases agricultural yields. Pollination affects fruit set in various crops, including coffee, almonds, and apples. A meta-analysis indicated that enhanced functional pollinator diversity led to higher yields in oilseed rape (*Brassica napus*), a globally significant crop. Wild bee diversity impacts fruit set in rural apple orchards, regardless of managed honeybee population. In systems with high flowers. Increased wild pollinators improve plant diversity and fruit set. High pollinator species richness in urban areas greatly boosts the seed establishment of the jalapeño crop (*Capsicum annuum*). The diversity of pollinator species can impact fruit output, both physiologically and chemically. Exclusion of nectarivorous bats found that extracting pitaya flowers lowered yield by 35%, reduced fruit weight by 46%, and resulted in less sweet fruit. Diverse pollinators provide not only pollination services but also are important to environmental safety, human health, culture and aesthetics.

Nature's Pest Control: The Role of Predators:

Food security and biodiversity conservation are key problems for sustainable development. Despite attempts to alleviate hunger, roughly 670 million people will still be considered undernourished by 2030. The annual loss of 32% (approx. 215 million tonnes) of major crop production, including wheat, rice, maize, potatoes, and soya beans, is exacerbated by animal pests, which account for approximately 10% (approx. 21 million tonnes). Native species can help reduce pest populations and provide ecosystem services through biological control, both naturally and with human intervention. Predators are one of the key class of natural species that can effectively suppress pest populations. Predators in agriculture include carnivorous insects like ladybirds (Coccinellidae), lacewings (Chrysopidae), predatory bugs like *Orius* and *Macrolophus*, and predatory mites like *Phytoseiulus persimilis*. These insects actively hunt and eat crop-damaging pests like aphids, thrips, whiteflies, spider mites, and caterpillars, acting as natural biological control agents to suppress outbreaks without the use of chemical pesticides. For example, predatory bugs pierce-suck thrips and leafminers in greenhouses, halving outbreaks in high-value tomatoes and peppers; ladybirds consume 50–100 aphids per adult every day, preventing defoliation in orchards and soybeans; lacewing larvae ("aphid lions") consume hundreds of soft-bodied pests weekly, supporting vegetable yield gains of over 25%; and predatory mites proliferate quickly, preventing 50%+ foliage loss in strawberries and beans. In addition to reducing resistance and environmental damage, this natural pest management reduces the need for pesticides by up to 50%. It also fosters sustainable farming resilience, as

resident predator populations are just as successful as introduced ones when supported by habitat enhancements like cover crops and semi-natural edges, ultimately boosting farm profitability through healthier plants and lower input costs.



Lacewing



Ladybird beetle



Spider



Dragonfly



Reduviid bug



Praying mantis

Synergy in the Field: Pollinators and Predators Working Together:

By providing complementary ecosystem services, pollinators like bees and hoverflies work in tandem with predators like ladybirds and lacewings in agricultural fields. Pollinators ensure crop reproduction through pollen transfer during flowering, while predators suppress harmful pests like aphids and thrips during vegetative and fruiting stages, resulting in net yield gains of 25% or more when their phenologies align, as modelled in agro ecosystem studies. Flower strips and hedgerows improve this partnership by offering shared nectar resources and habitats, increasing both groups' abundance and lowering the need for pesticides. Integrated management, such as timed releases or habitat design, to maximise co-benefits maintaining these cycles over isolating services, has demonstrated that increased biodiversity and profitability from these integrated management strategies

Future Difficulties: Handling a Changing Environment

Despite their advantages, these "Good Guys" are at risk from a number of new threats: Phenological Mismatch: Plants may bloom before pollinators appear or before predators are active to capture early-season pests due to climate change.

Habitat fragmentation: Large monocultures produce "green deserts" devoid of the year-round supplies necessary for the survival of beneficial insects.

The Pesticide Paradox: Sub-lethal chemical dosages might "disarm" our natural allies by hindering a bee's ability to navigate or a predator's ability to hunt quickly.

Invasive Species: New pests that local predators may not yet be able to hunt are brought in by international trade.

Conclusion: Safeguarding the "Good Guys" Future:

A key component of both the health of the ecosystem and our global food system is the complex association between pollinators and carnivores. These "Good Guys" are far more than simply biological oddities; they represent the unseen backbone of our economy, from the 87.5% of flowering plants that rely on animal-assisted reproduction to the silent, effective pest control offered by biocontrol agents like *Anystis baccarum*. However, there is no assurance that they will continue to serve. The transition to biodiversity-focused farming and Integrated Pest Management (IPM) is no longer optional as we confront the twin problems of habitat loss and climate change. We do more than merely conserve insects by preserving the synergy between these species through the development of flower strips, the use of fewer broad-spectrum pesticides, and the conservation of wild ecosystems. We protect our own food supply, maintain ecosystem stability, and create an environment where agriculture and nature coexist together. The message is clear: we are eventually investing in a more resilient and productive planet for ourselves when we give a home to the pollinators and predators that support us.

Horticulture: A Sustainable Pathway to Nutrition, Income, and Rural Development



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Introduction

Horticulture plays a vital role in strengthening agricultural sustainability and improving the nutritional security of a growing population. It involves the cultivation of fruits, vegetables, flowers, spices, plantation crops, and medicinal plants, which are rich sources of vitamins, minerals, antioxidants, and dietary fiber. In recent years, horticulture has gained increased attention due to its high productivity per unit area, employment potential, and contribution to farm income. As agriculture faces challenges such as climate change, shrinking land resources, and market volatility, horticulture offers a promising pathway toward resilient and profitable farming systems.

Importance of Horticulture in Indian Agriculture

India is one of the largest producers of horticultural crops in the world. The sector contributes significantly to agricultural GDP and supports millions of small and marginal farmers. Unlike cereal-based farming, horticultural crops generate higher economic returns and provide year-round income opportunities. Fruits and vegetables, in particular, are essential for balanced diets and play a key role in combating malnutrition and micronutrient deficiencies.

Horticulture also enhances diversification in farming systems. By integrating horticultural crops with traditional agriculture, farmers can reduce risk, improve soil health, and optimize the use of land and water resources. The growing demand for fresh produce, processed foods, and value-added horticultural products has further strengthened the importance of this sector.

Role of Horticulture in Nutritional Security

One of the major contributions of horticulture is its role in improving nutritional security. Fruits and vegetables are rich in vitamins such as A, C, and E, along with essential minerals like iron, calcium, and potassium. Regular consumption of horticultural produce helps prevent lifestyle diseases and supports overall health.

Kitchen gardening and urban horticulture have emerged as effective strategies to improve household nutrition. Even small home gardens can provide fresh, chemical-free vegetables and fruits, particularly in urban and peri-urban areas. These practices also promote awareness about healthy eating habits and sustainable food systems.

Employment and Income Generation

Horticulture is labor-intensive compared to field crops, generating substantial employment opportunities in rural and semi-urban areas. Activities such as nursery raising, planting, pruning, harvesting, grading, packaging, and processing provide work throughout the year. This is particularly beneficial for women and youth, who play an active role in horticultural operations.

Moreover, horticulture offers strong opportunities for entrepreneurship through floriculture, protected cultivation, seed production, and value addition. High-value crops like cut flowers, exotic vegetables, and medicinal plants can significantly increase farm income when linked with proper marketing and supply chains.

Sustainable Horticultural Practices

Sustainability is a key strength of horticulture when appropriate practices are adopted. Some important sustainable horticultural practices include:

- **Integrated Nutrient Management:** Combining organic manures, compost, biofertilizers, and judicious use of chemical fertilizers improves soil fertility and crop productivity.
- **Integrated Pest Management:** Use of biological control agents, resistant varieties, and cultural practices reduces pesticide dependence and protects beneficial organisms.

- **Protected Cultivation:** Polyhouses and shade nets allow year-round production, efficient water use, and reduced pest incidence.
- **Water-Saving Technologies:** Drip irrigation and mulching enhance water-use efficiency and reduce moisture loss.
- **Organic and Natural Farming:** These systems promote ecological balance and produce safe, high-quality fruits and vegetables.

Horticulture and Climate Resilience

Climate change poses serious threats to agricultural productivity. Horticultural crops, when properly managed, can contribute to climate resilience. Perennial fruit crops help in carbon sequestration, reduce soil erosion, and improve microclimatic conditions. Crop diversification through horticulture minimizes the risk of total crop failure under adverse weather conditions.

Additionally, climate-smart practices such as selection of tolerant varieties, efficient irrigation, and improved post-harvest management help reduce losses and enhance adaptability to changing climatic conditions.

Post-Harvest Management and Value Addition

Post-harvest losses remain a major challenge in horticulture. Proper harvesting, storage, transportation, and processing are essential to maintain quality and reduce wastage. Cold storage facilities, improved packaging, and value addition through processing into juices, jams, pickles, and dried products can significantly increase shelf life and farmer income.

The promotion of farmer-producer organizations and better market linkages plays an important role in strengthening the horticulture value chain and ensuring fair returns to growers.

Challenges and Future Prospects

Despite its vast potential, horticulture faces challenges such as limited access to quality planting material, inadequate infrastructure, price fluctuations, and lack of technical knowledge. Strengthening extension services, research support, and policy interventions can help overcome these constraints.

The future of horticulture lies in innovation, sustainable practices, and market-oriented production. With increasing awareness about nutrition, health, and environmental sustainability, horticulture is expected to play a central role in shaping the future of agriculture.

Conclusion

Horticulture is a dynamic and high-potential sector that contributes significantly to nutrition, income generation, and sustainable agricultural development. By adopting improved technologies and sustainable practices, horticulture can enhance farmer livelihoods while ensuring environmental protection. Encouraging investment, research, and capacity building in horticulture will help unlock its full potential and support a resilient and prosperous agricultural system.

Panchagavya-Driven Eco-Innovations for Sustainable Cowpea Cultivation



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Abstract

In Indian agriculture, panchagavya is a traditional organic concoction. Five cow-derived products—cow dung, cow urine, milk, curd, and ghee—are used in its preparation. Curd and ghee are products made from milk, whereas cow manure, cow urine, and milk are direct components. Panchagavya, also referred to as cowpathy treatment, has been utilized in Ayurvedic and Indian ceremonies from ancient times.

Panchagavya is used in organic farming to improve early plant development, root growth, and seed germination. It boosts the fertility of the soil, encourages the growth of helpful microbes, and helps the general health of plants. Frequent application enhances the quality of fruits and vegetables and boosts crop yield. Panchagavya is a crucial component of sustainable agriculture since it is an eco-friendly and natural substitute for artificial pesticides and fertilizers.

Keywords: Panchagavya, Organic farming, Cowpathy, Sustainable agriculture, Plant growth

Introduction:

The Five cow-derived ingredients—cow urine, cow dung, milk, curd, and ghee—combine to make Panchagavya, a traditional Ayurvedic organic concoction. The Sanskrit terms "Pancha," which means five, and "Gavya," which means goods derived from cows, are the source of the phrase Panchagavya (Nekar, 2024). Each ingredient adds special nutrients, biostimulants, and microbial inocula that combine to improve the health of plants and soil.

Panchagavya is frequently called Cowpathy in Ayurvedic therapy because of the usage of compounds produced from cows in holistic health systems. Because cows are considered sacred by Hindus, it also has great religious and cultural importance. It has long been utilized in ceremonial purification and healing ceremonies (Behera et al., 2024).



Panchagavya can be used as a soil drench, which increases soil microbial activity and nutrient availability; as a foliar spray, which allows nutrients and hormones to be absorbed directly through leaves; or as a seed treatment, which increases germination and seedling vigor (Sugumaran et al., 2024).

Additional natural ingredients like jaggery, banana, tender coconut water are combined with the Panchagavya base to promote microbial activity and fermentation in order to increase effectiveness. They help create a powerful biofertilizer that is full of natural enzymes and micronutrients by acting as energy sources and nutritional enhancers (Behera et al., 2024).

In conclusion, Panchagavya is an effective combination of contemporary organic agricultural methods and traditional ecological knowledge. It is a promising tool for sustainable agriculture in the twenty-first century because of its functions as a natural biofertilizer, growth booster, and soil health enhancer.

Boosting Cowpea Growth with Panchagavya

Cowpea is a nutrient-dense, fast-growing legume that thrives on organic inputs like Panchagavya. Panchagavya can enhance germination, plant vigor, flowering, pod development, and yield at various phases of cowpea growth.

Seed Treatment (0 Days Prior to Sowing)

To promote germination and early growth, soak the seeds in diluted Panchagavya.

Stage of Seedlings (5–10 Days)

To boost young plants and encourage healthy root development, lightly spray the foliage.

Stage of Vegetation (15-30 Days)

Panchagavya promotes branching and luxuriant leaf growth during this time, better preparing the plant for flowering.

Stage of Blooming (30–40 Days)

Now, spraying Panchagavya promotes floral development and raises the likelihood of a successful pod set.



Stage of Pod Formation: (40–50 Days)

Panchagavya ensures high-quality pods by supporting their robust and healthy growth.



Stage of Pod Filling: (50–60 Days)

Panchagavya nutrients increase pod weight and seed fullness, which boosts production.



Stage of Maturation: (60–70 Days)

Final sprays promote healthy pod maturity for harvesting and improve overall plant health.

Benefits

Leaves & Stem: Stronger branches, denser canopy, and larger leaves.

Roots: Deep, abundant roots for improved absorption of nutrients and water.

Yield: Better quantity and quality of product, early harvest.

Drought Resistance: Promotes survival in dry settings and minimizes water loss.

Soil fertility: Boosts water retention, microbial activity, and nutrient levels.

Pest and Disease Resistance: Natural plant immunity is strengthened by pest and disease resistance.

Importance of Panchagavya

The excessive consumption of chemical pesticides and fertilizers damages crops, land, and water. A natural cow-based product called Panchagavya provides a secure substitute. By increasing plant growth, immunity, and soil fertility, it lessens the requirement for chemicals (Sugumaran et al., 2024).

Overuse of chemicals can contaminate the environment, kill useful creatures, and develop resistant pests and diseases. Panchagavya promotes ecological equilibrium, increases natural resistance, and aids in the robust and healthy growth of crops (Nekar, 2024).

Comparison of Panchagavya and Inorganic fertilizers:

In a cowpea field of 1ha, we apply Panchagavya and inorganic fertilizers separately and track the results.

S.No	Particulars	Inorganic fertilizers (t/ha)	Panchagavya (t/ha)
1.	Grain yield	2 t/ha (Rs. 47,240/t)	1.5t/ha (Rs.50,500/t)
2.	Fodder yield	5 t/ha (Rs. 2,000/t)	5 t/ha (Rs.3,000/t)
3.	Gross income	Rs. 1,04,480/ha	Rs. 90,750/ha
4.	Cost of Cultivation	Rs. 55,000/ha	Rs. 24,000/ha
5.	Net income	Rs. 49,480/ha	Rs. 66,750/ha
6.	BCR ratio	1.89	3.78

Conclusion:

Panchagavya is a natural, environmentally friendly remedy that improves fruiting, flowering, root health, and plant growth. It promotes beneficial microorganisms, increases soil fertility, and fortifies plant immunity. It encourages sustainable, economical, and superior agricultural production by lowering the demand for artificial pesticides and fertilizers. Panchagavya combines contemporary farming with ancient wisdom.

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NATURE'S OWN ANTIBIOTIC: BDELLOVIBRIO IN SUSTAINABLE AGRICULTURE



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INTRODUCTION:

“Everything is far and wide, but the terrain selects” (Bass Becking, 1934). This composition examines the significance of the order of predatory bacteria, *Bdellovibrio bacteriovorus* which is a well- studied member of the Bdellovibrio- and- like- organisms (BALOs). Bdellovibrio, a group of Gram-negative bacteria, obligate, largely motile with significant potential in sustainable agriculture as natural "living antibiotics" to control other Gram-negative bacteria and multi-drug-resistant pathogens. Their operation offers an environmentally friendly volition to conventional chemical treatments and antibiotics, helping to alleviate the rise of antimicrobial resistance (AMR). *B. bacteriovorus* can prey on Gram-positive *Staphylococcus aureus* (*S. aureus*) in an epibiotic manner. This predatory bacterium with lethal assault, access, and settle within the intraperiplasmic area of the bacteria they quest. Following addition within the intact, the predator breaks down the prey's cell membrane, performing in the death of the prey cell, discharging progeny cells and internal organic materials into the surroundings. These procedures give BALOs the capability to manage vulnerable bacterial populations, modify microbial community association, and play a part in biogeochemical cycling.

WHAT IS BDELLOVIBRIO?

Bdellovibrio bacteriovorus is a unique, predatory microorganism that naturally targets and destroys other bacteria, including various significant pathogens like *Escherichia coli*, *Salmonella typhimurium*, and *Helicobacter pylori*. In contrast to the majority of bacteria that merely vie for nutrients, Bdellovibrio actively seeks out its victims. This exceptional behaviour has drawn scientific interest for almost fifty years and has resulted in promising uses in medicine, agriculture, and environmental management.

Bdellovibrio has attracted attention as a possible living antimicrobial agent because it can eradicate harmful bacteria and assist in regulating microbial communities in environments like the intestinal tract. This dual function—serving as both an antibiotic and a probiotic—is referred to as “**amphibiotic**” to characterize its distinctive biological role.

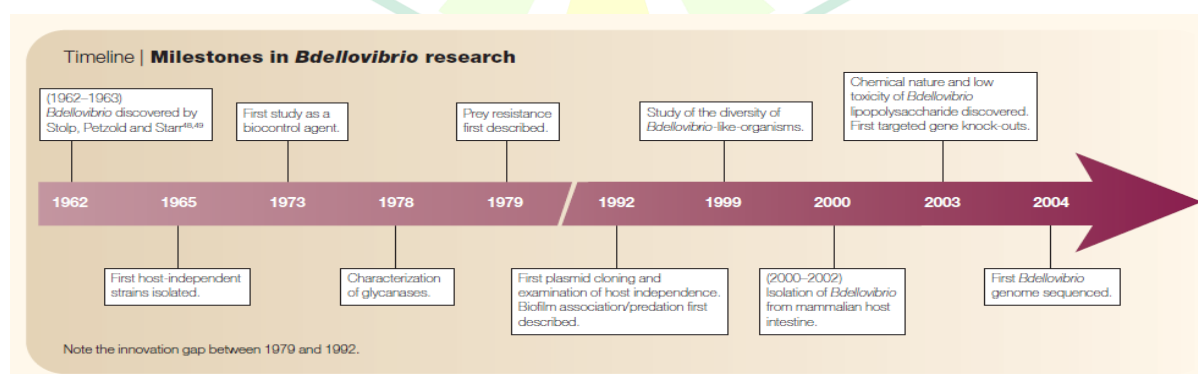


Image Source: Sockett, R., Lambert, C. *Bdellovibrio* as therapeutic agents: a predatory renaissance? *Nat Rev Microbial* 2, 669–675 (2004).

HISTORICAL PERSPECTIVE:

Bdellovibrio bacteriovorus was initially identified in 1962 by Stolp and Petzold while trying to extract bacteriophages from soil samples. Further studies showed that Bdellovibrio is a small, very mobile, Gram-negative predator found extensively in both aquatic and terrestrial habitats. From its discovery until the early

1990s, studies on this organism grew consistently, leading to numerous publications that investigated its unique biology and ecological functions.

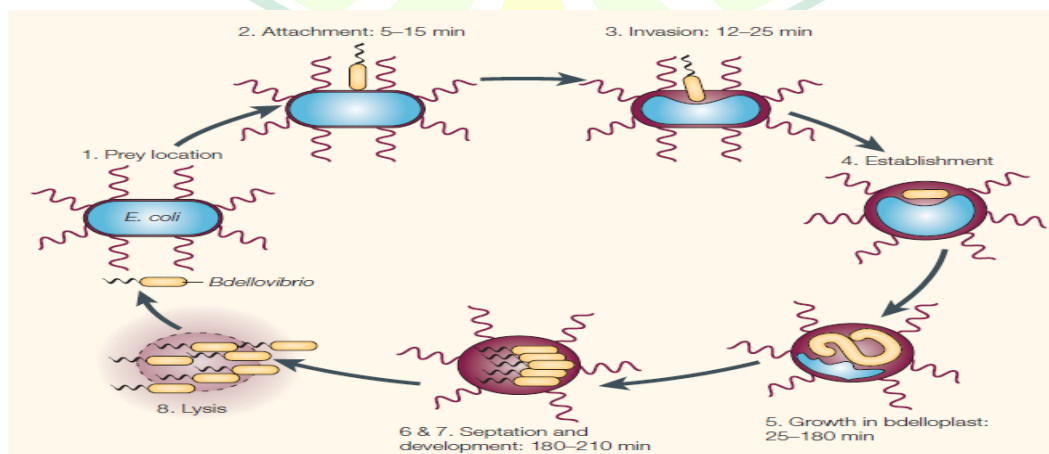
Initial research concentrated mainly on outlining the predatory life cycle, encompassing host identification, invasion, and development within the periplasm. In the late 1970s and 1980s, researchers started assessing its capability as a biological control agent for combating plant pathogens and for lowering bacterial contamination in food systems. Nonetheless, advancements in applied research were hindered by a lack of genetic resources and molecular knowledge. As a result, even with significant interest in its antibacterial capabilities, the initial three decades of *B. bacteriovorus* research were primarily focused on descriptive and physiological investigations rather than genetic examinations.

PREDATION STRATEGY:

Bdellovibrio follows a specialized, multi-step predation process that lets it locate, invade, and consume other bacteria. The process starts with the attack phase, when *Bdellovibrio* is a free-swimming, curved, rod-shaped cell that has a single polar flagellum. At this stage, it moves quickly through thin water films in soil or in aquatic settings, following chemical cues released by possible prey. When *Bdellovibrio* encounters a susceptible Gram-negative bacterium, it begins by attaching to the prey, adhering tightly to the outer membrane through specialized surface structures. After attachment, it moves into the penetration phase. During this step, it forms a tiny opening in the prey cell wall and enters the periplasmic space between the outer membrane and the cytoplasmic membrane. After entry, it seals the penetration site and converts the host cell into a sealed compartment known as a **bdelloplast**.

Inside this protected space, *Bdellovibrio* shifts into a growth and digestion stage and releases hydrolytic enzymes, including proteases, nucleases, and lipases. These enzymes break down the host's cell structures, which supplies nutrients that support the predator's growth and development. As feeding continues, the prey cell breaks down and shifts from a normal cell structure into a nutrient source that supports the predator's rapid elongation. During replication, *Bdellovibrio* elongates into a long filament and then divides in a synchronized manner, producing multiple daughter cells. In the release phase, the depleted prey cell wall breaks open and releases newly formed motile *Bdellovibrio* cells into the surrounding medium, where they promptly begin searching for new prey.

The full predation cycle occurs quickly and, in most cases, it is completed within a few hours. Because *Bdellovibrio* kills harmful bacteria directly instead of only slowing their growth, it may support bacterial control with fewer leftover compounds and a lower risk of driving resistance compared with approaches that rely on growth inhibition alone. Its precise, step-by-step hunting mechanism suggests it may serve as a natural biocontrol agent for managing bacterial pathogens in soil and crop systems.



The predatory life cycle of *Bdellovibrio*

Image Source: Sockett, R., Lambert, C. *Bdellovibrio* as therapeutic agents: a predatory renaissance? *Nat Rev Microbiol* 2, 669–675 (2004).

WHICH HARMFUL BACTERIA CAN IT CONTROL?

HARMFUL BACTERIA	DISEASE IT CAUSE	SIGNIFICANCE
<i>Escherichia coli</i> (<i>E. coli</i>)	1.Diarrhea 2.Urinary tract infections (UTI) 3.Food poisoning	Common human and animal pathogen; some strains are antibiotic-resistant
<i>Salmonella spp</i>	1.Salmonellosis 2.Typhoid fever	Major food-borne pathogen in poultry, livestock, and humans.
<i>Pseudomonas aeruginosa</i>	1.Wound infections 2.Lung infections (cystic fibrosis) 3.Plant soft rot and leaf spot	Strong biofilm former; highly antibiotic-resistant.
<i>Klebsiella pneumoniae</i>	1.Pneumonia 2.Bloodstream infections 3.Urinary tract infections	Important hospital-acquired pathogen.
<i>Vibrio cholerae</i>	Cholera	Water-borne pathogen causing severe diarrhoea
<i>Xanthomonas spp.</i>	1.Citrus canker 2.Bacterial leaf blight of rice 3.Black rot of crucifers	Serious plant pathogen affecting crops.
<i>Erwinia carotovora</i>	Soft rot of vegetables	Causes major post-harvest losses.
<i>Ralstonia solanacearum</i>	Bacterial wilt (tomato, potato, banana)	Soil-borne plant pathogen, difficult to control.
<i>Aeromonas hydrophila</i>	1.Fish diseases (Haemorrhagic septicaemia) 2.Gastrointestinal infections in humans	Important in aquaculture.

POTENTIAL APPLICATION IN AGRICULTURE:

- *Bdellovibrio* preys specifically on many Gram-negative bacteria, including several notorious plant disease agents such as *Pseudomonas*, *Xanthomonas*, and *Burkholderia*. By invading and digesting these pathogens from within, it directly reduces bacterial disease pressure in crops — a **biological solution** instead of chemical bactericides.
- Unlike conventional pesticides, *Bdellovibrio* leaves **no toxic residues** in soil, water, or harvested produce. This makes it highly compatible with organic farming, residue-free vegetable production, and export-oriented agriculture where chemical limits are strictly regulated.
- Chemical antibiotics and bactericides often lose effectiveness due to resistance. In contrast, *Bdellovibrio* physically invades and consumes its prey — a mode of action that makes long-term resistance far less likely. This offers a **durable solution** for managing bacterial diseases.
- Studies show *Bdellovibrio* naturally inhabits rhizosphere soils and selectively attacks harmful bacteria **without disturbing beneficial microbes** such as nitrogen fixers and plant growth-promoting bacteria. This helps maintain a healthy and balanced soil microbiome — a key factor for long-term soil fertility.
- Safety studies confirm *Bdellovibrio* is **non-pathogenic** to higher organisms and does not infect plant or animal cells. This safety profile makes it a suitable candidate for agricultural deployment.
- By regulating populations of harmful bacteria, *Bdellovibrio* indirectly promotes microbial diversity, nutrient cycling, and root zone stability. **Healthy microbial balance** translates into stronger root systems and improved plant resilience against stress.
- It acts as a potential biocontrol agent for **seed and soil treatment**. Research suggests *Bdellovibrio* could be applied as seed coatings to protect seedlings, soil drenches in nurseries, root-zone inoculants in high-value crops.

BENEFITS IN OTHER SECTORS:

- **B. bacteriovorus–Mediated Bio-extraction of Bioplastics:** *Bdellovibrio bacteriovorus* has been explored as a biological lytic agent for the recovery of intracellular bioplastics from Gram-negative bacteria. Biodegradable polyhydroxyalkanoates (PHAs), produced by bacteria such as *Pseudomonas* species and recombinant *Escherichia coli*, accumulate as intracellular granules, making their recovery technically challenging and costly using conventional mechanical or chemical methods. Studies using a depolymerase-deficient *B. bacteriovorus* strain achieved over 80% PHA recovery, compared to substantially lower yields

with the wild-type strain. This approach demonstrates strong potential as a one-step, sustainable downstream process for bioplastic recovery, reducing reliance on harsh chemicals and improving industrial feasibility.

- **Biocontrol agent in Aquaculture:** It has also been proposed that *B. bacteriovorus* might be useful in the freshwater farming industry as a biological control agent of the **shrimp pathogens** *V. cholerae* (Cao et al., 2015) and *V. parahaemolyticus* (Kongrueng et al., 2017). The same group subsequently showed that *Bdellovibrio* could be prepared as an encapsulated powder and stored at room temperature over several months for later use as a bio disinfectant in shrimp aquaculture.
- **Microalgae-derived biofuels:** This is gaining attention as a sustainable energy alternative; however, open-pond cultivation is highly susceptible to bacterial contamination. Li et al. (2018) demonstrated that predation by *Bdellovibrio* sp. reduced contaminating bacterial populations, thereby enhancing microalgal growth and biofuel productivity.
- **Treatment of activated sludge** with *Bdellovibrio bacteriovorus* has been shown to significantly enhance sludge dewaterability in a dose-dependent manner.

LIMITATION AND CHALLENGES:

- **Limited Prey Range:** *Bdellovibrio* mainly targets Gram-negative bacteria, rendering it ineffective against fungal or Gram-positive bacterial plant pathogens, which restricts its overall usefulness in controlling various crop diseases.
- **Sensitivity to Herbicides and Chemicals:** The existence of commonly utilized agricultural chemicals, especially specific herbicides like linuron, can greatly suppress or be fatal to *Bdellovibrio* activity, complicating its integration with traditional farming methods.
- **Efficacy and Environmental Variability:** Factors such as soil type, moisture content, pH (ideal range 7.5-8.1), temperature, and osmolarity can influence the predatory behaviour and survival of *Bdellovibrio*. This inconsistency makes it difficult to maintain uniform effectiveness. These bacteria were found to be strict aerobes, restricting their potential use in oxygen-limited environments
- **Population Dynamics and "Tragedy of the Commons":** *Bdellovibrio*'s efficiency in preying can swiftly exhaust its food supply, resulting in starvation and possible extinction of its predator population. The risk of overexploitation complicates the ability to sustain a stable, lasting predator population for long-term pathogen management in an environment with a single prey type.
- **Competition and Predation:** In natural habitats, *Bdellovibrio* may face competition from bacteriophages that infect the same hosts or be preyed upon by protozoan predators, which further restricts its capacity to sustain viable population sizes.
- **Host-Independent (HI) Mutants:** The possible rise of host-independent (HI) mutants, which do not predate efficiently and can create problematic biofilms, could threaten the intended biocontrol purpose.

FUTURE THRUST:

- **Bioremediation:** Antimicrobial resistance (AMR) is a serious global health threat, driven in part by the spread of resistance genes between bacteria through **horizontal gene transfer** (HGT). Wastewater treatment plants (WWTPs) are major hotspots for this spread due to antibiotic residues and high microbial densities. Although most bacteria are removed during treatment, many antibiotic resistance genes (ARGs) persist in activated sludge and treated effluent, either as free DNA from dead cells or carried by bacteriophages. Predatory bacteria such as *Bdellovibrio bacteriovorus* offer a potential strategy to limit AMR spread. These bacteria naturally occur in WWTPs, prey on other bacteria, and completely degrade their DNA, thereby reducing ARG reservoirs and the likelihood of HGT. In addition, *B. bacteriovorus* secretes nucleases and proteases that may degrade extracellular DNA and inactivate phages, further limiting gene transfer.
- **Biofilm Control:** A major area of research is the predator's unique ability to invade and destroy biofilms, which are a significant factor in chronic infections and are often resistant to conventional antibiotics.
- **Alternative to Conventional Antibiotics:** *B. bacteriovorus* is being vigorously investigated as a potential alternative or adjuvant to traditional antibiotics, particularly for treating infections caused by multidrug-resistant (MDR) Gram-negative pathogens.

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The Meritorious Presents of The Unwanted Weeds



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Abstract:

Weeds are notoriously known as the unwanted and unwelcome vegetation in an agricultural field or in our own home gardens. They compete with our desired crops and take away all the essential nutrients from the soil that are meant for our crop. As a result, there is a decrease in quality and yield of crops. To tackle this problem while making a better use out of it, we have come to use these weeds in a productive way. Weeds can be used to produce biofuels and essential oils. These are also used as biosorbents and biochar. They have found a good place in the pharmaceutical industry as well. In this article, we will see these uses of weeds in detail.

Introduction

In general, weeds are considered as a nuisance in the agricultural field or even in our gardens, when they grow among the desired plant population. They are biological pests that compete with our crop for nutrition, light, water, space and even pollinators. The resulting consequence is loss in biomass, yield, and economic returns. Weeds are extremely persistent and grow luxuriously even in adverse conditions like high temperature, humidity, altering climate, increasing CO₂, etc. As per Convention on Biological Diversity (1992), “biological invasion of alien species is the second worst peril after habitat destruction”. In India, weeds cause around 30% reduction in crop production every year which is about US \$90 billion. Amidst of all this, we often forget that weeds have existed in the fields even before the production of herbicides. They have somehow established an equilibrium with the growing desirable crops. In low densities, weeds play a crucial role in many arenas.

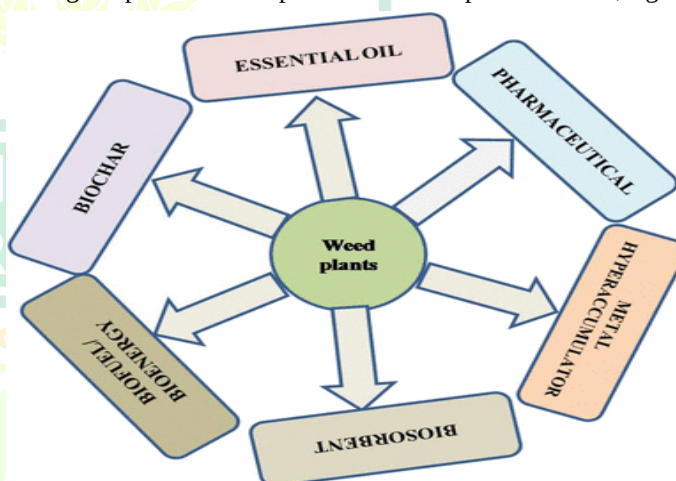


Fig. 1. Various Uses of Weeds

Use of weeds as biochar:

Biochar made up of invasive weeds like *Parthenium hysterophorus* L. and *Lantana camara* has been effective in improving the physico-chemical properties of soil. In an experiment conducted by Choudhary et.al. (2022), biochar made up of *Parthenium hysterophorus* L. (@ 2.5 t ha⁻¹ to 10.0 t ha⁻¹) and *Lantana camara*, when added to soil with inorganic fertilizers, increased the Water Holding Capacity (WHC), decreased Bulk Density (BD) and reduced the need of Recommended Fertilizer Dose (RDF) to 75%. The Soil Organic Carbon (SOC) and Cation Exchange Capacity (CEC) also increased compared to the control. At the same time, it also increased the micro and macro nutrient availability in the post-harvest soils. It proved to be a good method in both weed management strategy and soil improvement measure.

Use of weed as Pharmaceutical:

Undisturbed forested habitats are a good source of medicinal drugs. But according to some recent studies, disturbed habitats are also equally important areas to search for novel compounds in drug discovery. And most

of these disturbed habitats from where drugs are derived have weeds. The study carried out, showed that 36 out of the 101 plants in the disturbed habitat, which were used to produce pharmaceuticals, were weeds. the role of weeds in the present pharmacopeia has been overlooked, despite significant evidence that weeds are an important source of medicines for indigenous peoples and have a highly significant over representation in indigenous pharmacopoeias in relation to other types of plants (Stepp and Moerman, 2001). Weeds produce secondary metabolites which show allelopathy and inhibit the growth of nearby plants. These contributes to the herbivory mechanism in plants. These compounds are being studied to utilise them in formulation of protective drugs for both plants and animals benefit.

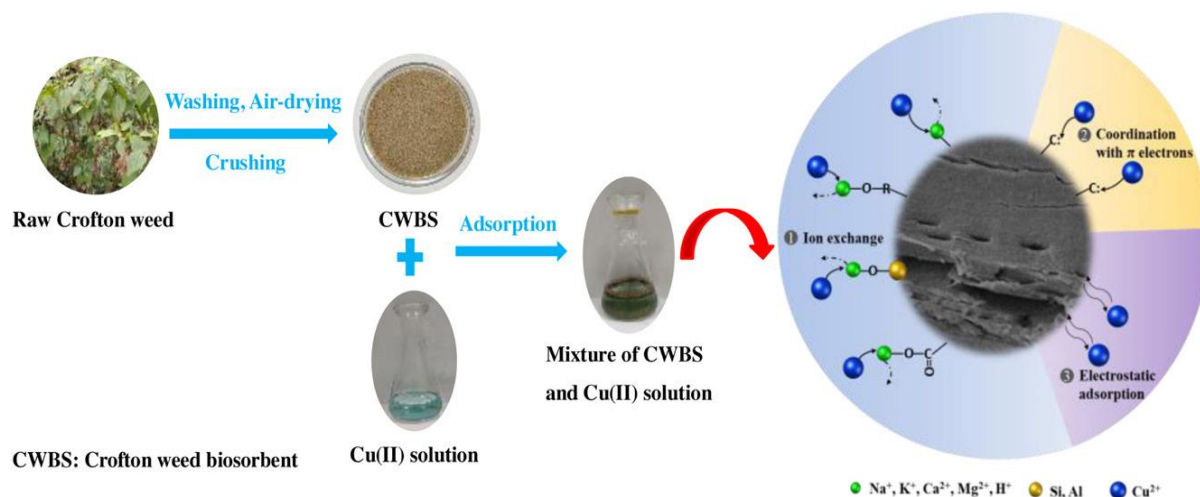


Fig. 2. Schematic representation of use of CWBS as an efficient Biosorbent

Use of weed as Biosorbent:

Weeds can be an excellent tool in bio-absorption of harmful contaminants from the environment. Liangquin et.al (2022) conducted an experiment where they showed that Crofton Weed Biosorbent (CWBS) was efficient in adsorbing Cu(II) from its aqueous solution (with an adsorption capacity of 33.87 mg g^{-1} at 308 K). CWBS retained its adsorption efficiency of 50.84% even after four adsorptions.

Use of weeds as Biofuel:

In the current scenario of massive pollution resulting in climate change, scientists are constantly working to invent new ways of energy production. One of these ventures is biofuel. Biofuels can be made from undesirable weed biomass. Lignocellulosic part of weed is an effective feedstock for economic production of bioethanol. Safdar Ali et al. (2020) conducted an experiment where from a mixed weed biomass of *Chenopodium album*, *Asphodelus tenuifolius*, and *Carthamus oxycantha*, biodiesel, biogas and biochar were produced using nickel and cobalt nano particles to expedite the process of biomass gasification. Their overall quality was enhanced with the use of nano particles.

Use of weeds as a source of Essential Oil:

Phytochemical analysis of weeds disclosed that they have many secondary metabolites (Alkaloids, polyphenols, terpenoids, flavonoids etc.) (Chavan et al. 2013). Weeds produce these secondary metabolites as a defense mechanism or to prevent other vegetation to grow nearby. These metabolites can be used in healing many psychological, physical and pharmacological disorders of human body. Due to the presence of such organic metabolites essential oils extracted from weeds could also be used as aroma-therapeutic agents to cure various ailments by inhalation or topical application (Bajpay et al. 2018).

Conclusion:

Although viewed as a threat in agricultural fields, weeds do have positive utilities. As mentioned above. Weeds are also traditionally used as vegetables in many rural households, as an alternate source of energy (weeds from families Amaranthaceaea, Cucurbiataceae, etc.). This sends a message of sustainability. Weeds promote and support biological diversity. If beneficial weeds are removed from a land, then it has been observed that the

beneficial fauna of birds and other biocontrol animals also get eliminated. This results in an increased population of pests and pathogens which then attack the crop. It is important to eliminate invasive weeds from agricultural niches. But making better use of these weeds is just an added advantage that we should not get rid of. One man's waste is other man's treasure.

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YELLOW JACKET WASP: NATURE'S PEST CONTROL



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Introduction

Yellow jacket is the common name for predatory social wasps of the genera *Vespula* and *Dolichovespula*. Members of these genera are known simply as "**wasps**". Most of these are black and yellow like the eastern yellow jacket (*Vespula maculifrons*) and the aerial yellow jacket (*Dolichovespula arenaria*); some are black and white like the bald-faced hornet (*Dolichovespula maculata*). Some have an abdomen with a red background color instead of black. They can be identified by their distinctive markings, their occurrence only in colonies, and a characteristic, rapid, side-to-side flight pattern prior to landing. All females are capable of stinging. Yellowjackets are important predators of pest insects.

Identification



Yellow jackets may be confused with other wasps, such as hornets and paper wasps such as *Polistes dominula*. A typical yellowjacket worker is about 12 mm (0.47 in) long, with alternating bands on the abdomen; the queen is larger, about 19 mm (0.75 in) long (the different patterns on their abdomens help separate various species). Yellow jackets are sometimes mistakenly called "bees" because that they are similar in size and general coloration to honey bees. In contrast to honey bees, yellowjackets have yellow or white markings, are not covered

with tan-brown dense hair on their bodies, and do not have the flattened, hairy pollen-carrying hind legs characteristic of honey bees (although they are capable of pollination).

Yellow jackets have lance-like stingers with small barbs, and typically sting repeatedly, though occasionally a stinger becomes lodged and pulls free of the wasp's body; the venom, like most bee and wasp venoms, is primarily dangerous to only those humans who are allergic or are stung many times. All species have yellow or white on their faces. Their mouthparts are well-developed with strong mandibles for capturing and chewing insects, with proboscis for sucking nectar, fruit, and other juices. Yellow jackets build nests in trees, shrubs, or in protected places such as inside man-made structures, or in soil cavities, tree stumps, mouse burrows, etc. They build them from wood fiber they chew into a paper-like pulp. Many other insects exhibit protective mimicry of aggressive, stinging yellow jackets; in addition to numerous bees and wasps, the list includes some flies, moths, and beetles.

Yellow jackets' closest relatives, the hornets, closely resemble them but have larger heads, seen especially in the large distance from the eyes to the back of the head.

Life cycle and habits

Yellow jacket wasps can be very aggressive if disturbed. Here the ground was pounded next to their nest starting an ongoing disturbance—with sound. Yellowjacket wasps are disturbed, but not enough to swarm around their nest entrance—with sound. The response is down to one wasp after seven minutes. Yellow jacket wasp catches green bottle fly to feed its larvae, followed by the final catch in slow motion. rabbit carrion is four days old. Yellowjacket wasps using a stone as a landmark to navigate to their nest entrance. When the stone moved, they continued for a time to return orienting with the stone. Yellowjacket response when a leaf blocks their entrance—with sound. Very late in season, nearly every morning is too cold for the yellowjackets to forage. In another several weeks all are dead—except the new queens sheltering somewhere else.

Yellow jackets are social hunters living in colonies containing workers, queens, and males (drones). Colonies are annual with only inseminated queens overwintering. Fertilized queens are found in protected places such as in hollow logs, stumps, under bark, leaf litter, soil cavities, and man-made structures. Queens emerge during the warm days of late spring or early summer, select a nest site, and build a small paper nest in which they lay eggs. After eggs hatch from the 30 to 50 brood cells, the queen feeds the young larvae for about 18 to 20 days. Larvae pupate, then emerge later as small, infertile females called workers. Workers in the colony take over caring for the larvae, feeding them with chewed-up meat or fruit. By midsummer, the first adult workers emerge and assume the tasks of nest expansion, foraging for food, care of the queen and larvae, and colony defense.

From this time until her death in the autumn, the queen remains inside the nest, laying eggs. The colony then expands rapidly, reaching a maximum size of 4,000–5,000 workers and a nest of 10,000–15,000 cells in late summer. The species *V. squamosa*, in the southern part of its range, may build much larger perennial colonies populated by dozens of queens, tens of thousands of workers, and hundreds of thousands of cells. At peak size, reproductive cells are built with new males and queens produced. Adult reproductives remain in the nest fed by the workers. New queens build up fat reserves to overwinter. Adult reproductives leave the parent colony to mate. Males die quickly after mating, while fertilized queens seek protected places to overwinter. Parent colony workers dwindle, usually leaving the nest to die, as does the founding queen. Abandoned nests rapidly decompose and disintegrate during the winter. They can persist as long as they are kept dry, but are rarely used again. In the spring, the cycle is repeated; weather in the spring is the most important factor in colony establishment.

The adult yellowjacket diet consists primarily of sugars and carbohydrates, such as fruits, flower nectar, and tree sap. Larvae feed on proteins derived from insects, meats, and fish. Workers collect, chew, and condition such foods before feeding them to the larvae. Many of the insects collected by the workers are considered pest species, making the yellowjacket beneficial to agriculture.^[4] Larvae, in return, secrete a sugary substance for workers to eat; this exchange is a form of trophallaxis. As insect sources of food diminish in late summer, larvae produce less for workers to eat. Foraging workers pursue sources of sugar outside the nest including ripe fruits and human garbage.

Nest

Two-year yellowjacket nest, with a one-gallon (3.8-liter) container for size reference. Collected in Alabama, USA, 2007. Dimensions approximately 18 inches by 24 inches by 12 inches (46 cm by 61 cm by 30 cm). *Dolichovespula* species such as the aerial yellow jacket, *D. arenaria*, and the bald-faced hornet, tend to create exposed aerial nests. This feature is shared with some true hornets, which has led to some naming confusion. *Vespula* species, in contrast, build concealed nests, usually underground.

Yellow jacket nests usually last for only one season, dying off in winter. The nest is started by a single queen, called the "foundress". Nests that survive multiple seasons become massive and often possess multiple egg-laying queens.

WASP POWER IN FARMS

Wasps are like the unsung heroes of agriculture.

- **Natural pest control:** Wasps prey on crop-destroying insects, reducing pesticide use
- **Pollination boost:** Some wasps help pollinate crops, increasing yields
- **Biological control agents:** Wasps can be used to control specific pests, making farming more sustainable.

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Recent advancements in molecular marker-assisted selection and applications in plant breeding programmes



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Abstract

DNA markers improved the productivity and accuracy of classical plant breeding by means of marker-assisted selection (MAS). The enormous number of quantitative trait loci (QTLs) mapping read for different plant species have given a plenitude of molecular marker-gene associations.

Molecular marker-assisted selection has considerably shortened the time for new crop varieties to be brought to the market. To explore the information about DNA markers, many reviews have been published in the last few decades; all these reviews were intended by plant breeders to obtain information on molecular genetics. In this review, we intended to be a synopsis of recent developments of DNA markers and their application in plant breeding programmes and devoted to early breeders with little or no knowledge about the DNA markers. The progress made in molecular plant breeding, plant genetics, genomics selection, and editing of genome contributed to the comprehensive understanding of DNA markers and provides several proofs on the genetic diversity available in crop plants and greatly complemented plant breeding devices.

MAS have revolutionized the process of plant breeding with acceleration and accuracy, which is continuously empowering plant breeders around the world.

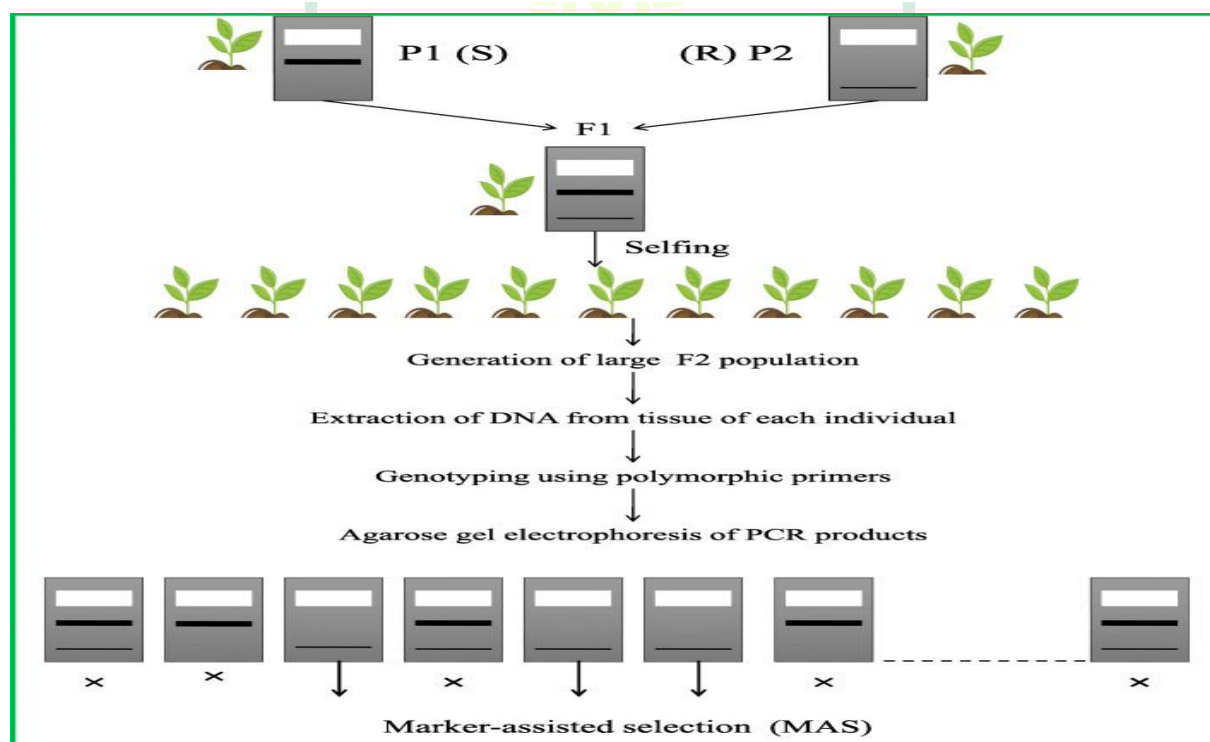
The advent of the Green Revolution in the 1960s brought a step change in the potential yield of wheat and rice and is credited with avoiding severe food crises. Since this time, there has been a constant expectation that plant breeding efforts will be able to sustain gains in yield, ironically against a background of decreasing funding (American Society of Agronomy, 2018). At the same time, new intensive cropping systems promoted by the Green Revolution resulted in increased pressure from pests and disease while farm areas continue to push into more marginal land. To meet these challenges, breeding and geneticists have been very successful in identifying sources of novel genetics from pre-Green Revolution landraces with the intention of bringing various biotic and abiotic stress tolerance into high-yielding semi-dwarf backgrounds prevalent in farmers' fields. The concept of MAS has been used extensively as justification to identify and clone hundreds of genes across many species. Rice in particular boasts dozens of cloned genes with significant phenotypic effects and serves as a useful case study to understand both the potential value of marker-assisted selection and its barriers to deployment. The rich genetic variations amenable to MAS in rice and other crops is a function of the partitioning of rice genetic diversity and its adoption as the first model species in monocots and subsequent worldwide efforts to publish its genome sequence (IRGSP 2005). For example, the Q-TARO database currently contains 114 cloned genes with natural variants affecting various traits, and the number of identified QTLs is many times this value. Marker-assisted selection is a newly emerging approach due to which various problems of conventional breeding avoid and enhance the selection criteria of phenotypes with the selection of genes, either indirectly or directly. Molecular or DNA markers are not regulated through the environment and conditions have no effects in which the crop plants are grown and observable in the stages of growth of the plant. With the accessibility of a variety of molecular markers and hereditary maps, MAS has gotten conceivable both for characteristics administered by significant quality just as for quantitative trait loci (QTLs). The handiness of a given molecular marker is reliant on its ability in revealing polymorphisms in the nucleotide sequences permitting segregation between various molecular marker alleles. These polymorphisms are revealed by molecular techniques such as restriction fragment length polymorphism (RFLP), amplified fragment length polymorphism (AFLP), microsatellite or simple sequence length polymorphism (SSR), random amplified polymorphic sequences (RAPD), cleavable amplified

polymorphic sequences (CAPS), single-strand conformation polymorphisms (SSCP), single nucleotide polymorphisms (SNPs) and others (Khlestkina,2014).

A fruitful utilization of molecular markers to help breeding systems depends on a few elements:

1. A molecular marker in association with a genetic map linked to a gene or quantitative trait loci (QTLs) of agronomic interest;
2. Molecular markers are tightly associated with the QTLs or major genes;
3. Sufficient recombination between the molecular markers that are associated with desirable traits and the rest of the genome; and
4. A possible analysis method of a large number of individuals in a time and cost-effective manner.

Most of the fruitful utilization of MAS examined beneath depends on this class of molecular markers. The gene located on a particular region of the chromosome can be shown by one or more QTLs. In this situation, genomic regions to be chosen are frequently chromosome fragments; it is in this manner best either to have two polymorphic markers flanking the targeted QTL or potentially at least one marker inside the QTL genomic region. A few models identified with the two methodologies for the introgression of QTLs into various genetic systems are discussed below. Until now, MAS has been demonstrated to be powerful for generally basic characteristics that are controlled by few genes, and a few examples are given in this review on the benefits and on the effective use of MAS for this class of traits. For progressively complex traits, it has been proven that MAS is not to be more effective; a few reasons in the premise of these challenges, a few instances of fruitful utilization of MAS for quantitative characteristics, and points of view for expanding the effectiveness of MAS for QTLs are talked about. The basic procedure of molecular marker-assisted selection.



Types of DNA markers used in MAS

There are five fundamental contemplations for the utilization of DNA markers in MAS: reliability; quality and quantity of required DNA; amount and nature of DNA required; specialized methodology for marker examination; the level of polymorphism; and cost.

Reliability

Markers ought to be firmly connected to the target loci, ideally under a 5-cm distance of genes. The utilization of flanking markers or intragenic markers will significantly build the reliability of the markers to foresee the phenotype.

Table 1. Comparison of most widely used DNA marker system in plants

Feature and description	RFLP	RAPD	AFLP	SSR	SNP
Genomic abundance	High	High	High	Moderate to high	Very high
Genomic coverage	Low copy coding region	Whole genome	Whole genome	Whole genome	Whole genome
Expression/inheritance	Co-dominant	Dominant	Dominant/co-dominant	Co-dominant	Co-dominant
Number of loci	Small (< 1000)	Small (< 1000)	Moderate (1000s)	High (1000s–10,000s)	Very high (> 100,000)
Level of polymorphism	Moderate	High	High	High	High
Type of polymorphism	Single base change, indel	Single base change, indel	Single base change, indel	Changes in length repeat	Single base change, indel
Cloning and/or sequencing	Yes	No	No	Yes	Yes
Type of probes/primers	Low-copy DNA or c DNA clones	10 bs random nucleotides	Specific sequence	Specific sequence	Allele-specific PCR primer
PCR-based	Usually no	Yes	Yes	Yes	Yes
Radioactive detection	Usually yes	No	Yes or no	Usually no	No
Reproducibility/reliability	High	Low	High	High	High
Amount of DNA required	Large (5–50 µg)	Small (0.01–0.1 µg)	Moderate (0.5–1.0 µg)	Small (0.05–0.12 µg)	Small (> 0.05 µg)
Genotyping throughput	Low	Low	High	High	High
Cost	Moderate to high	Low	Moderate	Moderate to high	High
Marker index	Low	Moderate	Moderate	Moderate to high	Moderate
Time demanding	High	Low	Moderate	Low	Low
Number of polymorphic per loci	1.0–3.0	1.5–5.0	20.100	1.0–3.0	1.0
Primary application	Genetic	Diversity	Diversity and genetic	All purposes	All purposes

DNA quantity and quality

Some marker strategies require enormous sums and a high caliber of DNA, which may some of the time be hard to get by and by, and this adds to the expense of the system.

Specialized system

The degree of effortlessness and the time required for the procedure are basic contemplations. High-throughput, straightforward, and snappy techniques are exceptionally attractive.

Level of polymorphism

Ideally, the marker ought to be profoundly polymorphic in the breeding material (for example it should separate between various genotypes), particularly in the central breeding material.

Affordability

The cost of DNA markers should be affordable. This infers the test ought to be modest, easy to understand, and simple to apply for effective screening of enormous samples/populations. The cost-effectiveness of the molecular marker assay should be considered to ensure the plausibility of the molecular marker-assisted selection. Sequence tagged site (STS), Simple sequence repeats (SSRs), single nucleotide polymorphism (SNP), or sequence characterized amplified region (SCAR) markers that are gotten from an explicit DNA sequence of markers (for example limitation piece length polymorphisms: RFLPs) that are connected to a quality or quantitative attribute locus (QTL) are likewise amazingly helpful for MAS [2015].

Classification of molecular markers

DNA or molecular markers are classified in different groups on the basis of:

1. Nature of gene action (dominant or co-dominant markers);
2. Detection methods of molecular markers (PCR based molecular markers or hybridbased molecular markers);
3. Transmission mode of molecular markers (maternal organelle inheritance, paternal organelle inheritance, maternal nuclear inheritance, or biparental nuclear inheritance).

DNA or molecular markers have been developed in various kinds and all these have applied successfully in breeding and genetic activities in different agricultural crops throughout the world. In this review, brief information has provided that is related to molecular markers based on the detection methods of molecular markers. Comparisons of the important characteristics of the most used molecular markers are given in table

DNA markers

Molecular markers are sequences of nucleotides and can be explored through the polymorphisms present between the nucleotide sequences of various people. Deletions, insertions, gene mutation, duplication, and translocation of these nucleotide sequences are the basis of polymorphisms among the population; however, they do not really influence the function of genes. A perfect DNA marker ought to be co-predominant, uniformly distributed, genome, more and having the capacity to recognize a more significant level of polymorphism.

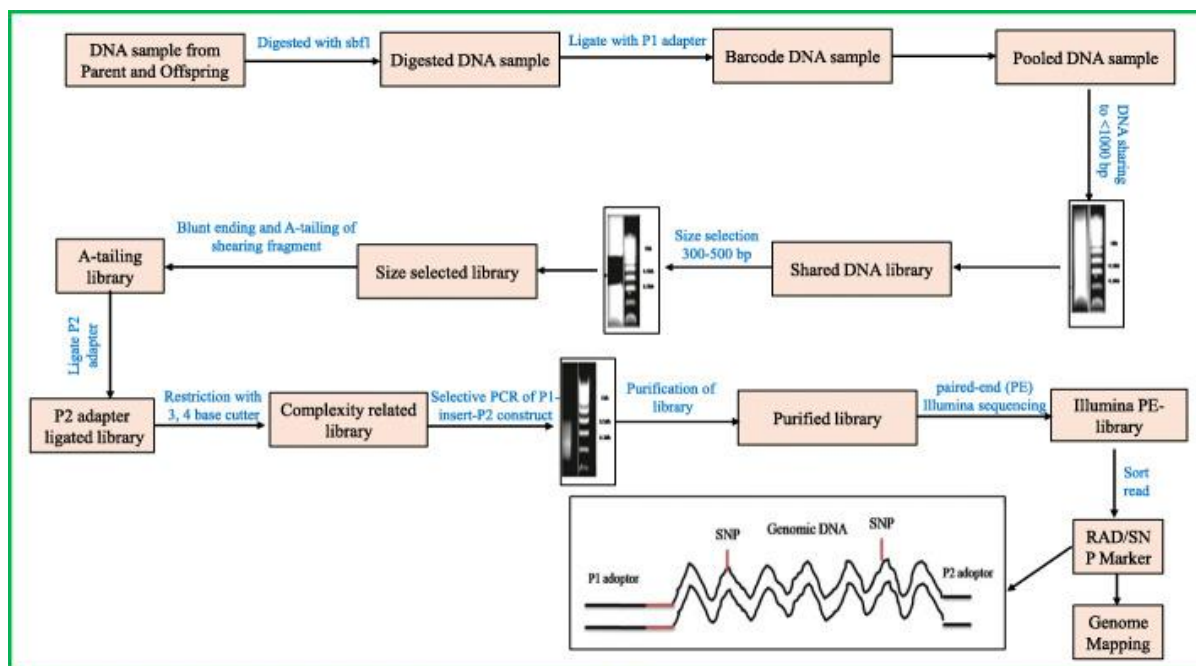
Hybridization-based

DNA markers, conventional, or first-generation RFLPs, require the utilization of a properly labelled DNA probe for the selection of the specific genes of interest from the digestion of DNA samples and then, by hybridization. RFLP was the primary molecular marker strategy and the main marker framework dependent on hybridization. People of the same species show polymorphisms because of insertions/deletions (known as InDels), gene mutations, duplications, translocations, and inversions. The isolation of pure DNA from the target is the primary step in the RFLP strategy. This DNA is blended in through the cutting enzymes (restriction endonucleases) which are isolated from the target such as bacteria, human cells, etc. and a specific function of restriction enzymes identify specific nucleotide sequences along the DNA strand, and therefore they cut DNA at specific loci (acknowledgment destinations). These outcomes are an immense number of segments with various lengths.

PCR-based DNA markers

Molecular markers based on PCR techniques do not require a probe hybridization step. PCR-based markers are atomic markers that do not require the hybridization step. Their improvement has prompted the disclosure of a few valuable and simple to screen new generation markers, for example random amplified polymorphic DNA(RAPD), amplified fragment length polymorphism (AFLP), microsatellite or SSRs, SNP, RAMP, SRAP, ISSR, SCAR, expressed sequence tagged (EST), and so forth . Being PCR-based, these molecular markers require the utilization of primer pairs for the selection of a specific part of the DNA to measure the variation in genetic material. Short sequences of nucleotides that are attached with the DNA to synthesize the full length of dsDNA are called primers. Most of the primers are used for the selection of specific regions of DNA to be amplified by polymerase chain reaction and sequence analysis techniques . They, therefore, start the amplification of the specific segment of DNA. After the amplification of DNA from various genotypes, the fragments of digested

DNA are separated on the gel to examine the variation in the pattern of bands and further DNA fragments may be subjected to the sequencing technique for observing the sequence variation in DNA resulting in species variation. Analysis of molecular markers based on PCR involves the extraction of DNA from the source and evaluation of the quality and quantity of isolated DNA and gel electrophoresis. If sequencing is required, the amplification products are usually purified, subjected to sequencing PCR, and further purified before sequencing. SNP genotyping through next-generation sequencing is shown in Fig.2



RAD-sequence: discovery and genotyping of SNPs by next-generation sequencing for genome mapping. EcoRI-MspI ligation as “adapter_P1-EcoRI” and “adapter_P2-MspI”

Importance of pollination and pollinizer in fruit crops production



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Introduction:

Fruit production depends heavily on pollinators and pollinizers, which have a big impact on crop yields and quality. Bees, butterflies, and other insects are examples of pollinators that help move pollen from the male to the female portions of flowers, allowing for fertilization and the formation of fruits. Conversely, pollinizers are the particular plants or flower types that supply the pollen required for fertilization. Many fruit crops, such as apples, pears, cherries, and almonds, depend on the interplay of pollinators and pollinizers for successful reproduction. To lower genetic barriers and increase fruit yield, many fruit crops are cultivated in numerous types. Declining pollinator populations due to habitat loss, pesticide use, climate change, and inadequate monitoring systems have raised concerns about the sustainability of fruit production. Lower fruit set, smaller fruit size, and poor fruit quality can result from decreased pollinator activity, which eventually affects the amount and market value of the produce. Maintaining pollinator populations and guaranteeing steady fruit production depend on conservation and management techniques including developing pollinator-friendly habitats, reducing the use of pesticides, and putting integrated pest control techniques into effect. Developing efficient agricultural techniques that support biodiversity and safe food production systems requires an understanding of the complex interactions between pollinators, pollinizers, and fruit crops.

In order to facilitate fertilization, pollen, usually from the male portion of a flower (the anther), is transferred to the female portion (the stigma) during the vital biological process of pollination. Pollination is necessary for fruit-bearing plants to produce seeds, which are a step before fruit development. Insects, especially bees, are the most prevalent and effective pollinators. The process can be carried out by a variety of natural agents, including wind, water, and animals. In order for plants to generate healthy seeds that will develop into new generations of plants, pollination is essential to the reproductive cycle of many fruit crops.

In fruit production, the success of pollination directly impacts the quantity and quality of the fruit harvest. For crops like apples, almonds and cherries, pollination is not just important for producing fruit but is also necessary to ensure genetic diversity. Without successful pollination, many fruit-bearing plants would fail to produce fruits, significantly affecting food production, agricultural economies, and biodiversity. A pollinator is a biotic agent that transfers pollens from anther to flower stigma, which by fertilization contributes to the production of fruits or seeds. The pollinators include bees, flies, bats, moths, or birds. Several fruits, vegetables, and field crops rely heavily on pollinators and numerous studies have praised insect pollination as an eco-system service for agricultural food production on a global and national scale. Insect pollinators are becoming increasingly common among farming communities as a way to boost crop productivity and feed the world's rising population. Improved pollination can shorten the time between flowering and fruit set, minimizing the risk of pests, disease, bad weather, and agrochemical exposure while also conserving water. More than one of each three nibbles of food we eat or refreshments we drink are straight forwardly a result of pollinator.

Five Conditions are Necessary for Satisfactory Cross-pollination:

1. Pollinizer and main variety bloom periods must overlap.
2. The Pollinizer variety must have viable diploid pollen.
3. The Pollinizer variety must be located near the producing tree.
4. Bees and other insects must be present in the orchard and be active at bloom.
5. Weed blossoms, such as dandelions, mustard, and wild radish, should not be present in quantity since they attract bees away from fruit tree blossoms.

Pollination is necessary for all fruit species to set fruit. Some species don't need more than one cultivar per block because they are self-fruitful. Most apricots, peaches, nectarines, tart cherries, and some European plums are self-fruitful; a single cultivar can be planted in a solid block. For sufficient cross-pollination, mixed plantings of various cultivars are necessary for apples, pears, and sweet cherries. Fruit harvests differ significantly in the proportion of flowers that must be established. A commercial crop requires 20 to 60 percent of sweet cherry flowers and 20 to 75 percent of sour cherry blossoms since pollination directly determines yield for crops like cherries, for which each individual flower provides a good-sized fruit at harvest without thinning. The percentage of flowers that require pollination is significantly lower for other fruit crops, such as apples (2 to 8 percent), pears (3 to 11 percent), peaches (15 to 20 percent), apricots (20 to 25 percent), and plums (3 to 20 percent), where size is more crucial for commercial purposes or to avoid biennial cropping. This is the rationale behind chemically thinning apples or hand-thinning numerous crops, such as peaches, later in the season. Under normal circumstances, these crops tend to set too much fruit that, if allowed to mature, will be too small commercially. Increased fruit size and shape, as well as more fruit per tree, can result from improved pollination. Fruit size and calcium content are strongly correlated with the quantity of seeds per fruit, which depends on effective pollination, according to research conducted in Massachusetts. The likelihood of cross-pollination increases with the number of pollinizer trees in a planting. However, orchard operations become less efficient when rows of apple pollinizers are used. In addition to confusing pickers and creating bins of mixed cultivars, having two or more cultivars in an orchard may cause issues with spray-to-harvest restrictions and cultural customs. Different growth patterns may also lead to an inefficient use of land. However, the higher yields linked to the usage of pollinizer greatly outweigh these drawbacks.

Importance of Pollination in Fruit Production and Biodiversity

Pollination is not only fundamental to agriculture but also to the global ecosystem. Approximately 75% of flowering plants and 35% of food crops depend on pollinators for reproduction. The role of pollinators extends far beyond fruit-bearing plants. They are crucial for maintaining biodiversity, supporting food webs, and ensuring the survival of various plant species. In agricultural terms, pollination is often the linchpin for high crop yields.

- **Increased fruit set, yield and fruit quality:** Pollinators enhance fruit set by ensuring that an adequate amount of pollen reaches the stigma of each flower. This increased pollination leads to a higher percentage of flowers developing into fruits. Adequate pollination can improve the quality of fruits. Proper pollination is often associated with more uniform fruit size, shape, and flavour. Fruit crops that rely on pollination by pollinators tend to have higher yields compared to crops that are self-pollinated. Increased yield is especially important for commercial fruit production, as it directly impacts economic returns. For fruit crops, pollinators increase the diversity of the gene pool, contributing to plants' resilience against pests, diseases, and changing environmental conditions. In the wild, pollination supports the growth of fruit trees, which in turn provide habitat and food for countless species. This creates a balanced ecosystem where pollinators, plants, and animals are interdependent. The loss of pollinators can lead to the collapse of these ecosystems, affecting both agricultural production and natural habitats.
- **Biodiversity support and ecosystem services:** The presence of diverse pollinator species contributes to overall biodiversity in agro-ecosystems. Protecting and promoting pollinators can have positive effects on the broader ecosystem. Pollinators play a crucial role in supporting biodiversity, and there exists a positive correlation between the diversity of plants and the diversity of pollinators. The abundance and variety of pollinators within an area serve as valuable indicators of the overall health and robustness of the ecosystem. The interdependence between plants and pollinators underscores the importance of maintaining a balanced and diverse ecological system. Pollinators provide valuable ecosystem services beyond fruit crop production. They contribute to the pollination of many other flowering plants, including those in natural ecosystems. This service is crucial for maintaining biodiversity and ecosystem stability.
- **Cultural and culinary significance:** Many fruit crops are culturally and culinary significant, and their production relies on pollinators. Examples include apples, cherries, blueberries, and almonds. Pollinators and the products derived from their activities have indirect benefits for society by serving as sources of inspiration across various domains, including art, music, literature, religion, traditions, technology, and education. Their

influence extends beyond agricultural and economic aspects, contributing to the cultural and educational richness of societies worldwide

Table 1: Examples of pollinating agents that affect pollination in fruit crops

Pollinating Agent	Fruit Crops
Insect	Apple, Pear, Almond, Apricot, Cherries, Ber, Litchi, Citrus, Mango, Annona
Wind	Aonla, Pecan Nut, Hazel Nut, Chestnut, Coconut, Papaya, Sapota
Bird	Pineapple, Banana

Factors Affecting Pollination:

Pollination efficiency is influenced by various factors that affect the pollinators and the plants involved. Over the past 50 years, the species richness of wild bees and other pollinators has decreased, with some species experiencing significant declines and a few even becoming extinct, largely due to insufficient monitoring systems.

• Environmental Factors: -

Environmental conditions significantly affect the pollination process. Temperature, humidity, and seasonal changes can all have a direct impact on the activity of pollinators and the success of fertilization.

Temperature, Humidity, and Seasonal Conditions

Temperature: Most pollinators, especially insects like bees, are highly sensitive to temperature. Optimal temperatures (typically between 18-25 °C for bees) are necessary for pollinator activity. If temperatures are too low or too high, pollinators may become inactive, reducing the chances of successful pollination.

Humidity: Humidity affects the behavior of both pollinators and plants. High humidity levels can cause

- **Abundance of pollinators:** The availability of healthy pollinators, including bees, butterflies and birds, plays a crucial role; a decline in their numbers or health due to diseases, parasites, or pesticide exposure can reduce pollination success.
- **Behavior of Pollinators:** behaviours including their foraging patterns and attraction to specific plant traits like colour and scent, influence the pollination process's effectiveness.
- **Plant characteristics:** such as the structure of flowers and the production of pollen and nectar, also affect how well pollinators can access and transfer pollen.
- **Agricultural practices:** the use of pesticides and the type of crop planting systems can either support or hinder pollinator populations. Habitat and land use changes, including urbanization and deforestation, further impact pollinator habitats and their availability.
- **The distance between flowering plants and the timing of their flowering** can affect the ease of pollen transfer and cross-pollination. Understanding and managing these factors are essential for optimizing pollination and enhancing crop yields and biodiversity and
- **Introduction of alien species:** competition for floral resources and nest
- **Interactions between different drivers:** the influence of various pressures, both direct and indirect on pollinator species affects different levels of biological organization. This includes the interactions between pesticides, pathogens and nutrition at the level of individuals or colonies, as well as the combined effects of climate change and habitat alterations at the population or species level.

Effects of Climate Change on Pollination Patterns: -

- **Shifting Flowering Times:** Climate change is altering the timing of flowering in many plants. Warmer temperatures are causing some plants to flower earlier, while others may flower later in the season. This shift can disrupt the synchronization between plants and their pollinators, leading to mismatched timing between the availability of flowers and the activity of pollinators [19, 20].
- **Changing Pollinator Populations:** As climate change affects ecosystems, it also impacts the distribution and abundance of pollinators. Some pollinator species may migrate to new areas due to temperature changes, while others may face declines in numbers due to habitat loss or temperature extremes. This has serious implications for pollination-dependent crops, which could suffer from reduced pollinator services in certain regions [21].

- **Extreme Weather Events:** Increased frequency of extreme weather events such as droughts, storms, and heatwaves can also affect pollination. For example, heavy rain or strong winds can damage flowers or disrupt the ability of pollinators to access the flowers, leading to lower pollination rates.

Conclusion: -

Most fruit crops need cross-pollination for fruit establishment and growth, pollination is essential for orchard crops. Early resolution of pollination problems is crucial to maximizing output and quality. This can be accomplished by using honey bees for efficient pollination and planting a suitable ratio of pollinizer cultivars. In addition to controlled bees, wild insects and animals like bats are important for increasing crop yields and farmer earnings. Furthermore, floral nectar is essential for the production of honey, which provides farmers with an additional revenue stream from honey and related goods. Fruit output and biodiversity are impacted by fruit pollination, which is an essential step for plant reproduction. In addition to discussing several forms of pollination, such as self-pollination and cross-pollination, each having pros and cons, this article examines the basic mechanisms of pollination, emphasizing the functions of male and female reproductive systems. It also looks at the elements that affect pollination, such as plant traits, pollinator health, and environmental circumstances. The loss in pollinator populations, the effects of monoculture farming, and the effects of climate change are among the major obstacles to fruit pollination that are identified in the article. It also explores pollination advancements including robotic pollinators and environmentally friendly farming methods.



Drudgery Reduction through Paddy Drum Seeder



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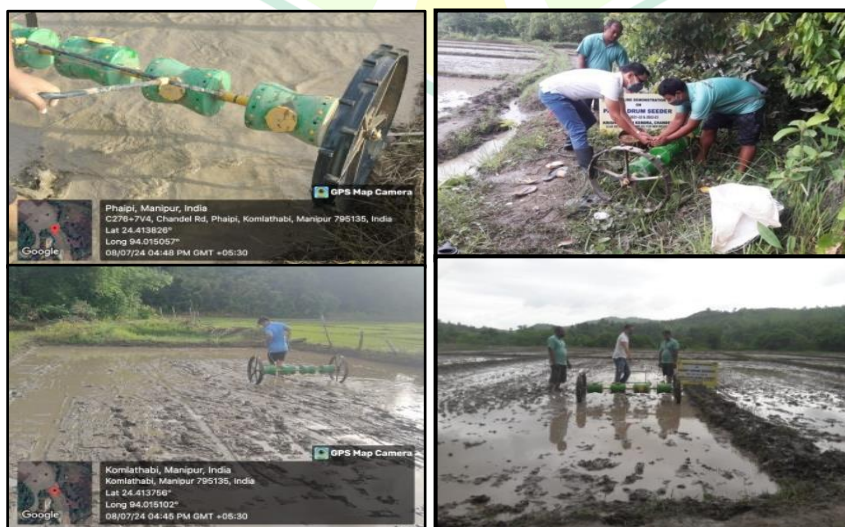
Paddy seeder is one of the few equipment that has revolutionised and changed the face of sowing paddy seeds in wetland fields. The need for transplantation and hours of manual work has been eliminated by the paddy drum seeder. The traditional manual process very often literally break the backs of the farmers involved in sowing the paddy seeds into the field. On an average, at a time, a single operator can cover 8 rows of 20 cm row to row spacing in a paddy field. Beight light-weight it is quite easy to be carried around and is gender-friendly.

PARTS & COMPONENTS OF THE DRUM SEEDER:

1. The seed drum is hyperboloidal in shape with a 200 mm diameter. There are eight seeding metering holes of 9 mm in diameter. There are baffles provided inside the seed drum between the seed holes which ensures a uniform seed rate in operation as well as to enable hill dropping of the seeds. Each seed drum has two rows of planting, and four drums are assembled together to form eight rows of planting in a single stretch.
2. There are wheels provided at both ends. These wheels are made of plastic material to provide floating characteristics. The average wheel diameter is 2 feet.
3. Also there is a square shaft, a handle base, and a handle. Four seed drums are assembled together with the square shaft. The handle is meant to be pulled along.

PREPARATIONS:

1. The puddled field should be well prepared and levelled.
2. It should be ensured that water should be drained out at least 24 hours before sowing so that a hard slurry pan of the puddled soil is formed.
3. During the time of sowing, only a thin layer of water should be maintained in the puddled field.
4. Care needs to be taken that only just sprouted seeds packed in gunny bags should be used.
5. There should be an arrangement with which water should be flooded into the puddled field once every three days after sowing and then drained out immediately. This practice should be continued for 12 days. Thereafter, depending upon the height of the seedlings, water should be allowed to stand in the field.



OPERATION PROCEDURE:

1. The paddy seeder needs to be assembled and all the bolts and nuts tightened.
2. Then the drums are to be filled up with pre-germinated seeds. It should be strictly observed that, only two-thirds of the drums are to be filled at a time.
3. The doors of the drums are then to be closed and locked.
4. The seeder then should be pulled manually at a normal walking speed (1 km/h) in the backward position.
5. The wheel impression in the first pass in the puddled field serve as a marker.
6. In the second rotation, the wheel should pass on the same wheel impression as the previous pass to maintain the row-to-row spacing of 20 cm.
7. While continuing the seeding operation, the dropping of the seeds through the holes of the seeder should be monitored frequently.
8. The drums need to be refilled when they reach one-fourth capacity.

SALIENT FEATURES

1. Drudgery and labour costs are reduced drastically
2. Uniformity is obtained in seed sowing and plant population.
3. The need for continuous drilling of seeds is eliminated.
4. Reduction in seed rate and thinning cost.
5. The crop gets matured 7-10 days earlier than the transplanted paddy.
6. It is light in weight and easy to be handled even by female farmers.
7. One farmer can easily cover an area of 1 hectare per day.

The paddy drum seeder is a specialized agricultural implement designed to plant seeds in paddy fields. It consists of a seed drum, main shaft, ground wheel, floats, and a handle. The seed drum dispenses paddy seeds while the floats prevent sinking and facilitate easy pulling of the seeder. This tool is available in many configurations, incorporating different row spacing options and seed metering hole sizes.

Advantages of Using a Paddy Seeder

A paddy seeder has truly emerged as a transformative agricultural implement that has significantly improved the efficiency of rice cultivation. This advanced technology not only simplifies the planting process but also offers several advantages, making it a valuable asset for modern farmers.

Labor and Time Savings

One of the major advantages of using a paddy drum seeder is the significant labour and time savings it offers. Traditional manual seeding requires a large number of workers to work in an uncomfortably bent posture, which can be both physically strenuous and time-consuming. With a paddy drum seeder, a single operator can cover a larger area in a brief duration of time. This allows farmers to allocate their labour resources more efficiently and focus on other important farming tasks.

Cost-Effectiveness

Investment in a paddy drum seeder can be remunerative in the form of long-term cost savings for farmers. By reducing the need for manual labour, farmers can save on wages and reallocate those resources to other areas of their farming operations and the initial investment in a paddy drum seeder can be recovered back through increased productivity and reduced weed control costs.

Improved Crop Health

Improper spacing and haphazard seed rates often causes reduced yield. By effectively maintaining proper seed rate & spacing with a paddy seeder, farmers can prevent the spread of resulting in healthier crops. Additionally, the improved airflow and reduced humidity between the crop rows promote better ventilation, reducing the risk of fungal diseases.

“Impact of Tillage Practices on Weed Dynamics in Agroforestry Systems”



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ABSTRACT

By affecting soil disturbance, weed seed dispersal, soil moisture, and crop–tree–weed interactions, tillage techniques significantly influence weed dynamics within agroforestry systems. Weed emergence, composition, and competitiveness are greatly impacted by the diverse microclimatic and edaphic conditions created by agroforestry systems, which are defined by the integration of trees with crops. While reduced and zero tillage methods tend to favour perennial weeds due to low soil disturbance, conventional tillage practices frequently encourage the sprouting of annual weed species by bringing buried weed seeds to the soil surface. Reduced tillage and tree-induced shading in agroforestry systems can decrease light demanding weed species and gradually change the composition of weed flora. By increasing residue cover and microbial activity, conservation tillage techniques improve soil structure, increase soil organic matter, and promote biological weed suppression. However, improper tillage intensity can negatively impact crop output by increasing weed pressure and competition for nutrients, water, and light. Thus, choosing the right tillage techniques in agroforestry systems is crucial for long-term weed control. Weed dynamics can be successfully controlled while enhancing soil health and system production through integrated approaches that combine appropriate tillage techniques with mulching, crop rotation, and canopy management. In order to create weed management techniques that are both economically and environmentally sound, it is essential to comprehend how tillage practices and weed ecology interact in agroforestry systems.

Keywords: Agroforestry, Tillage practices, weed dynamics, Conservation agriculture,

Introduction

The word *tillage* comes from the Anglo-Saxon words *tilian* and *teolian*, which mean to plough and prepare the soil for sowing seeds and growing crops.

Tillage is one of the oldest practices in agriculture and has been used since early human civilization, when people loosened the soil to place seeds. It involves the mechanical working of soil using tools and implements to create suitable conditions for seed germination, seedling establishment, and healthy crop growth.

What is weed?

Weed unwanted plants that grow wild in fields or gardens alongside cultivated ones

Impact: They steal resources (water, light, nutrients) from desired plants, stunt their growth, and can spread pests.



Based on Life Cycle

a) Annual weeds

- Complete life cycle in one season
- Examples: *Amaranthus*, *Chenopodium album*.



b) Biennial weeds

- Complete life cycle in two seasons
- Examples: *Daucus carota* (wild carrot)



c) Perennial weeds

- Live for many years, reproduce by roots/rhizomes
- Examples: *Cyperus rotundus*, *Cynodon dactylon*



Based on Morphology

a) Grassy weeds

- Narrow leaves,
- Examples: *Echinochloa*, *Phalaris minor*



b) Broad-leaved weeds

- Broad leaves,
- Examples: *Parthenium hysterophorus*, *Xanthium spinosum*



Weed Management

Method	Practices	Examples / Notes
Preventive	Clean seed, clean tools, field sanitation	Prevents entry of new weeds
Cultural	Crop rotation, timely sowing, proper spacing	Reduces weed growth naturally
Mechanical / Physical	Hand weeding, hoeing, ploughing, mulching	Effective in small fields
Chemical	Use of herbicides	Pendimethalin (pre-emergence), 2,4-D (post-emergence)
Biological	Insects, pathogens	<i>Zygogramma</i> for <i>Parthenium</i>
Integrated Weed Management (IWM)	Combination of methods	Most effective & eco-friendly

Importance of Weed Dynamics

Aspect	Importance	Explanation
Crop yield protection	Very high	Reduces crop-weed competition for nutrients, water, and light
Weed population prediction	High	Helps forecast future weed infestation and dominant species
Herbicide resistance management	High	Aids in planning rotation and integrated weed management
Cost-effective farming	Medium	Minimizes unnecessary herbicide use and labor cost
Soil health	Medium	Supports conservation tillage and soil biodiversity

What is Tillage?

Tillage is the agricultural practice of preparing the soil by ploughing, digging, or stirring it before sowing seeds.

Role of Tillage in Agriculture

Tillage is important in agriculture for preparing the soil for planting, as it loosens the earth to improve aeration and water absorption, which helps plant roots grow. It is also crucial for weed and pest control, by disrupting weeds and destroying pest habitats, and for incorporating organic matter and fertilizers to improve soil fertility.

Importance of Tillage

Aspect	Importance	Explanation
Seedbed preparation	Very High	Creates fine soil tilth for good seed germination
Weed control	Very High	Uproots and buries weeds, reducing competition
Soil aeration	High	Improves air circulation and root respiration
Moisture conservation	High	Breaks soil crust and reduces moisture loss
Nutrient availability	Medium	Enhances nutrient release and uptake
Pest & disease control	Medium	Exposes soil pests and pathogens
Residue management	Medium	Mixes crop residues into soil to improve fertility

Types of Tillage

Type of Tillage	Nature	Purpose / Description
Primary tillage	Deep (20–30 cm)	First operation to open, loosen, and invert soil
Secondary tillage	Shallow (5–10 cm)	Seedbed preparation after primary tillage
Inter tillage	Shallow	Weed control and soil aeration during crop growth
Zero tillage	No soil disturbance	Direct sowing without ploughing
Minimum tillage	Reduced disturbance	Conserves moisture and reduces cost
Conservation tillage	Crop residue cover	Reduces soil erosion and improves soil health
Strip tillage	Narrow tilled strips	Tillage only in crop rows

Advantage of Tillage

1. Improved soil conditions due to decomposition of plant residues in place.
2. Higher infiltration caused by the vegetation present on the soil and channels formed by the decomposition of dead roots.
3. Less resistance to growth due to improved structure.
4. less soil compaction by the reduced movement of heavy tillage vehicles and less soil erosion compared to conventional tillage.

Disadvantage of Tillage

1. Seed germination is lower.
2. More nitrogen has to be added as rate of decomposition of organic matter is slow.
3. Nodulation is affected in some leguminous crops like pea and cowpea.
4. Sowing operations are difficult with ordinary equipment.
5. Continuous use of herbicides causes pollution and perennial weed problems.

Agroforestry System Overview

Agroforestry is a land-use system in which trees are grown together with crops and/or livestock on the same land to improve productivity, sustainability, and income.

There are three main types of agroforestry systems:

1. Silvi + Agriculture Systems

It is an agroforestry system in which trees are grown together with agricultural crops on the same land to improve productivity and sustainability.



Combination of trees and crops

2. Horti + Silviculture Systems

The Horti-Silvi system is an innovative approach within agroforestry that combines horticulture (cultivation of fruits, vegetables, and ornamental plants) with silviculture (the practice of growing and managing trees) to create a balance and productive ecosystem.



3. Silvi + Pastoral System

The Silvi-Pastoral system is an agroforestry practice in which forest trees or shrubs are combined with pasture grasses and/or livestock on the same land to produce fodder, fuelwood, timber, and animal products, while improving soil fertility, biodiversity, and sustainable land management.

Effect of five years old lohakat tree (*Xylia dolabriformis*) on the growth and yield of carrot. (A. Akter, et al., 2013)



Cash Study

Effect of five years old lohakat tree (*Xylia dolabriformis*) on the growth and yield of carrot. (A. Akter, et al., 2013)

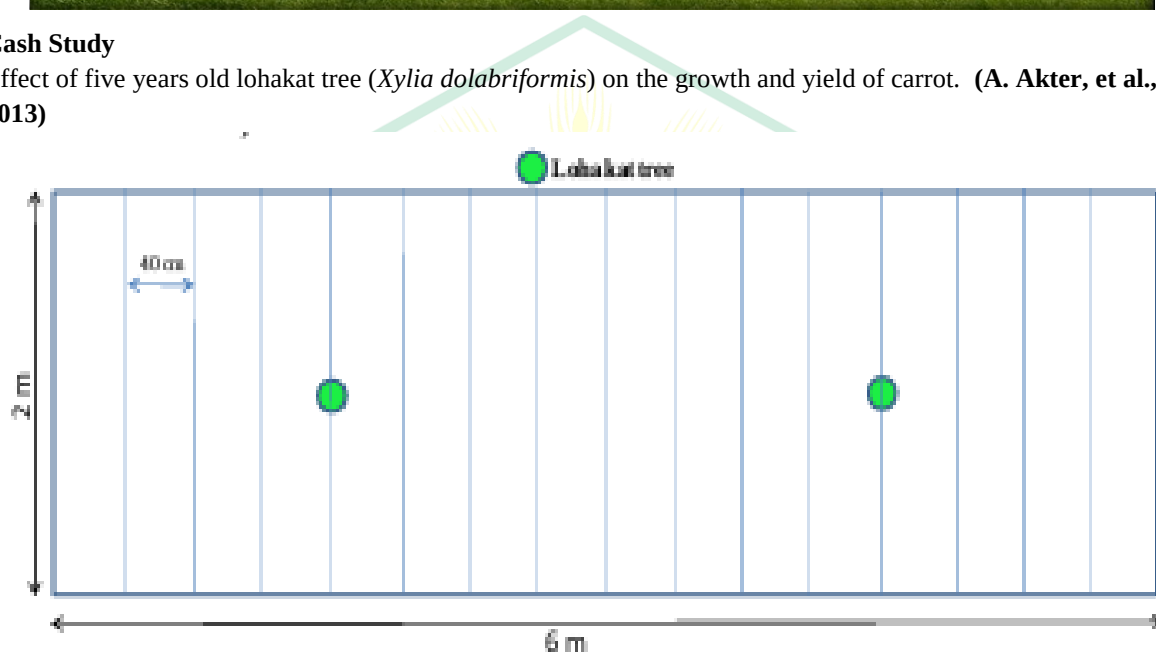


Fig.1. Layout of experiment showing one research plot



Fig. 2. Carrot cultivation along with lohakat tree

Table 1. Morphological Characteristics of Carrot at vegetative stage

Treatment	Plant height (cm)	No. of leaf /plant	Leaf size		Root length (cm)
			Length (cm)	Breadth (cm)	
T ₀	34.23a	9.48a	25.67a	15.39a	8.56a
T ₁	33.42a	9.81a	25.43a	14.94b	7.99a
T ₂	27.54b	6.83b	20.93b	12.14bc	6.61b
T ₃	23.37c	5.92c	18.58b	10.43c	4.79c

Means in column followed by the different letter are significantly different by DMRT at $P \leq 0.05$, T₀ = Control, T₁ = 1.0-1.5m from tree base, T₂ = 0.5-1.0m from tree base, T₃ = upto 0.5m from tree base.

Table 2. Morphological Characteristics of Carrot during harvest

Treatment	Plant height (cm)	No. of leaf/plant	Leaf wt./plant (g)	Root length (cm)	Root girth (cm)	Root wt./plant (g)
T ₀	62.25a	12.00a	48.50a	15.88a	11.38a	84.87a
T ₁	59.5a	12.25a	51.25a	15.38a	10.95a	84.25a
T ₂	51.00b	8.65b	28.75b	10.25b	6.70b	35.00b
T ₃	42.25c	7.80c	13.75c	7.42c	5.80c	22.00c

Means in column followed by the different letter are significantly different by DMRT at $P \leq 0.05$, T₀ = Control, T₁ = 1.0-1.5m from tree base, T₂ = 0.5-1.0m from tree base, T₃ = upto 0.5m from tree base.



Fig. 3. Carrot in different treatments of this study

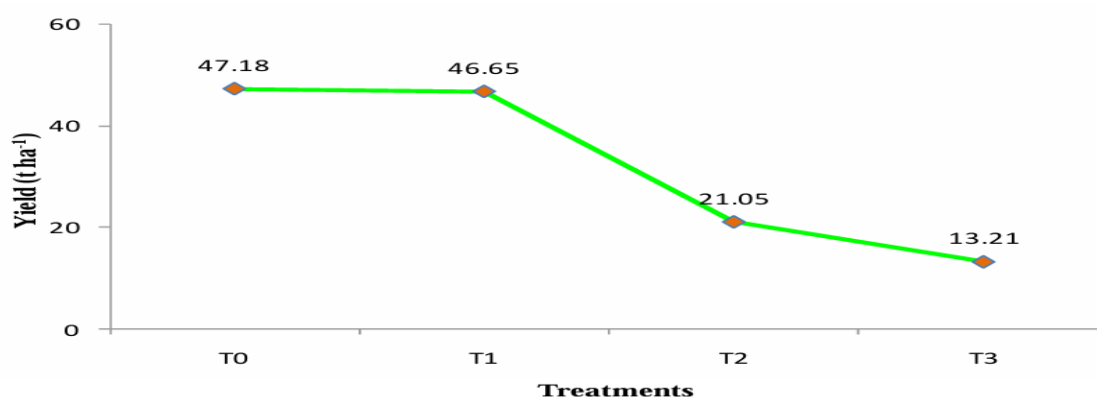


Fig. 4. Yield of Carrot in different treatments

Agroforestry System Advantages

Environmental

- Soil Health
- Biodiversity
- Climate Mitigation
- Water Management

Economic

- Diversified Products
- Income Stability

Social

- Livelihood
- Community

Agroforestry System Disadvantages

- Initial Investment & Returns
- Competition
- Management Complexity
- Land Constraints
- Market & Policy Barriers

Conclusion

Tillage practices play a crucial role in shaping weed dynamics within agroforestry systems. Appropriate tillage can effectively reduce weed pressure by disrupting weed emergence and seed banks, thereby supporting better crop establishment. However, excessive or improper tillage may increase weed infestation and degrade soil health. Integrating reduced or conservation tillage with agroforestry enhances weed suppression through tree-crop interactions, improves soil structure, and promotes sustainable weed management.

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ICT AND CLOUD COMPUTING IN AGRICULTURE



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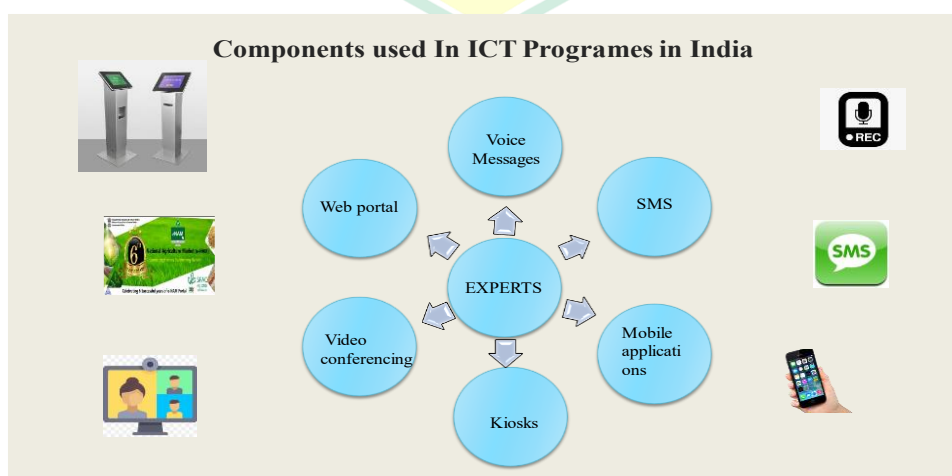
INTRODUCTION

Agriculture forms the backbone of the Indian economy, serving as a crucial pillar for national growth and rural development. Nearly 58% of India's population relies on agriculture and allied activities for their livelihood, highlighting the sector's significance in ensuring food security, employment, and socio-economic stability. According to recent fiscal policy statements, the Indian agricultural sector recorded a growth rate of 3.5% during the financial year 2022–2023, reflecting its resilience and steady progress despite various climatic and market challenges. This consistent growth underscores the vital role of agriculture in sustaining India's economic structure and supporting millions of farming households across the country.

The Indian agricultural sector continues to face several persistent challenges that hinder productivity and farm profitability. Inadequate and uneven irrigation facilities remain a major constraint, making crop production highly vulnerable to rainfall variability. The impacts of climate change—such as erratic monsoons, rising temperatures, and frequent extreme weather events—further exacerbate production risks. Many farmers continue to struggle with poor socio-economic conditions and fragmented, small land holdings, which limit their capacity to invest in improved inputs and modern practices. The inadequate use of farm machinery and equipment also contributes to low operational efficiency, while limited access to reliable market information often results in distress sales and reduced income. Moreover, the adoption of advanced technologies, including Information and Communication Technologies (ICT), remains insufficient, restricting farmers' ability to benefit from precision farming, digital advisories, and efficient supply chain management. These interconnected challenges collectively impede the sustainable growth and modernization of Indian agriculture.

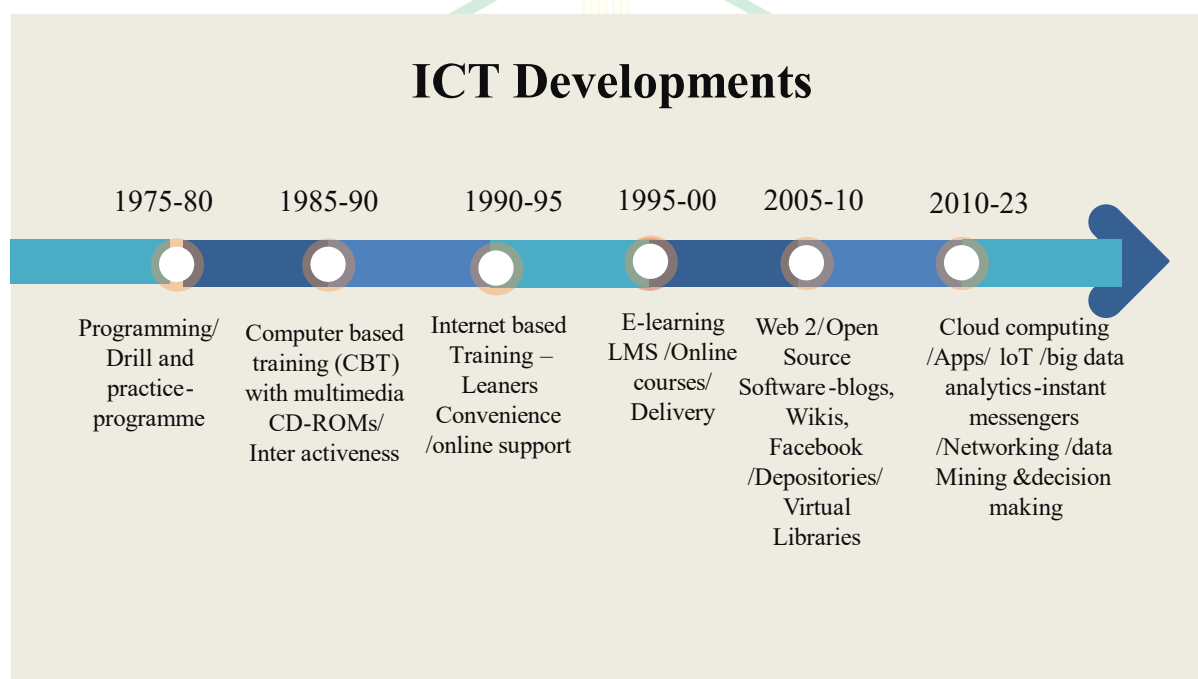
WHAT IS ICT?

Information and Communication Technology (ICT) is an umbrella term that encompasses a wide range of communication devices, tools, and applications used to create, store, transmit, and share information. It includes traditional media such as radio and television, as well as modern digital tools like cellular phones, computers, network hardware and software, and satellite communication systems. By integrating these technologies, ICT plays a pivotal role in enhancing information flow, improving connectivity, and supporting data-driven decision-making across various sectors, including agriculture.



ICT programmes in India integrate multiple digital tools to deliver timely agricultural information to farmers. These programmes rely on components such as web portals, mobile applications, SMS services, voice messages, video conferencing platforms, and village-level kiosks, all of which connect farmers directly with agricultural experts. Through these communication channels, farmers receive real-time advisories on crop management, weather updates, pest and disease alerts, and market information, thereby improving decision-making and enhancing farm productivity.

The evolution of Information and Communication Technology (ICT) has progressed rapidly over the past few decades, transforming the way information is created, shared, and utilized. During the early period of 1975–1980, ICT focused mainly on programming and drill-based practice programmes. By 1985–1990, computer-based training (CBT) emerged with multimedia CD-ROMs, offering greater interactivity. The 1990–1995 phase marked the rise of internet-based training, providing learners convenience and online support. Between 1995 and 2000, e-learning platforms and Learning Management Systems (LMS) enabled structured online courses and digital content delivery. The 2005–2010 period saw the development of Web 2.0 technologies, including blogs, wikis, social media platforms, and virtual libraries. From 2010 onwards, ICT has advanced into cloud computing, mobile applications, IoT, big data analytics, instant communication tools, and data-driven decision-making systems, significantly enhancing connectivity and digital innovation across sectors.

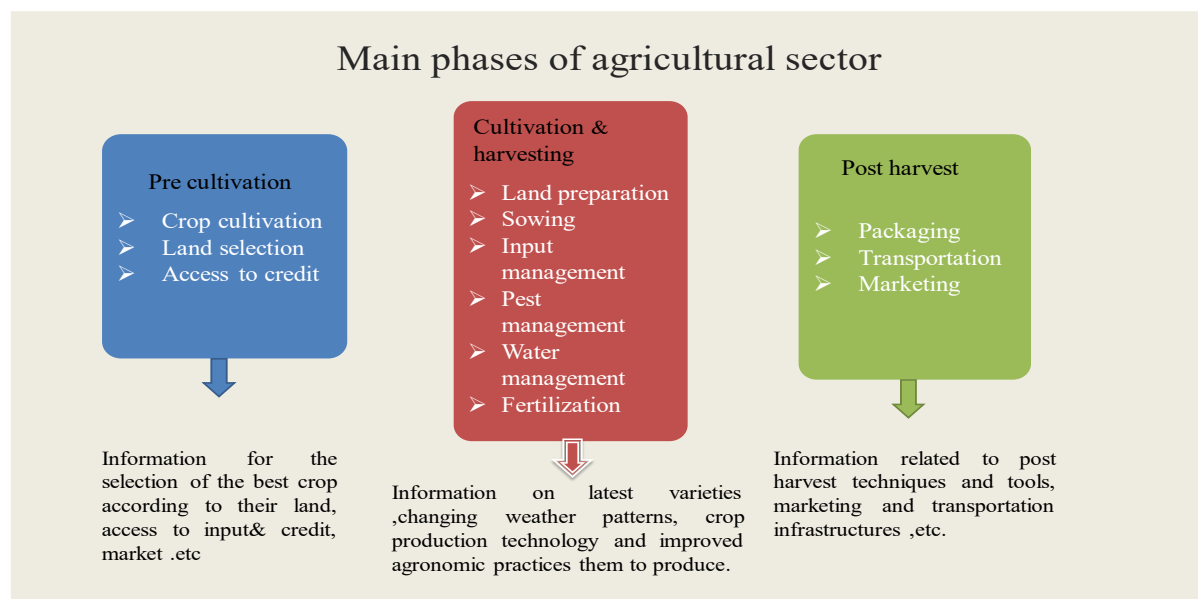


Current Status of ICT In India

The Indian telecom market is one of the fastest growing markets globally, playing a vital role in expanding digital connectivity across the country. With approximately 1170.06 million telephone connections, India holds the position of the second largest telecommunications network in the world, next only to China. It is also the second largest wireless network, with wireless connections dominating the sector. Wireless telephones account for nearly 97.63% of total phone connections, while wireline services contribute only 2.36%, reflecting the rapid growth and preference for mobile communication. India's overall tele-density has reached 84.51%, supported by a significantly high urban tele-density of 134.37%. Although rural tele-density stands at 57.58%, it continues to increase steadily, highlighting the expanding adoption of telecom services and the ongoing efforts to bridge the digital divide.

The penetrations of broadband and internet have also improved with 815.93 mn broadband subscribers and 850.09 million internet subscribers across the country. urban internet subscribers are 500.7 Mn, whereas rural internet subscribers are at 340.38 mn which is also steadily increasing. The share of urban internet subscribers

contributes 58.89% of the total internet subscription and the share of rural internet subscribers contribute 40.9% of the total internet subscription. The share of rural phones in the total telephones has constantly increased, from 377.78 mn in 2013 to 517.79 mn in Jan 2023.



ICT Initiatives for Agriculture in India

Approximately 45% of the world's ICT projects have been implemented in India, and the country also hosts the largest number of information kiosks operating in rural areas. Despite this extensive deployment, the distribution of ICT interventions in agriculture remains uneven. Most projects have been concentrated in socio-economically advanced states in South and North India, where infrastructure, literacy, and digital readiness are comparatively higher. In contrast, many economically weaker states have not benefitted adequately from these ICT initiatives, resulting in regional disparities in access to digital agricultural services and information. This uneven adoption highlights the need for targeted policies and inclusive strategies to ensure that ICT benefits reach marginalized farming communities across the country.

TOP MOBILE APPLICATIONS

Agriplex	Delivering agricultural inputs
Crop insurance	Policy details
Coconut expert (Tamil)	Cultivation practices for coconut.
Agromedix	Information and guidance regarding farming practices.
IFFCO Kisan	Advice from agricultural experts and scientist.
Agri app	Crop & Agro advisory, smart farming& buy Agri inputs.
My agri guru	Information and guidance regarding farming practices.
Tumaini	To detect pest and diseases affecting banana

Market yard	Buy, sell & rent everything related to agriculture
Indian satellite weather	Weather information.
Machinery guide	Lowcost GPS app for android devices
Uzhavan (Tamil)	Information and service related app.
Kisan suvidha	Information regarding agriculture.
Agrowon	Agriculture news.
KVSMT	open discussion platform for farmers and agri experts.
Agri live	Showcase crops & agriculture produces for sale.

ICT Projects In Agriculture

e- velanmai	Agro advisory services.
eNam	online trading platform for agri commodities
warana	Information services
SRISTI	Rooftop solar power plant.
KCC	Customized information through telecom
e-choupal	Linkage b/w farmers & buyers
IMD	Weather information

ICT MOBILE APPLICATIONS UZHAVAN APP

Tamil Nadu is recognized as a pioneer state in India for its effective use of Information Technology (IT) in agriculture, consistently leveraging digital tools to support and uplift the farming community. The State has introduced several ICT-based services to enhance information delivery, streamline extension activities, and improve farm-level decision-making. One notable initiative is the *Uzhavan App*, which has gained increasing acceptance among farmers, particularly in the Delta region-one of the seven agro-climatic zones characterized by uniform weather patterns. With its user-friendly features and region-specific services, the app is enabling more farmers in the Delta areas to access timely advisories, market information, weather updates, and government schemes, thereby contributing to more efficient and informed agricultural practices.

CROPS COVERED UNDER SUBSIDY IN UZHAVAN APP

Tamil Nadu has implemented a wide range of crop-specific development programmes to strengthen agricultural productivity and farmers' income across the State. Under the Farm Nutrition Security (FNS) initiatives, targeted schemes such as FNS-Cotton, FNS-Pulses, FNS-Coarse Cereals, FNS-Sugarcane, FNS-Rice, and FNS-Cereals aim to enhance the production, quality, and sustainability of major field crops. The Palmyra Development Mission (PDM) focuses specifically on promoting Palmyra cultivation through large-scale production and distribution of Palmyra seed nuts. National-level programmes such as the National Bamboo Mission and the National Mission on Edible Oils (covering crops like groundnut and other oilseeds) further support diversification, value addition, and regional crop suitability. In addition, the National Agricultural Development Programme (NADP) plays a vital role in crop-specific interventions through projects such as NADP-Red gram, NADP-Cotton, NADP-Paddy,

and NADP-Castor, aimed at improving productivity, strengthening market linkages, and promoting modern cultivation practices across Tamil Nadu.

LIST OF SERVICES PROVIDED IN UZHAVAN APP

- Subsidy scheme
- Benefit registration
- Crop insurance
- Fertilizer stock
- Agricultural machinery for rental
- Market price
- Weather advisory
- Farmer officer contact program
- Farm guide
- Organic products
- TN green mission tree seedlings
- FPO products
- Reservoir levels
- Agriculture news
- Pest /Disease/Monitoring/Remedial
- ATMA training and demonstration
- Uzhavan e-market
- Agri budget
- Kalnadai maruthuvam
- Kalaighar agriculture development program

MERITS

The Uzhavan App, launched by the Government of Tamil Nadu, serves as a comprehensive digital platform specifically designed to empower the farming community by centralizing vital agricultural and horticultural information. It aims to facilitate easy assessment of marketing information by providing real-time information on crop prices from regulated markets and *Uzhavar Sandhais* (farmers' markets). Furthermore, it simplifies the process to easily assess input dealers and get the required inputs by offering real-time stock position details for seeds and fertilizers from both government and private outlets, ensuring farmers can procure them on time. The app enhances farm management by offering the "My Farm Guide" service, which provides crop information from sowing to harvest for both agricultural and horticultural crops, essentially helping to update the crop information daily and informing farmers about the suitable crops in their areas based on local conditions. For mechanization, the app features an easy hiring of farm equipment option through its integration with Custom Hiring Centres and private vendors, allowing farmers to rent machinery. Finally, the platform's commitment to continuous improvement is highlighted by the inclusion of a dedicated Feedback service, ensuring user suggestions and issues are taken into consideration and rectified. In addition to these features, the Uzhavan App is an essential tool for accessing subsidy and government scheme details, checking crop insurance status, and receiving crucial weather updates and agricultural news. This multi-faceted approach transforms the app into a single, user-friendly solution, fostering knowledge sharing and transparency, which helps to influence other fellow farmers through shared information and collective benefit. All farmers should not have android mobile phones.

UZHAVAN APP- NO OF REGISTERED FARMERS

YEAR	NO OF REGISTERED FARMER/LAKH
2018	1.08
2019	4.98
2020	7.53
2021	9.50
2022	12.2
2023	14.39

TAMILNADU

S.NO	DISTRICT	NO OF REGISTERED FARMER/THOUSANDS
1	Salem	85.8
2	Villupuram	84.6
3	Tiruvanamalai	77.2
4	Thanjavur	73.1
5	Cuddalore	67.8
6	Namakkal	55.6
7	Erode	54.1
8	Coimbatore	49.7
9	Tiruppur	49.3
10	Trichy	49.3
11	Sivagangai	47.8
14	Thiruvavur	42.1
15	pudukkottai	40.1
16	Dindigul	39.9
17	Madurai	38.6
18	Krishnagiri	34.7
19	virudhunagar	32.4
20	Thiruvallur	32.2
21	Thoothukudi	31.8
22	Ariyalur	31.7
23	Ramanathapuram	31.3
27	Theni	23.7
28	Kanyakumari	23.3
29	Perambalur	21.7
30	Karur	21.6
31	Chengalpattu	21.0
32	Ranipet	19.1
33	Thirunelveli	18.7
34	Vellore	17.8
35	Kancheepuram	14.3
36	Thirupathur	13.5
37	Chennai	7.34
38	Nilgiris	4.07

Development of ICT based tool/technology towards an interactive multimedia Agriculture advisory system

The multimedia based interactive advisory system besides images, videos, has a strong voice component which is unique and the voice component can be developed in multiple regional languages.

- Sponsoring agency: ICAR-NAIP.
- Lead center of consortium: IIT-M's rural technology and business incubator, chennai.
- Consortium partners: TNAU, NAF, EPFPCL, DPFASL.
- Budget outlay: Rs.321.54 lakhs.

OBJECTIVES

- 1 • Multimedia interface between mobile phones and a central database.
- 2 • Farm plot historian database system
- 3 • Market information database.
- 4 • Voice based interactive system.
- 5 • Multimedia agri advisory system.
- 6 • Multi party conferencing system between farmers, experts and extension worker.

WHAT IS CLOUD COMPUTING?

Cloud computing refers to the delivery of computing services such as servers, storage, databases, networking, software, analytics, and intelligence over the internet, commonly known as "the cloud." It enables users to access technology resources on demand, offering faster innovation, flexible resource management, and economies of scale. With cloud computing, businesses and individuals can efficiently store and process data, run applications, and gain insights without maintaining physical infrastructure, making it a cost-effective and scalable solution for modern computing needs.

Nano Ganesh

Nano Ganesh is an innovative mobile phone-based remote-control system that allows farmers to remotely control and monitor their water pumps. Acting as an interface between high-voltage electrical starters and low-voltage mobile phones, it enables a farmer to switch the water pump on or off and check water availability near the pump. By entering a preset code into a mobile phone, the farmer can operate the pump from any location, ensuring efficient water management and reducing the need for manual intervention, which is especially useful in areas with limited access to electricity or water resources.

Functions of Nano Ganesh

- A farmer can switch his pump on/off with a mobile or landline phone from anywhere.
- He can receive alert messages about 'Power ON/OFF', 'Pump ON/OFF', theft attempts etc. on his mobile phone.
- He can check availability of the power supply near the pump end.
- In a recent development, water pumps are using Cloud technology for analytics of daily, weekly and monthly reports of pump operations, energy consumption, region wise distribution of energy etc.

CLOUD TECHNOLOGY FOR WATER PUMPS IN THE RURAL SECTOR

Computation and analytics are possible with various telecommunication platforms. This business model can be driven by the government and international institutions on a larger scale for a country or a region. One state in India has declared Nano Ganesh as one of the major m-Governance initiatives as a strategy for addressing rural sector resources efficiently and effectively.

Agricultural mobile applications like Uzhavan face significant challenges in serving the diverse farming community, primarily due to low digital literacy (only skilled farmers use it), lack of awareness, and critical infrastructure issues such as network problems in remote areas and the requirement for clear images for effective diagnosis services. To address these limitations, adopting robust Cloud Computing technology offers a scalable solution, as demonstrated by the success of platforms like AgroStar. AgroStar, a multilingual app using Google Cloud, leverages cloud-based analytics and historical data to deliver localized, season-specific advice from agronomy experts. Critically, this cloud implementation enabled AgroStar to dramatically enhance its services, resulting in technology modules that speed up loan processing, identify crop diseases, and improve supply chain logistics. By delivering high rates of analytics processing and using Firebase to support near real-time updates for millions of devices, cloud computing effectively demonstrates how technical barriers can be overcome to provide faster, more accurate, and widely accessible services, setting a clear path for apps like Uzhavan to enhance their reach and effectiveness.

Applications

In sum, cloud computing can help with real-time computation, data access, and storage to users without having to know or worry about the physical location and configuration of the system that delivers the services.

CONCLUSION

Impact of ICT in the agriculture shows significant positive results in market linkages, supply chain analysis, online trading, better communication opportunities for farmer etc. E-agribusiness depends upon information and telecommunication networks. Online retailing of agri inputs is futuristic and very much relevant. Cloud computing may deliver the agriculture-based knowledge along with management of natural resources and knowledge directly to the consumers not only in a small region like in nonstop marketing or shops but also in wider region. Cloud computing technology, applicable for the improvement of agriculture growth, food, grain, product, economic condition, ensure food safety & circulate information related to agriculture etc.

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Story of a hard-working Rural Tribal Women of Udalguri District, BTR, Assam



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Smt. Kashila Daimary's remarkable journey from a small-scale homemaker to the owner of a highly diversified and commercially viable farm enterprise stands as a compelling model of women entrepreneurship in agriculture due to her perseverance, scientific empowerment, and entrepreneurial vision in transforming rural livelihoods and agri-preneurship development. Beginning with a modest piggery unit, she progressively expanded her farming system over three decades, integrating paddy, livestock, fisheries, and high-value horticultural crops across more than 26 bighas of cultivated land. Through scientific interventions of Krishi Vigyan Kendra (KVK), Udalguri, enabled her to adopt Integrated Farming System, green manure-based soil enhancement, and high-density fruit plantation technologies and contributed to measurable improvements in soil organic carbon, with 10–12% and 20–25% increase in paddy and fruit production respectively. Incorporation of Horticultural fruit like apple ber, dragon fruit, guava, animal components like dairy and duckery and fishery leads her to generate an annual net farm income of nearly ₹14.59 lakhs. Smt. Kashila now a key model in her area and actively sharing knowledge as a master trainer, motivating rural women and youth to pursue agriculture related income generating activities.



Introduction:

Smt. Kashila Daimary a progressive woman farmer belongs to Village Chetia para, Rowta Charilai, Udalguri, BTR, Assam. Born as the eldest child in her family, Kashila grew up with a strong sense of responsibility from an early age. She studied up to High School level and engaged herself in agriculture from her early age at 19 years just after marriage, stand today as an inspiring example of determination, hard work, and vision.

Success Journey of Kashila Daimary:

Smt. Kashila Daimary, at the age of 19, she was married into a farming family, where agriculture was the main source of livelihood. Her husband also a farmer, worked tirelessly to sustain the family and Kashila was equally determined to contribute to their household income. Before marriage, Kashila had taken training in stitching which not only enhanced her skills but also gave her an opportunity to earn money. Through her dedication and savings, she managed to save ₹8,000, which she wisely invested after her marriage. With that amount, she bought one pig, marking the beginning of her entrepreneurial journey. The income she earned from selling that pig became the seed capital for expanding her piggery enterprise.

Over the years, Kashila gradually expanded her piggery unit while actively supporting her husband in farming activities. The couple's hard work and careful financial management enabled them to save and reinvest their earnings. From the proceeds of farming and livestock rearing, they were able to purchase 10 bighas of agricultural land, adding to their 3 bighas of own land and 13 bighas taken on lease for cultivation. With two children to raise, Kashila continued to balance her household responsibilities with her farming and livestock activities. Through perseverance and dedication, she diversified their farming system by integrating paddy cultivation with pumpkin, dhaincha, duckery, goatery, and piggery. Her continuous efforts and adaptive mindset helped the family build a stable and sustainable livelihood over the past 32 years.

In 2019, Kashila and her husband took another bold step by venturing into commercial cultivation of high-value fruit crops such as apple ber, dragon fruit, apple, and guava on a large scale. This diversification not only enhanced their farm income but also marked their transition towards modern and market-oriented farming practices. Today, Smt. Kashila Daimary's journey reflects the power of perseverance, innovation, and women's empowerment in agriculture. From a single pig to a diversified farm enterprise spread across several bighas of

land, her story stands as a testament to how vision and hard work can transform lives and inspire others in the farming community.

Intervention made by KVK:

The Krishi Vigyan Kendra (KVK), Udalguri played a crucial role in accelerating the progress of Smt. Kashila Daimary by equipping her with scientific knowledge and technology-driven interventions across her diversified farming system. Through KVK's guidance, she adopted integrated farming practices, including the incorporation of green manure crops like dhaincha, which enhanced soil organic carbon by 0.3–0.4% and increased paddy yields by 10–12%. KVK further supported her by providing technical expertise on high-density planting of apple ber and dragon fruit, along with precise nutrient and canopy management practices that boosted her fruit production by 20–25% in the initial years. Continuous field diagnostics, soil testing, and timely advisories empowered her to implement cost effective, sustainable, and climate-resilient farming methods. Strengthened by KVK's scientific interventions, Kashila transformed her farm into a highly productive and profitable enterprise, emerging as a role model for rural women farmers.

Training Attended:

Smt. Kashila Daimary participated in a seven-days training programme under the Horticulture Mission for North East and Himalayan States (HMNEH), Assam where she received comprehensive guidance on commercial flower production, honeybee rearing, dragonfruit cultivation, and other promising horticultural ventures. The programme equipped her with scientific knowledge, practical skills, and exposure to modern technologies. The active involvement of KVK Udalguri played a crucial role in her success, as their experts provided continuous technical support, field-level demonstrations, and personalized advice that boosted her confidence and encouraged her to adopt improved practices. This training became a turning point for Mrs. Daimary, empowering her to expand her horticultural activities and move towards sustainable income generation.

Attitude/contribution to the Society:

Smt. Kashila Daimary embodies a positive and progressive attitude that extends beyond her own household and benefits the wider community. Her journey from a small piggery unit to a highly diversified farm enterprise demonstrates her commitment to hard work, innovation, and sustainable agriculture. With her disciplined approach, willingness to learn, and continuous efforts to adopt modern farming practices, she has set an example for many rural women and young farmers. Kashila often shares her experiences and motivates others to pursue income-generating activities, especially in livestock and horticulture.

Production Economics of her Farm:

Her success story inspires the community to embrace perseverance, responsible financial management, and diversification for a better livelihood, making her a role model and a source of empowerment for the society.

Sl No.	Farm Components	2023-24		2024-25	
		Production	Income (Lakhs)	Production	Income (Lakhs)
1.	Apple ber (5.5 bigha)	300 qt	6.00	280 qt	5.60
2	Cow (Breed: Sahiwal) Milk	800lt milk from 8cow for 6 month	2.56	830 lt Milk from 9 cow for 6 month	2.98
	Cowdung	10t from 13 Cow	0.50	11t from 13 cow	0.55
3	Paddy (Local Var.:Bismuthi)	11.35 ton	2.50	10.15 ton	2.23
4	Fishery (1bigha area)	4qt	0.80	4.1qt	0.82
5	Dragon fruit (300 Nos plant)	10qt	2.00	9.32qt	1.86
6	Guava (2 bigha) Var. L- 49	13.30qt	0.27	14.11qt	0.28
7	Malta (5 plant), New plantation	2 qt	0.040	2.50qt	0.05
9	Duckery (Var: Khaki Campbell, 7 nos)	-	-	1200 (egg)	0.12
10	Goatery (2 nos.)	-	-		0.10
	Total Rs.		14.57		14.59

(Sale Price: Apple be Rs. 20/-, Milk Rs. 40/-, Cow dung Rs 5/-, Paddy Rs. 22/-, Fish Rs. 200/-, DragonFruit Rs. 200/-, Guava Rs. 20/-, Malta Rs. 20/-)

Conclusion:

Smt. Kashila Daimary's inspiring rise as a progressive and innovative farmer reflects the true strength of determination, vision, and lifelong dedication to growth. Through her commitment to modern, diversified farming and her willingness to embrace new opportunities, she has not only transformed her own livelihoods but has also become a motivating force for countless others in her community. Her journey stands as a shining example of empowerment, resilience and agricultural excellence.



Plate 1. Discussion with Kashila



Plate 2. Dragon Fruit Plot



Plate 5. Multistoried Cropping



Plate 3. Apple Ber Plot



Plate 4. Guava Plot

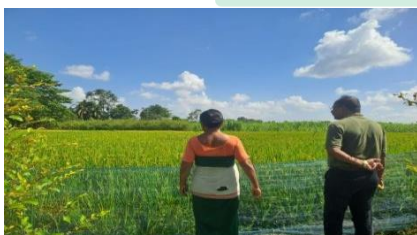


Plate 6: Paddy Field



Plate 7. Guava Plot



Plate 8. Field Visit by KVK, Scientist



Plate 9. Apple plot

Microplastics and Nanoplastics: A Worldwide Environmental Challenge



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Abstract

The extensive production and widespread use of plastics since the mid-twentieth century have led to severe environmental contamination, particularly in aquatic ecosystems. Plastics degrade into smaller particles known as microplastics (1 mm–5 mm) and nanoplastics (1 nm–1 µm), collectively referred to as micro- and nanoplastics (MNPs). These particles are now ubiquitous in marine and freshwater systems across the globe. Their small size, persistence, and ability to adsorb toxic contaminants enhance their bioavailability and bioaccumulation potential within aquatic food webs. Recent studies indicate that MNPs exert adverse effects on aquatic organisms, including phytoplankton, algae, macrophytes, invertebrates, and higher trophic organisms, by inducing oxidative stress, disrupting photosynthesis, altering metabolism, and causing tissue damage. This review synthesizes current knowledge on the sources, distribution, ecological impacts, and risks associated with micro- and nanoplastics, with particular emphasis on aquatic ecosystems. Case studies from marine and freshwater environments are discussed to highlight the extent of contamination and potential ecological risks. The review emphasizes the urgent need for continuous monitoring, improved analytical techniques, and mitigation strategies to reduce plastic pollution and safeguard aquatic biodiversity.

Keywords: Aquatic ecosystems, Bioaccumulation, Ecotoxicology, Marine pollution, Microplastics, Nanoplastics

1. Introduction

Plastics have become an indispensable part of modern society due to their versatility, durability, lightweight nature, and low production cost. Since the 1950s, plastic production has increased exponentially, rising from approximately 1.7 million metric tons in 1950 to over 400 million metric tons in 2022 (Barnes et al., 2009; Statista Research Department, 2022). However, the rapid growth in plastic usage has been accompanied by improper disposal and inefficient waste management, resulting in large quantities of plastic debris entering the environment. Aquatic ecosystems, particularly oceans, are considered the ultimate sinks for plastic waste originating from terrestrial and freshwater sources. It is estimated that 4.8–12.7 million metric tons of plastic waste enter the oceans annually, accounting for nearly 60–80% of marine litter (Barnes et al., 2009). Over time, larger plastic debris undergoes physical, chemical, and biological degradation, fragmenting into microplastics and nanoplastics.

Microplastics (MPs) are defined as plastic particles smaller than 5 mm but larger than 1 µm, whereas nanoplastics (NPs) range from 1 nm to 1 µm in size. Due to their minute dimensions, these particles are easily ingested by a wide range of aquatic organisms and can penetrate biological membranes, posing serious ecological and health concerns. The present article reviews the global distribution, environmental behavior, and toxicological impacts of micro- and nanoplastics, highlighting their implications for aquatic ecosystems.

2. Sources and Global Distribution of Micro- and Nanoplastics

Micro- and nanoplastics originate from both primary and secondary sources. Primary microplastics are intentionally manufactured at small sizes for use in cosmetics, personal care products, industrial abrasives, and medical applications. Secondary microplastics result from the fragmentation of larger plastic items such as bottles,

fishing gear, packaging materials, and agricultural plastics due to ultraviolet radiation, mechanical abrasion, and microbial activity.

Studies have reported the presence of MNPs in diverse aquatic environments, ranging from coastal waters and open oceans to rivers, lakes, and even polar regions. Rodrigues et al. (2018) documented the spatial and temporal distribution of microplastics in the Antua River in Portugal, demonstrating their presence in both water and sediments. These findings highlight the role of freshwater systems as important transport pathways for plastic debris from land to marine environments.

Marine ecosystems are particularly vulnerable, as plastics persist for long periods and accumulate in surface waters, sediments, and biota. The widespread distribution of MNPs underscores their status as a global environmental contaminant rather than a localized pollution issue.

3. Ecotoxicological Effects on Aquatic Organisms

3.1 Factors Influencing Toxicity

The toxicity of micro- and nanoplastics to aquatic organisms is influenced by several factors, including particle size, shape, polymer type, surface charge, concentration, exposure duration, and environmental conditions. According to Kogel et al. (2020), smaller plastic particles, particularly those below 10 μm , tend to exhibit greater toxic effects due to their higher surface area and increased potential for cellular uptake.

Additionally, MNPs can act as vectors for chemical pollutants and microorganisms by adsorbing heavy metals, persistent organic pollutants, and pathogenic microbes onto their surfaces, thereby enhancing their toxicity.

3.2 Effects on Phytoplankton and Microalgae

Aquatic primary producers such as phytoplankton and microalgae form the foundation of aquatic food webs and play a crucial role in global biogeochemical cycles. Gao et al. (2021) conducted a comprehensive quantitative analysis of the impacts of micro- and nanoplastics on aquatic microalgae. Their study revealed that MNPs negatively affected algal growth, although the effective concentration (EC₅₀) was generally high (>25 mg/L). However, positively charged nanoplastics exhibited significantly lower EC₅₀ values (<1 mg/L), indicating enhanced toxicity.

MNP exposure was found to reduce the maximum photochemical efficiency of photosystem II (Fv/Fm) and chlorophyll-a content, suggesting impaired photosynthesis. Furthermore, increased levels of reactive oxygen species (ROS) and oxidative stress biomarkers such as superoxide dismutase (SOD) and malondialdehyde (MDA) were observed, particularly in marine algae compared to freshwater species.

4. Impacts on Aquatic Plants and Higher Trophic Levels

Macrophytes have been shown to trap micro- and nanoplastics through physical entanglement and surface adsorption, potentially acting as sinks for plastic particles within aquatic systems (Gao et al., 2021). While this may reduce the immediate bioavailability of MNPs in the water column, it also increases the risk of trophic transfer to herbivorous organisms.

In higher trophic levels, micro- and nanoplastics have been reported in corals, zooplankton, fish, seabirds, and marine mammals. Their ingestion can lead to reduced feeding efficiency, intestinal damage, inflammation, neurotoxicity, and organ pathology. The bioaccumulation and biomagnification of MNPs along food chains raise concerns about ecosystem health and potential risks to human consumers of seafood.

5. Case Study: Microplastics in St. Mary's Island Marine Environment

Khaleel et al. (2023) investigated the distribution, composition, and ecological risks of microplastics in the marine environment of St. Mary's Island. The study reported an average microplastic abundance of 0.218 particles per liter in water samples. Blue fibers and white foam particles were the dominant forms identified, indicating significant contributions from fishing activities and packaging materials.

Six polymer types—low-density polyethylene (LDPE), polystyrene (PS), polyamide (PA), polypropylene (PP), polyethylene (PE), and high-density polyethylene (HDPE)—were detected. Risk assessment using the Polymer Hazard Index (PHI) and Potential Ecological Risk Index (PERI) suggested a medium environmental risk for the island.

This baseline study highlights the growing concern of microplastic contamination in coastal ecosystems and emphasizes the importance of continuous monitoring to evaluate long-term ecological impacts.

6. Environmental and Human Health Implications

The pervasive presence of micro- and nanoplastics in aquatic ecosystems poses significant environmental challenges. Their ability to persist, bioaccumulate, and interact with other pollutants amplifies their ecological risks. The transfer of MNPs through food webs ultimately raises concerns for human health, as seafood consumption represents a major exposure pathway.

Although current evidence on human health impacts remains limited, the detection of microplastics in drinking water, seafood, and even human tissues suggests the need for precautionary approaches and further interdisciplinary research.

7. Conclusion

Micro- and nanoplastic pollution has emerged as a global environmental issue with far-reaching ecological consequences. Evidence from laboratory experiments and field studies demonstrates that these particles adversely affect aquatic organisms at multiple trophic levels, particularly through oxidative stress, photosynthetic disruption, and tissue damage. Case studies such as those conducted in freshwater systems and coastal marine environments provide valuable baseline data for assessing ecological risks.

Mitigating the impacts of micro- and nanoplastics requires a combination of improved waste management practices, reduction in plastic usage, development of biodegradable alternatives, and implementation of robust monitoring programs. Continued research is essential to better understand the long-term ecological and health effects of micro- and nanoplastics and to inform effective environmental policies.

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Approaches for Direct Carbon Capture from the Atmosphere: Technologies, Performance, and Future Prospects



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Abstract

Anthropogenic carbon dioxide (CO₂) emissions are the primary driver of global climate change. Despite international mitigation efforts, achieving the 1.5 °C temperature stabilization target outlined by the Intergovernmental Panel on Climate Change (IPCC) appears increasingly unlikely through emission reductions alone. This realization has led to the development of negative emission technologies (NETs), among which direct air capture (DAC) has emerged as a promising engineered solution. DAC involves the extraction of CO₂ directly from ambient air using chemical or physical sorbents, followed by its storage or utilization. Although DAC is currently associated with high energy and economic costs, rapid technological advancements indicate significant potential for optimization and large-scale deployment. This review examines major approaches for direct carbon capture from the atmosphere, focusing on sorbent-based technologies, including aqueous scrubbing and solid sorbent systems. Key case studies are discussed to evaluate performance, energy requirements, regeneration strategies, and economic feasibility. The review highlights DAC as a critical technology for achieving net-zero emissions and emphasizes the need for accelerated deployment, innovation, and policy support to enable its integration into global climate mitigation strategies.

Keywords: Direct air capture, Carbon sequestration, Negative emission technologies, Solid sorbents, Climate change mitigation

1. Introduction

Climate change driven by rising atmospheric concentrations of carbon dioxide (CO₂) represents one of the most pressing global challenges of the 21st century. Fossil fuel combustion, industrial processes, and land-use changes have led to unprecedented CO₂ emissions, significantly altering Earth's climate system. According to the Intergovernmental Panel on Climate Change, limiting global warming to 1.5 °C above pre-industrial levels requires rapid and deep reductions in greenhouse gas emissions. However, recent assessments indicate that emission reductions alone may be insufficient to meet this target.

This growing gap between mitigation ambition and achievable emission reductions has prompted interest in negative emission technologies (NETs), which aim to remove CO₂ directly from the atmosphere. Among these, direct air capture (DAC) stands out due to its high removal potential and independence from emission point sources. DAC technologies extract CO₂ from ambient air through chemisorption or physisorption processes, producing concentrated CO₂ streams suitable for geological storage or utilization.

Although DAC is still at an early stage of development and is associated with high energy demands and capital costs, it is increasingly recognized as a cornerstone technology for achieving long-term climate goals. This article reviews current approaches for direct carbon capture from the atmosphere, focusing on material performance, process design, energy efficiency, and economic feasibility.

2. Concept and Importance of Direct Air Capture

Direct air capture involves processing large volumes of atmospheric air to selectively remove CO₂, which is present at a low concentration of approximately 420 ppm. This inherent dilution makes DAC thermodynamically and kinetically challenging compared to point-source carbon capture. Nevertheless, DAC offers several unique advantages, including flexibility in siting, compatibility with renewable energy sources, and the ability to address legacy emissions.

Artificial removal of CO₂ from the atmosphere is expected to play a pivotal role in achieving net-zero and net-negative emission targets. Among available NETs, DAC features the highest theoretical removal capacity and scalability potential. While natural climate solutions such as afforestation are limited by land availability and permanence, DAC represents a controllable and verifiable engineered solution.

Current DAC systems rely on engineered contactors packed with liquid or solid sorbents that repeatedly capture CO₂ from air and release it upon regeneration. Despite high initial costs, DAC technologies are rapidly evolving, with ongoing research focused on improving sorbent performance, reducing energy requirements, and lowering overall costs through scale-up and learning-by-doing.

3. Sorbent-Based Approaches for Direct Air Capture

DAC technologies can broadly be classified into aqueous scrubbing systems and solid sorbent-based systems, depending on the nature of the CO₂ capture medium.

3.1 Physisorbent and Chemisorbent Materials

Kumar et al. (2015) conducted a comprehensive evaluation of sorbent materials for direct air capture and CO₂ sequestration from gas mixtures. Five benchmark materials representing different sorbent classes were investigated: one chemisorbent and four physisorbents. The chemisorbent studied was TEPA-SBA-15, an amine-modified mesoporous silica, while the physisorbents included Zeolite 13X, HKUST-1, Mg-MOF-74 (Mg-dobdc), and SIFSIX-3-Ni.

Temperature-programmed desorption experiments provided insight into CO₂ adsorption capacity, regeneration behavior, and recyclability. The study demonstrated that physisorbents were effective in capturing CO₂ from CO₂-rich gas streams; however, their performance under ambient air conditions was significantly compromised by competition with atmospheric moisture. Water adsorption reduced CO₂ uptake and hindered regeneration efficiency, making physisorbents less suitable for DAC without further material modification.

In contrast, chemisorbents such as amine-functionalized materials exhibited stronger CO₂ binding and greater tolerance to moisture, although at the expense of higher regeneration energy requirements. These findings underscore the importance of balancing adsorption strength, selectivity, stability, and energy efficiency in DAC material design.

4. Aqueous Scrubbing with Amino Acid Salts

An alternative approach to DAC involves aqueous absorption using alkaline or amino acid-based solutions. Custelcean et al. (2019) reported a bench-scale DAC process employing aqueous amino acid salts, specifically potassium glycinate and potassium sarcosinate, as CO₂ absorbents. In this system, atmospheric CO₂ is absorbed into the aqueous solution and subsequently regenerated through reaction with solid meta-benzene-bis(iminoguanidine) (m-BBIG).

The regeneration step leads to the crystallization of hydrated m-BBIG carbonate, effectively separating CO₂ from the liquid phase. CO₂ is then released by mild heating of the carbonate crystals at temperatures between 60 and 120 °C, regenerating the solid m-BBIG quantitatively. The total regeneration energy, including the enthalpy of CO₂ and water release as well as sensible heat, was estimated at 360 kJ mol⁻¹.

Alternatively, the amino acid solutions could be regenerated by boiling under reflux, achieving cyclic capacities of up to 0.64 mol CO₂ per mol of absorbent. This approach demonstrates the feasibility of low-temperature regeneration and highlights the potential of amino acid-based systems as energy-efficient DAC solutions.

5. Comparative Assessment of DAC Technologies

A comprehensive comparative evaluation of DAC technologies was conducted by Sabatino et al. (2021), who assessed two aqueous scrubbing processes and one solid sorbent-based system. Using process simulations and

mathematical optimization, the study quantified productivity, energy consumption, exergy demand, and cost ranges for large-scale deployment.

The results indicated that all evaluated technologies were capable of producing high-purity CO₂ suitable for storage or utilization. Among them, the solid sorbent-based process exhibited superior performance, with an exergy demand ranging from 1.4 to 3.7 MJ kg⁻¹ CO₂ and a productivity of 3.8–10.6 kg CO₂ m⁻³ h⁻¹. These values reflect a favourable balance between energy efficiency and capture capacity.

Economic analysis revealed that capital costs were the primary drivers of overall DAC costs. Under favourable but realistic assumptions regarding energy prices and reactor costs, all technologies had the potential to operate below 200 USD ton⁻¹ CO₂. Notably, the solid sorbent-based system achieved this cost threshold over a broader range of operating conditions and was less sensitive to installation costs when high mass transfer rates were achieved.

6. Scale-Up Challenges and Deployment Potential

Despite promising performance metrics, scaling DAC technologies to climate-relevant levels presents significant challenges. Processing vast volumes of air requires large contactor areas, efficient airflow management, and durable materials capable of withstanding repeated adsorption–desorption cycles. Additionally, ensuring access to low-carbon energy sources is critical to maintaining the net-negative impact of DAC systems.

Nevertheless, DAC has been identified as a central technology for ambitious climate change mitigation, comparable in strategic importance to solar photovoltaics, wind energy, batteries, and electrolyzers. Rapid and sustained market ramp-up is essential to drive cost reductions through technological learning and economies of scale.

Industrial deployment of DAC facilities will not only lower costs but also generate valuable operational data, enabling researchers to refine designs and target performance improvements. As with other clean energy technologies, learning-by-doing is expected to significantly reduce DAC costs over time, making it an increasingly viable component of global decarbonization pathways.

7. Future Outlook and Policy Implications

The successful integration of DAC into climate mitigation strategies will require coordinated efforts across research, industry, and policy domains. Continued material innovation is needed to develop sorbents with higher selectivity, moisture tolerance, and lower regeneration energy. Process optimization and modular system designs will further enhance scalability and flexibility.

From a policy perspective, long-term carbon pricing, incentives for negative emissions, and support for demonstration projects are essential to accelerate DAC deployment. Public–private partnerships and international collaboration can further drive innovation and reduce investment risks.

8. Conclusion

Direct air capture represents a powerful and versatile approach for removing CO₂ directly from the atmosphere and addressing residual and legacy emissions. Sorbent-based DAC technologies, including aqueous scrubbing and solid sorbent systems, have demonstrated technical feasibility and promising performance metrics. Comparative assessments indicate that solid sorbent-based processes currently offer the most favourable balance between energy efficiency, productivity, and cost.

Although significant challenges remain, particularly in scaling and cost reduction, DAC is poised to become a cornerstone technology in achieving net-zero and net-negative emissions. Continued research, deployment, and supportive policy frameworks will be critical to realizing the full potential of direct carbon capture from the atmosphere.

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PRECISION VEGETABLE FARMING USING DIGITAL TOOLS



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Abstract

Precision vegetable farming uses a wide range of technological innovations, from edge-computed artificial intelligence (AI) and autonomous robotic systems to sophisticated remote sensing and Internet of Things (IoT) sensor networks, with the aim of driving a paradigm shift in horticultural management from extensive algorithmic approaches to plant-centric interventions. By using real-time spatiotemporal data for site-specific moisture and fertilizer control, these digital-physical systems reduce the anthropogenic environmental impact of intensive farming while optimizing resource use efficiency (RUE). It highlights current advancements in multispectral diagnostic tools and automated decision-support frameworks while addressing the sociotechnical barriers to farm-level adoption and the data-integration challenges present in different agricultural situations. In conclusion, it is argued that achieving global food security and bioeconomic sustainability requires a shift to digitalized vegetable agriculture. In conclusion, rather than being only a technological development, the shift to digitalized vegetable production is presented as a crucial step in achieving global food security and bioeconomic sustainability using data-driven predictive modeling and precision agriculture approaches.

Introduction

The production of vegetables, which provide vital vitamins, minerals, dietary fiber, and health-promoting phytochemicals, is a key component of the world's food and nutritional security. Additionally, it is essential for maintaining rural livelihoods, especially in developing nations where horticulture provides small and marginal farmers with a high-value source of income. Conventional vegetable production methods, despite their significance, are confronted with growing issues, such as inefficient use of water and nutrients, increased susceptibility to climate variability, an increase in insect pests and diseases, and indiscriminate application of agro inputs. These limitations seriously jeopardize soil health, agro-ecosystem stability, and environmental sustainability in addition to lowering productivity and profitability.

Precision vegetable farming has become a game-changing, technology-driven solution to these problems, allowing for data-driven, site-specific, and time-sensitive crop management. The basic idea behind precision farming was to match input application—such as fertilizer, irrigation, and plant protection chemicals—to real crop requirements in order to overcome within-field variability. This strategy maximizes input efficiency while reducing resource waste by highlighting temporal and regional variation in soil properties, crop development patterns, and microclimatic conditions.

Precision farming is now much more applicable to high-value and input-intensive vegetable crops because of recent developments in digital agriculture. Intelligent decision-support systems with real-time monitoring and adaptive management are now possible thanks to the integration of Internet of Things (IoT) sensors, artificial intelligence (AI), machine learning (ML), remote sensing, unmanned aerial vehicles (UAVs), and autonomous machinery. In order to provide predictive analytics for irrigation scheduling, fertilizer management, disease risk, and yield forecasting, IoT-based sensors continuously produce high-resolution data on soil, plant, and atmospheric parameters.

By allowing targeted interventions like variable-rate irrigation, precision fertigation, and site-specific pest management, the combination of ground-based sensor data with drone and satellite imaging further improves

precision. By enabling a transition from reactive to proactive crop management, these digital technologies work together to create an integrated ecosystem that enhances production, resource efficiency, and environmental sustainability. Thus, precision vegetable farming is a future-focused and scientifically sound approach to the sustainable intensification of vegetable production systems.

Fundamentals of Precision Vegetable Farming

Precision vegetable farming is a sophisticated crop management strategy that uses site-specific and time-specific agricultural input application to maximize crop output, quality, and resource-use efficiency. Precision farming acknowledges the inherent spatial and temporal diversity within vegetable fields resulting from variations in soil characteristics, microclimate, crop growth stages, and biotic stress loads, in contrast to traditional uniform management techniques. Precision vegetable farming maximizes economic returns while minimizing environmental externalities by using digital technologies to ensure that inputs like water, nutrients, and plant protection chemicals are applied in the proper quantity, at the right time, and at the right location.

The five interconnected and mutually reinforcing pillars that make up the precision farming framework work together to provide a closed-loop decision-support system that is specific to the physiological and managerial needs of vegetable crops.

1. Data Acquisition

Since precise and high-resolution data are necessary for making well-informed decisions, data capture is the cornerstone of precision vegetable growing. Critical soil, plant, and atmospheric factors are continuously monitored by a variety of IoT-enabled devices and in-situ sensors. These include electrical conductivity and pH probes, temperature and humidity sensors, leaf wetness sensors, soil moisture sensors, and visual sensors for evaluating crop health.

Vegetable crops are extremely vulnerable to short-term changes in soil moisture, nutrient availability, and microclimatic conditions because of their shallow root systems and quick growth cycles. Continuous data collection makes it possible to identify stress circumstances like nutrient imbalances, water shortages, and habitats that are conducive to illness early on. Drones and satellites are examples of remote sensing platforms that can collect data in addition to ground-based sensors. These platforms offer spatial information on crop vigor, canopy cover, and stress distribution throughout the field.

2. Connectivity

Field-level data may be seamlessly sent from sensors to be centralized systems for data processing and storage thanks to connectivity. Even in geographically scattered agricultural environments, wireless communication technologies including cellular networks, LoRaWAN, ZigBee, and NB-IoT enable real-time or nearly real-time data transfer.

In precision vegetable farming, where prompt decisions—like timing irrigation during crucial development stages or responding quickly to pest outbreaks—can greatly impact production and quality, reliable connectivity is especially important. As data repositories, cloud-based platforms allow for the safe storage, aggregation, and accessibility of massive datasets. These platforms also make it possible to incorporate additional data sources, such historical climate records and weather forecasts, which strengthen management decisions even more.

3. Analysis and Decision Support

The analytical layer uses machine learning (ML), artificial intelligence (AI), and advanced data analytics to turn unprocessed data into useful insights. To find patterns, connections, and anomalies that are difficult to spot through human observation, algorithms examine multi-dimensional datasets.

Decision-support tools can produce accurate irrigation scheduling recommendations based on soil moisture dynamics and evapotranspiration rates, crop growth stage-specific nutrient management plans, and early pest and disease incidence alerts based on microclimatic thresholds in vegetable production systems. Additionally, predictive models allow for the optimization of harvest time and yield forecasts, both of which are essential for market-oriented vegetable production.

AI-driven decision-support systems increase their predicted accuracy and relevance under various field settings by continuously learning and improving through the integration of both historical and real-time data.

4. Actuation

The practical application of analytical insights using automated or semi-automated systems is known as actuation. Precision sprayers, variable-rate fertigation devices, smart irrigation systems, and autonomous or GPS-guided equipment with site-specific input application capabilities are examples of this.

Because inputs are expensive and crops are sensitive to excessive or insufficient application, precision actuation is especially useful in vegetable cultivation. For example, automated drip irrigation systems can precisely feed water and nutrients to the root zone, minimizing losses from evaporation or leaching. Like this, tailored spraying systems allow for the limited delivery of bioagents or insecticides, reducing chemical residues and safeguarding beneficial organisms.

Actuation technology integration guarantees uniformity in field management procedures, improves operational efficiency, and lowers human error.

5. Feedback Loop and System Optimization

One of the key features of precision vegetable farming is the feedback loop, which guarantees ongoing system improvement and flexible management. Sensors and monitoring equipment reevaluate field conditions following actuation in order to determine crop response and the efficacy of implemented interventions.

Decision-support systems can dynamically modify suggestions depending on crop performance and environmental changes in real time thanks to this iterative process. The accumulation of data over subsequent cropping seasons improves system learning, resulting in better model calibration and more accurate suggestions. As a result, the feedback mechanism makes it possible to switch from reactive to proactive and predictive crop management.

Together, these elements form a closed-loop system that facilitates precise decision-making suited to particular crops and field circumstances.

Digital Tools in Precision Vegetable Farming

The strategic integration of various digital technologies is essential to precision vegetable farming because it allows for site-specific crop management, data-driven decision-making, and real-time monitoring. By carefully controlling the geographical and temporal variability present in vegetable cropping systems, their synergistic application enables growers to improve sustainability, productivity, and quality.

Table 1 lists the main digital technologies used in precision vegetable production together with their corresponding purposes.

Table 1: Digital Tools and Their Primary Functions

Digital Tool	Primary Function	Vegetable Farming Application
IoT Sensors	Real-time soil/plant monitoring	Soil moisture, nutrient levels, micro-climate monitoring
Remote Sensing & Drones	Aerial imagery & crop health assessment	Plant vigor mapping, early detection of stress
AI & ML Platforms	Data integration and predictive analytics	Yield forecasting, disease prediction
Autonomous Machinery	Automated field operations	Seeding, weeding, spraying, harvesting
Mobile & Web Interfaces	Farmer interaction & alerts	Real-time alerts, farm dashboards, advisory services, and record keeping

Role of IoT in Precision Vegetable Farming

Precision vegetable farming relies heavily on the Internet of Things (IoT), which makes it possible to monitor soil, plant, and microclimatic factors in real time. IoT-based sensors send high-resolution data to cloud-based systems for analysis and decision assistance while continuously measuring variables like soil moisture, temperature, pH, electrical conductivity, and humidity. By matching input application to real crop requirements, these systems enable timely irrigation and nutrient management, increasing water-use efficiency and decreasing nutrient losses. Vegetable crops especially benefit from IoT-enabled adaptive management because of their short growth cycles and great sensitivity to environmental variations. Rapid corrective actions made possible by real-time feedback result in increased resource efficiency, higher produce quality, and increased yield stability.

Remote Sensing and Drone Technology

Satellite images and drone-mounted multispectral sensors are examples of remote sensing technologies that offer thorough, field-scale evaluations that go beyond the constraints of traditional ground reconnaissance. The Normalized Difference Vegetation Index (NDVI) and other vegetation indices allow for the objective assessment of crop vigor, nutritional status, and early biotic and abiotic stress detection. High-resolution cameras on unmanned aerial vehicles (UAVs) enable regular, spatially accurate crop monitoring, facilitating prompt and well-informed management decisions. Early detection of nutrient



deficits, pest and disease hotspots, and water stress, as well as site-specific input administration via targeted or spot spraying, are important uses. In large-scale vegetable production systems, where manual scouting is time-consuming, labor-intensive, and prone to observational errors, these technologies are very helpful.

AI, Machine Learning & Big Data Analytics

Precision vegetable growing relies heavily on artificial intelligence (AI) and machine learning (ML) to convert massive amounts of agricultural data into useful decision assistance. ML models can anticipate yields, identify disease beginnings before symptoms appear, and predict crop growth dynamics by combining historical information with real-time sensor and remote sensing data. By continuously adjusting recommendations to changing field conditions, the convergence of AI with IoT (AIoT) offers intelligent optimization of irrigation scheduling, nutrient management, and pest control. For example, image-based machine learning algorithms assess drone imagery to detect early disease hotspots, enabling prompt and site-specific interventions, while AI-driven models examine soil moisture trends in conjunction with weather forecasts to anticipate crop water needs.

Challenges to Adoption and Practical Limitations

Despite precision vegetable farming's shown advantages, several institutional, financial, and technical barriers prevent it from being widely used. For small and marginal farmers, the high upfront costs of IoT infrastructure, sensors, analytics platforms, and automation technologies present a major obstacle. Inadequate digital connectivity in rural areas further limits cloud-based decision assistance and real-time data delivery. Inadequate training and low technical literacy can make it difficult for farmers to use digital tools and analyze data. Concerns about security, privacy, and data ownership also have an impact on farmers' trust in digital platforms. Public-private collaborations, improved extension services, capacity-building initiatives, and the creation of reasonably priced, context-specific precision solutions adapted to regional farming systems are all necessary to address these issues.

Conclusion

Precision vegetable farming is turning traditional horticulture methods into intelligent, data-driven systems thanks to digital resources like IoT sensors, drones, AI analytics, and automated machinery. These technologies make it possible to implement precise, site-specific treatments that maximize input utilization, boost yield and quality,

cut down on resource waste, and raise overall farm profitability. Targeted tactics, such as public-private partnerships, capacity-building initiatives, and context-specific technology solutions, can promote wider adoption even in the face of persistent obstacles including high initial prices, a lack of technical skills, and connectivity limitations. Precision vegetable farming is set to become a key component of sustainable horticulture as digital innovations develop further, encouraging robust, effective, and market-responsive vegetable production that benefits growers and consumers alike.



Soil Carbon Management: Pathways to Multifunctional Ecosystem Benefits



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Abstract

Soil carbon management has emerged as a cornerstone of sustainable agriculture, climate change mitigation, and ecosystem resilience in the post Green Revolution era. Intensive tillage, monocropping, and heavy external inputs have enhanced food production but simultaneously degraded soil health, reduced biodiversity, and accelerated losses of soil organic carbon (SOC). This article synthesizes on soil carbon management concepts, key practices, and their multifunctional ecosystem benefits. Practices such as no-till farming, cover cropping, diversified crop rotations, agroforestry, and the application of organic amendments enhance SOC sequestration by increasing organic inputs, improving soil aggregation, and stabilizing carbon in long-lived pools. Enhanced SOC improves soil structure, water-holding capacity, nutrient cycling, and biological activity, thereby increasing crop productivity and resilience to climatic extremes. Soil carbon-rich systems also contribute to climate change mitigation by functioning as effective carbon sinks while supporting adaptation through improved moisture regulation and reduced erosion. Overall, soil carbon management represents a holistic, climate-smart approach that integrates environmental, economic, and social benefits, underscoring its critical role in building resilient and sustainable agroecosystems.

Keywords: Soil Carbon Management, Ecosystem Benefits, Carbon sequestration, No-till farming

1. Introduction

During the Green Revolution, widespread adoption of high soil disturbance practices, modern high-yielding varieties, energy-intensive technologies, heavy capital inputs, and simplified farming systems led to sharp increases in food grain production (Sarkar et al., 2023a). However, in the post-Green Revolution era, despite remarkable gains in productivity even under land scarcity, these practices also generated unintended environmental and resource challenges (Sarkar et al., 2023b). Tillage-intensive agriculture adversely affected key natural resources soil, water, land, biodiversity, and the ecosystem services they provide (Kasam et al., 2009). Although tillage is a fundamental agronomic practice, excessive and poorly managed tillage can degrade soil health, increase runoff, and accelerate erosion (Angon et al., 2023). Intensive tillage has also contributed to declining wildlife populations, depletion of natural resources, biodiversity loss, inefficient fuel use, and rising greenhouse gas emissions. Persistent monoculture further deteriorates soil fertility and undermines long-term sustainability, primarily through soil structural degradation, reduced moisture retention, and declining soil organic carbon (SOC), even under sufficient nutrient application. Against the backdrop of climate change and environmental stress, soil carbon management has gained prominence as a key strategy to bolster ecosystem resilience and sustainability. Enhancing soil carbon sequestration can mitigate greenhouse gas emissions while improving soil health, water retention, biodiversity, productivity, and livelihoods. This explores soil carbon management concepts, mechanisms, and global success cases, demonstrating how scientifically informed and community-driven practices can deliver significant environmental, social, and economic benefits, while guiding broader adoption toward a more resilient and sustainable future.

2. Soil Carbon Management Practices

Amid accelerating climate change and intensifying food security challenges, soil carbon management has emerged as a critical strategy at the intersection of agriculture, environmental sustainability, and climate policy.

This approach has gained global attention due to its dual advantages removing atmospheric carbon dioxide through sequestration while simultaneously improving soil quality and productivity (Sarkar and Sarkar., 2025a). There is growing consensus among farmers, policymakers, and researchers that soils can function as significant carbon sinks when managed effectively. Consequently, soil carbon management is increasingly being integrated into national climate frameworks.

Soil carbon management encompasses a broad array of practices (Fig. 1) aimed at increasing or preserving soil carbon stocks. Key practices include no-till or reduced tillage cultivation, cover cropping, diversified crop rotations, agroforestry systems, and the incorporation of organic amendments.

2.1. No-till farming

No-till farming, also referred to as zero tillage or direct drilling, is a core conservation agriculture practice aimed at minimizing soil disturbance while maintaining continuous soil cover (Sarkar et al., 2025a). In this system, crops are sown directly into undisturbed soil, and crop residues from previous harvests are retained on the soil surface. This approach reduces the physical disruption of soil aggregates, thereby slowing the decomposition of organic matter and promoting the accumulation of soil organic carbon. Over time, no-till systems improve soil structure, enhance aggregate stability, and increase pore continuity, which together support better water infiltration and retention. The surface residue layer acts as a protective mulch, reducing erosion, moderating soil temperature, and suppressing weed emergence. In addition, reduced soil disturbance fosters a more stable and diverse soil biological community, supporting long-term carbon stabilization.

2.2. Cover cropping

Cover cropping involves the intentional cultivation of plant species during fallow periods or alongside main crops to ensure continuous soil cover and sustained biological activity. These crops contribute to soil carbon storage by adding above- and below-ground biomass, particularly through root systems that enhance carbon inputs at deeper soil layers (Sarkar et al., 2025b). Leguminous cover crops enrich the soil through biological nitrogen fixation, while non-leguminous species contribute substantial biomass and improve nutrient scavenging. Mixed cover crop systems often provide complementary benefits by combining functional traits such as deep rooting, rapid biomass production, and enhanced residue quality. Beyond carbon inputs, cover crops protect the soil surface from erosion, improve soil structure, and enhance microbial activity by supplying diverse organic substrates. The effectiveness of cover cropping in building SOC is strongly influenced by climate, soil texture, crop species selection, and management practices, particularly when integrated with reduced tillage systems. When appropriately designed, cover cropping serves as a powerful, context-specific strategy for enhancing soil carbon stocks while improving overall agroecosystem resilience.

2.3. Crop rotation

Crop rotation refers to the planned sequence of different crops grown on the same field over time, with the aim of improving soil health, productivity, and sustainability. Rotational diversity enhances soil carbon accumulation by increasing the quantity and diversity of organic inputs, including crop residues and root exudates. Different crops contribute varying root architectures and residue qualities, which promote microbial diversity and improve the stabilization of organic carbon within soil aggregates (Saleem et al., 2020). Legume-based rotations are particularly effective due to their capacity to enhance nitrogen availability, thereby supporting greater biomass production and carbon inputs. Crop rotation also disrupts pest and disease cycles, improves nutrient use efficiency, and strengthens soil structure. Over the long term, diversified rotations contribute to greater yield stability and improved resilience to climatic stresses such as drought and temperature extremes. When combined with reduced tillage and residue retention, crop rotation becomes a key driver of sustained soil carbon sequestration and climate-smart agricultural production (Bai et al., 2019).

2.4. Agroforestry

Agroforestry systems integrate woody perennials with crops and/or livestock in the same land-use system, creating structurally and functionally diverse agroecosystems (Sarkar et al., 2026). These systems enhance carbon sequestration by storing carbon both above ground in tree biomass and below ground through extensive root systems and increased organic matter inputs. Tree litter, root turnover, and rhizodeposition contribute significantly to SOC accumulation, particularly in deeper soil layers that are less prone to carbon loss.

Agroforestry systems also improve soil physical properties, enhance nutrient cycling, and reduce erosion through continuous canopy and ground cover. The magnitude of carbon sequestration varies depending on tree species, system design, climate, and management practices, with silvopastoral and multistrata systems often showing particularly high potential. In addition to carbon storage, agroforestry enhances biodiversity, improves microclimatic conditions, and increases system resilience to climate variability, making it a multifunctional approach to sustainable land management.

2.5. Addition of organic amendments

The application of organic amendments such as compost, animal manure, biochar, and crop residues is an effective strategy for enhancing SOC and improving overall soil quality (Aytenew and Bore 2020). These materials supply both labile and stable forms of organic matter, supporting microbial activity and contributing to the formation of long-lasting soil carbon pools. Organic amendments improve soil structure, increase water-holding capacity, and enhance nutrient availability, thereby supporting plant growth and productivity. Biochar is characterized by its resistance to decomposition, making it a valuable option for long-term carbon storage in soils. The effectiveness of organic amendments depends on factors such as amendment type, application rate, soil texture, climate, and management practices. While potential trade-offs related to greenhouse gas emissions may occur under certain conditions, carefully managed applications can maximize carbon sequestration benefits while minimizing environmental risks. Overall, organic amendments play a crucial role in integrated soil carbon management strategies.

3. Ecosystem benefits of soil carbon management

Soil carbon management delivers a wide range of ecosystem benefits (Fig.2) by enhancing soil functionality, agricultural productivity, and environmental sustainability. Practices that increase SOC improve soil structure, fertility, and water-holding capacity, leading to more efficient nutrient cycling and greater resilience to climatic extremes such as droughts and floods. Enhanced SOC reduces soil erosion and surface runoff, thereby protecting water quality and reducing sediment and nutrient losses to surrounding ecosystems. Increased carbon stocks also support diverse soil biological communities, strengthening ecosystem stability and reducing reliance on external chemical inputs. Collectively, soil carbon management represents a holistic approach that links climate change mitigation with sustainable agriculture, biodiversity conservation, and long-term ecosystem health.

3.1. Effect on agricultural productivity

Soil carbon management significantly enhances agricultural productivity by improving the physical, chemical, and biological properties of soil (Page et al., 2020). Higher SOC levels strengthen soil aggregation, improve porosity, and enhance water infiltration and retention, creating favourable conditions for root development and nutrient uptake. These improvements reduce crop vulnerability to moisture stress and support more consistent yields under variable climatic conditions. Increased SOC also enhances nutrient cycling and availability, reducing dependence on synthetic fertilizers and lowering production costs. By improving soil resilience and resource-use efficiency, soil carbon-enhancing practices contribute to sustainable yield improvements and long-term food security.

3.2. Effect on soil health

Soil carbon is a central determinant of soil health, influencing microbial activity, nutrient dynamics, and structural stability. Increased SOC supports a diverse and active soil biological community that drives organic matter decomposition, nutrient transformation, and disease suppression. Carbon-rich soils exhibit improved structure, enhanced cation exchange capacity, and greater buffering against pH fluctuations and environmental stresses. These attributes collectively promote long-term soil fertility and stability. By sustaining biological processes and improving physical properties, soil carbon management strengthens soil health and underpins the sustainability of agricultural systems.

3.3. Effect on climate change

Soil carbon management plays a vital role in climate change mitigation by capturing atmospheric carbon dioxide and storing it in stable soil organic matter pools (Lal, 2013). Agricultural soils managed with carbon-enhancing practices function as long-term carbon sinks, reducing net greenhouse gas concentrations in the atmosphere. Increased SOC also improves soil aeration and moisture regulation, which can lower emissions of other

greenhouse gases such as nitrous oxide under appropriate management. In addition to mitigation, carbon-rich soils enhance adaptive capacity by improving water retention and resilience to extreme weather events. Thus, soil carbon management provides both mitigation and adaptation benefits in the context of global climate change.

3.4. Effect on soil biodiversity

Soil carbon management strongly supports soil biodiversity by providing energy sources and habitat for a wide range of soil organisms, including microbes, fauna, and beneficial symbionts (Lal, 2016). Higher SOC levels stimulate microbial biomass and functional diversity, which are essential for nutrient cycling and organic matter stabilization. Improved soil aggregation and porosity create favourable living conditions for soil fauna such as earthworms and arthropods, which further enhance soil structure and biological activity. Enhanced plant-microbe interactions, including mycorrhizal associations, improve nutrient acquisition and plant health. By fostering a diverse and functional soil food web, soil carbon management enhances ecosystem resilience, productivity, and sustainability.

4. Future Aspects of Soil Carbon Management

The future of soil carbon management holds substantial promise for advancing agricultural sustainability while addressing climate change, as emerging technologies, innovative practices, and supportive policy frameworks converge to enhance soil organic carbon sequestration. The integration of precision agriculture with soil carbon management enables site-specific interventions through advanced soil monitoring, remote sensing, and data-driven decision-making, allowing conservation practices and organic inputs to be optimized according to soil type, crop requirements, and climatic conditions, thereby maximizing carbon gains while minimizing environmental trade-offs. Biochar is gaining increasing attention as a long-term carbon stabilization strategy, with continued advancements in its production, characterization, and application methods enhancing both carbon persistence and soil health benefits. Climate-smart land management practices, including agroforestry, intercropping, and cover cropping, further contribute to SOC accumulation while delivering multiple co-benefits such as improved biodiversity, enhanced water regulation, and greater resilience to climate variability. In parallel, developments in microbial-based inputs and novel soil amendments are expanding opportunities to stimulate biological processes that support efficient carbon cycling and long-term sequestration. The widespread adoption of these approaches will depend heavily on enabling policy environments, economic incentives, and market-based mechanisms that recognize and reward ecosystem services provided by carbon-rich soils. When embedded within national and global climate strategies and supported by farmer capacity-building and infrastructure investment, soil carbon management is poised to become a central pillar of sustainable agricultural systems and climate mitigation efforts.

5. Conclusion

Soil carbon management is a key strategy for enhancing ecosystem services, agricultural productivity, and climate resilience. Practices such as conservation tillage, cover cropping, organic amendments, and agroforestry increase soil organic carbon (SOC), improving soil structure, water retention, and nutrient cycling. These changes boost crop yields and strengthen resilience to extreme weather, supporting food security in a changing climate. Higher SOC also promotes diverse microbial communities and soil fauna, enhancing nutrient cycling, disease suppression, and organic matter decomposition, which are essential for sustainable soil health. Additionally, these practices reduce dependence on chemical inputs, lowering production costs and environmental pollution. Financial mechanisms such as carbon markets and payments for ecosystem services provide incentives for adoption, supporting rural livelihoods. Global examples demonstrate that soil carbon management delivers ecological, economic, and social benefits, highlighting the importance of continued research, policy backing, and farmer engagement to integrate these practices into sustainable, climate-smart agricultural systems.

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“Donkey Milk: An Emerging Alternative Dairy with Medicinal Importance”



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Abstract

Donkey milk has gained international attention as a new alternative dairy product because it resembles human milk and unique nutraceutical and medicinal properties. Donkey milk, which has long been utilised in traditional medicine, is now backed by scientific data that emphasises its benefits for baby feeding, the treatment of milk protein allergies, immune modulation, and antibacterial activity. It is a promising functional meal because of its low fat level, favourable fatty acid profile, high lactose concentration, and plenty of bioactive components including lactoferrin and lysozyme. This article reviews the composition, health benefits, medicinal importance, and future prospects of donkey milk in human nutrition. Regular donkey milk consumption improves gut microbiota and lowers intestinal illness, according to numerous studies.

Keywords: Donkey milk, alternative dairy, medicinal properties, functional foods

Introduction

The market for donkey milk is expected to develop at a compound annual growth rate of 8.7% to 9.64% through 2033, with a projected value of \$35.44 million in 2024. As of early 2026, the Food Safety and Standards Authority of India have yet to officially list donkey milk as a formal food item, though production and informal sales are expanding rapidly. Donkey milk has been more popular recently because of its resemblance to human milk and its unique advantages as a supplement. For example, donkey milk has a lot of whey protein. One of the most frequent causes of food allergies in children under one year old is milk. Research on the serum of children with milk hypersensitivity has revealed that the proteins primarily causing the allergy are α - and β -caseins however, in certain instances, β -lactoglobulins and α -lactalbumins may also be allergenic (Businco *et al.*, 2000).

Traditionally obtained from cows, buffaloes, goats, and sheep, milk is an essential part of human diet. Interest in non-conventional dairy sources has increased recently due to growing concerns about lactose intolerance, cow milk allergies, and lifestyle-related diseases. Its molecular resemblance to human milk and established health advantages make it a special food with therapeutic value. Donkey milk contains a variety of compounds that strengthen the human immune system and has potent antioxidant activity, delaying the ageing process. Asthma, bronchitis, diabetes, anabrosis, gastritis, and even climacteric discomfort are all treated with donkey milk in Peru. In Xinjiang, China, a lot of people use donkey milk to heal gastric ulcers and tuberculosis. In the past, donkey milk was frequently used in substitute of human milk due to its minimal allergenicity and similar chemical composition and protein content. It makes sense that donkey milk is still mostly utilised in nations where donkey breeding is still practiced, particularly in Asia, Africa, and several eastern European nations. In several western European nations, the use of donkey milk as a potential human milk substitute has recently emerged. Since Queen Cleopatra's time, donkey milk has also been utilised for cosmetics in Europe. Because donkey milk has a positive reputation, some cosmetic goods created with it, like soaps and/or bath creams, are marketed and well-liked by consumers. Since comparable items created with cow's milk are less expensive, these products obviously continue to be marginal. (Silvia Vincenzetti *et al.*, 2007).

Due to its functional qualities and nutritional worth, donkey milk has grown in popularity as a commercial product. According to studies, donkey milk can be a useful adjuvant for people with a range of food intolerances and milk protein allergies. Donkey milk is a lucky star for babies who don't get enough human milk, especially if they have a protein allergy from cow's milk. It can be used as a supplement to human milk. Therefore, the use of

donkey milk as a raw ingredient for baby food or milk powder will unavoidably grow popular. The premium donkey milk powder has been successfully acquired. Numerous studies have confirmed the high digestibility, antiviral, antibacterial, antioxidant, anticancer, and anti-inflammatory properties of donkey milk in human nutrition. Donkey milk-based diets are a safe and effective treatment for the majority of complex food allergy patients, according to clinical research (Monti G *et al.*, 2007). Donkey milk has been shown to have positive benefits not just on infants but also on osteogenesis, the treatment of individuals with atherosclerosis, cardiovascular disease, or early ageing, and hypocholesterolemic diets.

Individual milk yield on specialized farms, which often maintain animals in semi-extensive settings and are concerned about their well-being, ranged from 1.54 to 1.73 kg/day, according to recent studies on donkey lactation curves. Donkey milk is very different from the milk of the major dairy animals (sheep, cow, buffalo, goat, and camel). One quick energy source is lactose. It makes this milk tasty, sweet, and kid-friendly. However, most people and some ethnic groups are intolerant of milk sugar. Additionally, the high lactose content promotes the intestinal absorption of calcium, which is necessary for the development of an infant's nervous system and bone mineralisation. Donkey milk, however, was found to contain 4.70% lactose.

Physico-chemical Properties: Bovine milk is somewhat acidic (mean pH: 6.7 and mean % lactic acid: 0.16), whereas donkey milk is slightly alkaline (mean pH: 7.2) and low acidity (mean % lactic acid: 0.052), similar to human milk (mean pH: 7.2; mean % lactic acid: 0.06). Donkey milk has less acidity because it contains fewer caseins and phosphates. In addition, donkey milk has smaller fat globules (2 μ) than bovine and human milk (4 μ).

Therapeutic Properties: Donkey milk is referred to as "pharma food," "functional food," "nutraceutical," "elixir of youth," and is regarded as nourishment for both children and the elderly. About 3% of children under three years old have cow milk protein allergies, which can result in anaphylactic reactions as well as negative cutaneous, intestinal, and respiratory symptoms. As a result, donkey milk has long been used to replace human milk for babies who don't have access to mothers' own milk (MOM). Because donkey milk contains high concentrations of lysozyme, lactoferrin, and lactoperoxidase, it is said to have strong antibacterial properties. Milk from donkeys Additionally, it has been shown to inhibit the growth of tumours, lower inflammation, lower the risk of atherosclerosis and cardiovascular disorders, and benefit those with irritable bowel syndrome (Crohn's disease and ulcerative colitis). By hydrolysing the glycosidic linkages of mucopolysaccharides in bacterial cell walls, lysozyme demonstrates its antimicrobial activity.

Donkey milk's nutritional role

Donkey milk is less allergenic than cow milk, according to several research. Because of its excellent bioactive molecules, it was utilised to feed sick children and orphaned infants in European countries in the late 20th century. In terms of lactose, protein, and minerals, donkey milk and human breast milk are extremely similar. Vegetable oil (4 ml/100 ml) added to donkey milk simulates breast milk.

Fermented donkey milk: Lactobacillus bacteria are frequently utilised to produce probiotic beverages from donkey and mare milk. Koumiss is fermented horse milk that has been utilised since ancient times in central Asia. Mangolia's national beverage is koumiss. The milk's high lactose content is what makes it so palatable and optimises intestinal calcium absorption, which is crucial for infants' bone mineralisation (Playford *et al.*, 2000). Due to its high lactose content, especially lysozyme, donkey's milk has been demonstrated to be a favourable growing medium for probiotic lactobacilli strains advantageous for the creation of fermented beverages with therapeutic features (Chiavari *et al.*, 2005). Lastly, as demonstrated by Doreau (1991) & Solaroli (1993), donkey's milk has nutritional and medicinal qualities that have been known since antiquity.

Cosmetics with donkey milk: Nowadays, natural ingredients are the primary emphasis of the cosmetics sector. One important component that is frequently utilised in the cosmetics business is milk, which has a natural origin. Numerous scientific investigations have demonstrated the remarkable and significant skin advantages of cosmetics made with donkey milk.

Lysozyme and lactoferrin, two naturally occurring antibacterial compounds found in donkey milk, prevent the formation of harmful bacteria on the skin and lower the incidence of skin infections. Because of these qualities,

donkey milk that has been chemically prepared can be used to treat skin infections such as psoriasis, eczema, and acne. These days, soap and face lotion are also made from donkey milk.

Table 1: Percentage composition (g/100 g) of donkey milk (evidenced in bold) and comparison with human milk

Milk	Water	Dry Matter	Fat	Proteins	Lactose	Ashes	Energy Value (kJ/kg)
Human	87.57	12.43	3.38	1.64	6.69	0.22	2855.6
Donkey	90.39	9.61	1.21	1.74	6.23	0.43	1939.4

(Salimei E, 2004& Paolo Polidori, 2009)

Here are some of donkey milk's health benefits:

Hypoallergenic Nature: Donkey milk's resemblance to human milk is one of its advantages. For generations, infants have been fed with it. Additionally, compared to cow's milk, donkey milk is less allergic. Donkey milk is frequently safe to consume for those who are allergic to cow's milk or have lactose intolerance.

Antimicrobial Activity: The food-borne diseases that can be present in other types of milk are typically absent from donkey milk. As a result, it has a longer shelf life before going bad. Donkey milk is thought to have antibacterial properties due to its high protein content. According to certain research, it can lessen stomach ailments brought on by bacteria and viruses. (Xiao-Ying Zhang *et al.*, 2008).

Additionally, donkey milk may encourage the formation of beneficial bacteria for your digestive system. Some nations have used it as a traditional remedy to treat illnesses like whooping cough. However, there is currently no scientific evidence to support this.

Immunomodulatory Effects: Proteins found in donkey milk may be beneficial to your health. It can trigger the release of potent immune response cells in the lab, such as cytotoxic T cells, natural killer cells, and macrophages. Your body's inflammatory response scan be lessened by these cells. Nitric oxide release can also be encouraged by donkey milk. This substance can improve circulation and stop the accumulation of plaque in your arteries by widening your blood vessels. Donkey milk may help older persons' immune systems work better overall, according to research.

Function in Infant and Geriatric Nutrition: Donkey milk is regarded as a useful alternative in infant nutrition when nursing is not feasible because of its resemblance to human milk. Additionally, aged people with impaired digestive ability can benefit from it due to its easy digestion.

Other donkey milk uses: There is more to donkey milk than just food. Its use as an ingredient in cosmetics is also well-known. Donkey milk skin moisturizers and soaps are actually considerably more likely to be found than donkey milk drinks. Donkey milk is a great moisturiser because its proteins can draw in and retain water. Donkey milk contains several proteins that have antioxidant properties. They offer anti-aging advantages by shielding cells from oxidative damage, particularly those brought on by sun exposure. Skin creams, face masks, soaps, and shampoos are among the cosmetics that may contain a significant amount of donkey milk.

Limitations and Difficulties: Despite its advantages, there are a number of obstacles to the widespread use of donkey milk:

1. Low milk production per animal
2. Limited supply and increased cost of production
3. Inadequate infrastructure for cultivation and processing
4. Short shelf life because of high lactose and low fat

Commercialisation requires addressing these limitations.

Future prospects: Donkey milk has a lot of potential in the nutraceutical, pharmaceutical, and cosmetics industries as people become more conscious of functional foods and natural remedies. It's economic and health worth can be further increased by research on value-added products, processing technology, and sustainable donkey farming practices.

Conclusion: A new alternative dairy with substantial therapeutic value is donkey milk. It is appropriate for vulnerable groups and health-conscious consumers due to its distinct nutritional makeup, hypoallergenic nature, and bioactive components. The inclusion of donkey milk as a functional meal with therapeutic potential is firmly supported by scientific evidence, despite ongoing production and commercialisation hurdles.

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NATURAL SOLUTIONS IN LIVESTOCK SYSTEMS: THE PROMISE OF ESSENTIAL OILS



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Introduction

Animal production, which includes meat, dairy, wool, and leather, is a major industry contributing over half of the agricultural product value in our country. Optimizing animal health and performance by controlling diseases and maximizing growth and feed efficiency is essential for reaching full production potential. As livestock farming moves away from antibiotics and ionophores, natural feed additives like essential oils are gaining interest as alternatives to improve ruminal fermentation and feed efficiency in ruminants (Al-Suwaiegh et al., 2020). Given the importance of cost-effectiveness, essential oils affect key economic traits in ruminants, such as growth, milk production, and reproduction.

Effects of essential oils to replace conventional antimicrobial agents

Conventional antimicrobials have greatly benefited livestock production by reducing disease and promoting growth, but their widespread use has contributed to antibiotic resistance, prompting efforts to find alternatives. Essential oils, with their antibacterial, antiviral, antifungal, and antibiotic properties, present a promising natural alternative to control microbial infections in animals. Over 3,000 essential oils exist, with many showing commercial relevance and potential to treat diseases like mastitis and bovine respiratory disease (BRD), which cause significant economic losses. Studies show essential oils such as thyme, oregano, cinnamon, and clove effectively inhibit major bacterial pathogens by disrupting cell membranes or interfering with biofilm formation. Moreover, essential oils can enhance the efficacy of conventional antibiotics, reducing resistance and required dosages. Essential oils also show potential to reduce fungal infections and improve immunity in young animals, such as calves. Overall, essential oils could serve as valuable feed additives and therapeutic agents in livestock production, helping to reduce reliance on traditional antibiotics (Tavares et al., 2020).

Effects of essential oils on milk yield

Over the past 40 years, advances in nutrition, genetics, and management have doubled milk production per cow, benefiting both economics and sustainability. To further enhance dairy cattle performance, research has explored essential oils as dietary supplements, but results have been inconsistent. Low doses or specific blends of essential oils such as clove, oregano, juniper, and blends containing capsaicin, carvacrol, cinnamaldehyde, and eugenol can improve milk yield, feed efficiency, milk composition, and reduce bacterial counts without harming rumen microbes (Benchaar et al., 2008). Essential oils may also shift rumen fermentation patterns, potentially reducing methane emissions. Capsicum supplementation shows mixed effects, indicating a need to optimize dosing. Additionally, essential oil blends may increase plasma calcium levels, helping prevent hypocalcemia (milk fever) in dairy cows. Overall, combining essential oils could yield synergistic benefits for dairy production.

Effects of essential oils on rumen function, metabolism and feeding patterns

Rumen function is complex, involving energy metabolism, microbial populations, and methane production. Evaluating it includes measuring dry matter intake (DMI), analyzing ruminal fluid, and monitoring methane emissions. Increased DMI supplies more nutrients to rumen microbes, benefiting milk production, growth, reproduction, and body condition. Capsicum oleoresin at increasing doses boosts DMI and alters feeding patterns in cattle, also increasing volatile fatty acids, which suggests enhanced rumen fermentation. Blends of essential oils including capsaicin, carvacrol, cinnamaldehyde, and eugenol have been linked to improve feed efficiency by lowering the acetate-to-propionate ratio in ruminal fluid and modifying eating behavior positively (Rossi et al., 2022). Other essential oils such as rosemary, clove, cinnamon, and combinations with eugenol and thymol have been shown to increase average daily gain and DMI in feedlot cattle without negatively affecting digestion or behavior.

Commercial blends like Agolin Ruminant (coriander oil, geranyl acetate, eugenol) improve milk production while reducing feed intake and methane emissions, indicating better feed efficiency and environmental benefits. Thyme oil and other blends containing thymol, eugenol, cinnamaldehyde, and carvacrol also significantly reduce methane production by modifying rumen microbial populations.

Effects of essential oils to mitigate heat stress

Heat stress in cattle, caused by high temperatures and humidity, negatively impacts feed intake, milk production, reproduction, and overall health, leading to significant economic losses. Essential oils, particularly capsaicin, have shown promise in mitigating these effects by improving thermoregulation through vasodilation, increasing dry matter and water intake, stabilizing feeding behavior, and enhancing rumen efficiency. Capsaicin and blends containing cinnamaldehyde, eugenol, and other oils can boost milk yield, fertility, and feed efficiency in heat-stressed cows. While some essential oils have inconsistent effects, targeted use of these compounds offers a valuable nutritional strategy to support cattle performance and welfare during heat stress, with potential year-round benefits.

Effects of essential oils to control parasites and reduce economic losses

Parasite control is vital for maintaining livestock health, welfare, and productivity, as internal and external parasites cause significant economic losses, reduced performance, and increased mortality. Resistance to chemical antiparasitics is rising, prompting interest in essential oils as natural alternatives. Essential oils such as oregano, lavender, tea tree, and neem have shown strong acaricidal activity against ectoparasites, while carvacrol and citronella-based oils have demonstrated high efficacy against cattle ticks. Internal parasites, such as gastrointestinal nematodes, also threaten livestock, and essential oils like *Artemisia afra*, *Mentha longifolia*, and *Allium sativum* have shown comparable effectiveness to commercial dewormers in inhibiting parasite development in small ruminants. These findings suggest essential oils could serve as safe, effective, and eco-friendly options for parasite control in livestock.

Limitations to the use of essential oils in ruminant livestock production

Despite their potential to enhance animal health, production, and performance, the use of essential oils in livestock systems faces several limitations. With over 3,000 known essential oils, it is challenging to evaluate the specific biological effects of each one, especially when many studies use blends, making it difficult to identify which component drives observed outcomes. Ruminant animals have complex digestive systems, and any oral or topical application must avoid disrupting their normal physiology or beneficial gut microflora. Moreover, improper use for antimicrobial purposes could risk developing resistance. Essential oils can also be costly, emphasizing the importance of determining effective dosages to justify their economic viability. While oils like capsaicin, garlic, cinnamaldehyde, carvacrol, and eugenol are relatively well-researched, many others lack sufficient scientific study. Without a clear understanding of their mechanisms and impacts, it remains difficult to offer practical, evidence-based recommendations. More targeted research is needed to fully harness the potential of essential oils in ruminant production systems.

Conclusion

Essential oils present a promising natural alternative to traditional additives in ruminant livestock production, offering a range of benefits from improving rumen function and feed efficiency to enhancing milk yield, mitigating heat stress, and controlling internal and external parasites. As concerns about antibiotic resistance and consumer demand for more sustainable practices grow, essential oils can help bridge the gap between animal health and environmental stewardship. However, their application is limited by high variability in results, complex rumen interactions, cost concerns, and a lack of standardization in dosage and formulation. While certain compounds like capsaicin, eugenol, and cinnamaldehyde have been well studied, further research is critical to clarify mechanisms of action, optimize delivery methods, and evaluate long-term safety and efficacy. With continued scientific advancement, essential oils could play a significant role in the development of more sustainable and resilient livestock production systems.

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LIFE TABLES IN INSECT ECOLOGY: CONCEPTS, TYPES, AND MODERN APPLICATIONS



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Abstract

Life tables are essential tools in understanding the population dynamics of insects and play a critical role in ecological research and pest management. This article provides a comprehensive overview of life tables, detailing their two primary types—age-specific (horizontal) and stage-specific (vertical)—and their applications in analyzing survival, mortality, and reproductive rates of insect populations. It outlines the construction of life tables using parameters such as survivorship (l_x), mortality (dx), life expectancy (ex), and k -values, supported by examples from field studies. The article further highlights recent advancements in life table studies, including the age-stage, two-sex life table approach, integration with environmental factors, and use of computational tools, AI, and molecular techniques. These innovations enhance the accuracy and application of life tables in pest risk analysis, integrated pest management (IPM), and biological control. Despite certain limitations like data collection complexity, life tables remain one of the most powerful methods for identifying key factors affecting insect population growth and survival.

1. Introduction

Understanding population dynamics is crucial in ecology, particularly for managing insect pests and conserving beneficial species. One of the most important tools in population ecology is the life table. Life table is the systematic tabulation of birth and deaths of an organism. It is summary statement on the life of a typical individual of population or a cohort of individuals. The life table concept was initially developed by Raymond Pearl (1924) for studies on human demographics, and Morris and Miller (1954) adapted it for insect populations. It has since developed to be an essential component of entomological research, supporting ecologists and pest managers to assess population trends, forecasting outbreaks, and implementing more precise control measures into practice.

The most important tool to understanding how insect pest populations fluctuate during the course of their life cycles is the life table. Life table is an important analytical technique in studying distribution, determination of age and mortality of an organism and individuals can be calculated.

2. Types of Life Table: -

2.1 Age-Specific or Horizontal Life Table: It was first time introduced by Deevy, in 1947. age-specific life tables track a cohort from birth to death. They assume that age is the primary determinant of mortality and reproduction. Parameters such as survivorship (l_x), mortality (dx), life expectancy (ex), and mortality rate ($100q_x$) are calculated for each age interval. Key characteristics include:

- ✓ Cohort is followed continuously through its lifespan.
- ✓ Mortality and reproduction are expressed as functions of age.
- ✓ Useful for organisms with short life cycles and discrete generations.
- x = Age of the insect in days/Cohort
- l_x = Number surviving at the beginning of each interval, out of 100
- dx = Number dying during the age interval, out of 100
- $100q_x$ = Mortality rate at the age interval x and calculated by using formula,

$$100q_x = [dx/l_x] \times 100$$
- L_x = The number of living individuals between the ages X and $X+1$

$$L_x = L_x = l_x + (l_{x+1})/2$$

- T_x = The total number of individuals of age units beyond the age x .

$$T_x = L_x + (L_x + 1) + (L_x + 2) \dots + L_w$$
- e_x = Expectation of life or mean life remaining for x individuals of age x .

$$e_x = T_x / l_x$$

2.2 Stage-Specific or Vertical Life Table: This concept of Life table was proposed by Harcourt, 1969 and Southwood. stage-specific life tables categorize data by developmental stage (egg, larva, pupa, adult) rather than chronological age. Notable features are:

- ✓ Suitable for insects with overlapping generations.
- ✓ Mortality is recorded separately for each stage.
- ✓ Provides insight into which developmental stages contribute most to population decline.
 - x = Stage of the insect.
 - l_x = Number surviving at the beginning of the stage x .
 - dx = Mortality during the stage indicated in the column x or Number of dying within the age interval.
 - L_x = The number of living individuals between the ages X and $X+1$

It is based on the fate of an imaginary cohort found by determining the age structure. Here population remains stationary with considerable overlapping of generations.

According to Hasan and Ansari (2009), age specific survivorship (l_x) of *Earias vitella* (Fabricius) decreased from 1st to 10th day while, survivorship was greatly reduced on the 38th day whereas the highest mortality (dx) was noticed on the 36th day (15 %) and on the basis of stage specific life table, the apparent mortality ($100q_x$) of eggs were calculated (16 %).

The data calculated through various life parameters as given below:

- **Apparent Mortality (100qx):-** It gives the information on number dying as percentage of number entering that stage.

$$\text{Apparent Mortality} = [dx / l_x] \times 100$$

- **Survival Fraction of Particular Stage (S_x):-**

$$S_x = [l_x \text{ of subsequent stage} / l_x \text{ of particular stage}]$$

- **Mortality Survival Ratio of particular Stage (MSR):-** [Mortality in particular stage] / [l_x of subsequent stage].

$$MSR = [\text{Mortality in particular stage} / l_x \text{ of subsequent stage}]$$

- **K-values:** - It is a key factor which is primarily responsible for increase or decrease in number from one generation to another and was computed as difference between successive values for “log l_x ”. However, the total generation mortality was calculated by adding K-values of different development stages or the insect which is indicated as “K”.

$$K = kE + kL1 + kL2 + kL3 + kL4 + kpp + kp$$

Where, kE , $kL1$, $kL2$, $kL3$, $kL4$, kpp , kp are the K values at egg, first instar, second instar, third instar, fourth in stars of larval stage, pre-pupal and pupal stages of one insect.

3. Difference between Age-Specific and Stage-Specific Life Table: -

Age-Specific Life Table	Stage-Specific Life Table
Horizontal Life Table	Vertical Life Table
Constructed for those organisms which have short life span	Constructed for Long Lived organisms
Interval of observation is not regular but decided by the stage present	Certain fixed intervals are pre decided and observations are taken during the fixed intervals
Called Horizontal life table as all the stages are closely observed moving horizontally along the life of an organism	The flow of life cycle is cut vertically and observations are noted in each of the stage
Life history is prerequisite	Age determination is pre requisite
Ex.- Annual Plants/Insects	Ex.- Herd of elephants because following cohort of such individuals from birth to death would take long time

4. Construction of Life Tables for Study of Population: -

Developing a life table requires detailed field or laboratory observations. The general procedure includes:

- a. **Estimating potential natality:** Number of individuals entering the post-ovarial stage is derived from fecundity and the number of reproductive females.
- b. **Determining survivorship (lx) and mortality (dx)**
 - **Eggs:** Survivorship calculated from viable eggs; mortality from infertility percentage.
 - **Larvae:** Early instars sampled directly; later instars adjusted for parasitism and unknown losses.
 - **Pupae and Adults:** Survivorship determined by subtracting parasitoid- and environment-related mortality.
- c. **Trend Index:** This was simply “Ix” for the early instars larvae in the next generation expressed as a ratio of previous generation.

$$\text{Trend index} = N_2/N_1$$

Where, N₂= Population of larvae in next generation N₁= Population of larvae in previous generation.

- d. **Generation Survival:** This was index of population trend without the effect of fecundity and adult mortality.

$$\text{General survival (SG)} = N_3/N_1$$

Where, N₃= Population of adults in a generation N₁= Population of larvae in the same generation.

- e. **K-values:** K-values quantify cumulative mortality across all life stages. Summing the k-values gives total generational mortality (K), indicating the strength of different mortality factors.

$$K = kE + kL_1 + kL_2 + kL_3 + kL_4 + kpp + kp$$

Where, kE, kL₁, kL₂, kL₃, kL₄, kpp, kp are the “K” values at egg, first instar, second in star, third in star, fourth in star, pre-pupal and pupal stage.

5. New Developments in Life Table Studies:

Life table research has recently expanded to give a clearer picture of how insect populations change under real-world conditions. Major advancements include:

- a) **Age-Stage, Two-Sex Life Table Approach:** This method includes both males and females and considers individual variation in development, giving a more accurate view of population growth (Chi *et al.*, 2023).
- b) **Climate-Based Life Table:** These life tables use temperature, humidity, and other weather factors to predict how insects survive and reproduce, helping in better pest forecasting.
- c) **Field-realistic and microclimate-based life tables** are tools used to study how insects grow and survive in natural field conditions.
 - i. **Field-realistic life tables** Uses natural outdoor conditions instead of lab data.
 - ii. **Microclimate-based life tables** Focuses on small-scale environmental factors, like temperature near leaves or soil. Both make population predictions more accurate.
- d) **Non-Target Insect Life Tables:** Used to study how pest control methods affect beneficial insects such as pollinators and predators.
- e) **Use of AI in Insect Life Table Study:** AI quickly analyzes large datasets and predicts insect growth and survival under different conditions, supporting smarter pest management.
- f) **Molecular and Genetic Integration in Insect Life Table Study:** DNA-based tools help understand genetic factors behind insect survival, development, and resistance, improving pest control strategies.
- g) **Use of Computational Tools and Software:** Programs like TWOSEX-MSChart allow fast and precise calculation of life table parameters, even for insects with overlapping generations.
- h) **Incorporation of Host Quality and Food Sources:** Life tables now compare insects fed on different host plants or prey, helping identify resistant crops or effective natural enemies.
- i) **Application to Pest Risk Analysis and IPM:** Life tables help identify the weakest stages of pests, allowing targeted and eco-friendly pest control.

6. Application of Life-Tables: -

Life tables serve numerous ecological and agricultural purposes:

- **Population Ecology:** Assess population stability, growth, and decline.
- **Pest Management:** Identify weak points in pest life cycles for targeted interventions.
- **Biological Control:** Evaluate survival and effectiveness of natural enemies.
- **Evolutionary Biology:** Study life-history traits such as fecundity, longevity, and survival.
- **Risk Forecasting:** Predict pest outbreaks and prepare management strategies.

7. Limitation of Life-Tables: -

- Require continuous and labor-intensive monitoring.
- Accuracy depends heavily on sampling precision.
- Environmental variability can complicate interpretation.
- Field-based life table construction often demands extensive manpower and time.

8. Conclusion:

Life tables are essential tools for understanding how insect populations grow, survive, and decline. By recording survival, mortality, and reproduction at different ages or stages, they help identify the most vulnerable points in an insect's life cycle. Although creating life tables requires careful and time-consuming observations, they provide valuable information for predicting population trends and improving pest management. Modern advancements such as two-sex life tables, climate-based models, AI tools, and molecular techniques have made life table studies more accurate and practical. Despite some limitations, life tables remain highly important for designing effective, environmentally friendly pest management strategies and for maintaining ecological balance.

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FIGHTING CROP PESTS WITH AI: THE FUTURE OF FARMING IS HERE



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Abstract

Artificial Intelligence (AI) is reshaping agriculture by delivering intelligent, data-driven solutions to address key challenges such as pest outbreaks, labor shortages, and the need for sustainable farming practices. This article explores the classification, components, and diverse applications of AI, with a specific focus on its transformative role in pest detection and monitoring. Leveraging technologies like machine learning, deep learning, and computer vision - along with edge and cloud computing - AI enables early pest detection, accurate identification, real-time monitoring, and predictive analysis. Models such as CNN, YOLO, and R-CNN support high-precision interventions, while real-world case studies demonstrate successful implementation across countries. Despite its growing potential, the adoption of AI in agriculture faces challenges including data quality, system integration, cost, and accessibility, especially for smallholder farmers. The study underscores the critical role of AI in enhancing agricultural productivity, sustainability, and decision-making in pest management.

Keywords: Artificial Intelligence, Pest Detection, Deep Learning, Computer Vision, IoT, Smart Agriculture, IPM

1. Introduction:

Agriculture faces a significant challenge due to insect pests, which are responsible for 20–40% of crop yield losses globally (FAO, 2019). Traditional pest detection methods are largely manual, labor-intensive, and prone to human error. This creates a pressing need for more accurate, timely, and scalable pest monitoring systems.

Artificial Intelligence (AI) is emerging as a transformative tool in addressing these issues. Technologies such as Machine Learning (ML), Deep Learning (DL), and Computer Vision are revolutionizing pest detection and monitoring. These AI-driven systems enable automated identification, real-time monitoring, and predictive analysis, enhancing the precision and efficiency of pest management (Kamilaris & Prenafeta-Boldú, 2018).

“Artificial Intelligence (AI) simulates human intelligence in machines for decision-making, learning, and problem-solving (IBM, 2023).” Its integration into pest management holds the potential to achieve early and accurate detection, reduce manual labor and human error, and support data-driven decisions for sustainable and efficient agricultural practices.

2. Classification of artificial intelligence:

Artificial Intelligence (AI) can be classified in three major ways based on its purpose and functioning (Kariyanna and Sowjanya, 2024). By functionality, AI includes Narrow AI, which handles specific tasks like virtual assistants, and General AI, which aims to perform a wide range of activities with human-like intelligence. Based on the learning approach, AI uses supervised learning with labeled data, unsupervised learning to discover patterns in unlabeled data, and reinforcement learning, where systems learn through rewards and trial-and-error. Finally, by application domain, AI covers areas such as Natural Language Processing (NLP) for understanding human language, Computer Vision for analyzing images, and Robotics, which focuses on creating intelligent machines capable of performing autonomous or assisted tasks.

3. Components of Artificial Intelligence:

Artificial Intelligence (AI) is powered by two major areas: Machine Learning (ML) and Deep Learning (DL), which help machines learn and make decisions (Harish and Shetty, 2025).

a) Machine Learning (ML): Machine Learning (ML) allows computer systems to learn from data and improve their performance with experience. It works through three main approaches: **supervised learning**, where

models are trained using labeled examples; **unsupervised learning**, which identifies hidden patterns in unlabeled data; and **reinforcement learning**, where systems learn by interacting with an environment and receiving rewards or penalties based on their actions.

- b) Deep Learning (DL):** Deep Learning (DL) is an advanced branch of machine learning that uses neural networks to process and understand complex data. It involves **Artificial Neural Networks (ANNs)**, which function like simplified brain structures with input, hidden, and output layers to classify and predict information. It also includes **Convolutional Neural Networks (CNNs)**, a specialized form of ANN designed to analyze images, audio, and speech by learning detailed patterns through multiple layers.

4. Uses of Artificial Intelligence (AI):

Artificial Intelligence (AI) is widely used across many sectors and continues to shape modern life. It helps track diseases in public health and improves personalized content in media. In finance and business, AI supports fraud detection, forecasting, and customer service. Healthcare uses AI for early diagnosis, robotic surgeries, and tailored treatments. Online shopping platforms rely on it for recommendations and chatbots, while navigation systems use AI for better routes and traffic updates. Smart homes, transportation, and education all benefit from automation and personalized support, and agriculture uses AI for crop monitoring, pest detection, and yield prediction.

5. History of Artificial Intelligence (AI):

Period	Milestones
1950–1970s	Early foundations were laid with Turing's test and the creation of expert systems like DENDRAL and MYCIN.
1980s	AI-based expert systems began appearing in agriculture for diagnosing crop diseases and managing orchards.
1990s	Rise of precision agriculture with GPS, decision support systems, and early neural networks for yield prediction.
2000s	ML methods such as SVMs and AI-driven remote sensing improved pest detection, soil analysis, and farm automation.
2010–2015	Computer vision and robotics powered weed detection, drones, and autonomous tractors.
2016–2020	DL advanced plant disease diagnosis, smart farm tools, and forecasting apps.
2021–2024	AI reached maturity with digital twins, sustainability-focused systems, blockchain-based traceability, and generative AI for large-scale pest prediction.

6. Role of Artificial Intelligence (AI) in modern agriculture:

- **Precision Farming:** It helps optimize planting, irrigation, and harvesting for better yields.
- **Crop and Soil Monitoring:** Drones and sensors give real-time field information for better management.
- **Pest and Disease Detection:** AI tools identify problems early, reducing crop loss.
- **Automation:** Smart tractors, robots, and machines cut labor needs and increase efficiency.
- **Weather Insights:** It provides accurate climate forecasts to support timely farm decisions.
- **Supply Chain Support:** It improves storage, transport, and distribution through smarter logistics.
- **Decision Support:** Combines data to guide better farm management.

7. Importance of AI in Pest detection and Monitoring:

Artificial Intelligence (AI) greatly improves pest detection and monitoring by making the process quicker and more accurate (Kariyanna and Sowjanya, 2024).

- It helps identify pests early using data from drones and sensors.
- Accurately recognizes species through image-based tools.
- Tracks pest populations in real time.
- AI also guides precise pesticide use.
- It supports better decision-making with integrated data.
- Reduces chemical overuse, promoting safer and more sustainable farming.

8. How AI works in Pest Detection?

AI-based pest detection begins with data collection through drones, sensors, and cameras that capture real-time field images and environmental conditions. Machine learning and deep learning models then analyze these images

to identify pests or early signs of damage. Continuous sensor data helps reveal patterns linked to pest activity, while AI apps can automatically recognize pests using image or sound inputs. By studying crop details, weather trends, and pest life cycles, AI can also forecast future outbreaks. Smart traps and drones pinpoint infestation areas and pest density. All this information is combined to support better pest management decisions, reduce pesticide use, and send quick alerts for timely action.

9. Edge Computing v/s Cloud AI in Smart Agriculture:

a) Edge Computing: Intelligence at the Farm Level

Edge computing processes data directly on devices like sensors and drones, allowing quick decisions without relying on constant internet access. It enables real-time pest detection, reduces delay, saves bandwidth, and keeps data more secure.

b) Cloud AI: Centralized Smart Farming Support

Cloud AI uses powerful remote servers to analyze large amounts of agricultural data and train advanced models. It offers big-scale processing, easy model updates, smooth integration with decision-support tools, and remote monitoring and expert guidance for farmers.

10. Different AI Models Used for Pest Detection and Monitoring (Kariyanna and Sowjanya, 2024).

Sr. No.	AI Model/Technique	Application in Pest Detection	Key features
1	Deep Learning (DL)	Image classification of pests	Automatically extracts features from pest images
2	Convolutional Neural Network (CNN)	Pest species identification from field images	Commonly used for high accuracy in visual classification
3	Support Vector Machine (SVM)	Classification of pest and non-pest areas in images	Often used with handcrafted features
4	Artificial Neural Network (ANN)	Pest prediction based on climatic and crop data	Predictive modeling
5	K-Nearest Neighbors (KNN)	Pest classification based on image similarity	Simpler model, sometimes used for comparison
6	Random Forest (RF)	Decision support for pest infestation prediction	Ensemble learning method
7	YOLO (You Only Look Once)	Real-time pest detection in field environments	Fast and effective object detection
8	Faster R-CNN	Detection and localization of multiple pest types	High accuracy but computationally intensive
9	Transfer Learning	Pest detection with limited datasets using pre-trained models	Efficient with small data
10	Unsupervised Learning (eg. Clustering)	Grouping pest species or anomaly detection	Useful when labeled data is unavailable

11. AI Success Stories from Around the World:

- **China:** A robot equipped with cameras and sensors was developed to detect *Pyrallidae* pests using deep learning (Hu *et al.*, 2018).
- **Japan:** Smart E-traps were created to send daily pest updates, offering faster reporting than traditional traps (Kawakita and Sato, 2023).
- **Morocco:** Faster R-CNN was used to classify arthropod groups with accuracy above 90% (Akarid *et al.*, 2023).
- **Indonesia:** A mobile app using GoogleNet helps farmers identify several insect pests directly from their phones (Yulita *et al.*, 2023).
- **Pakistan:** AI-powered traps using YOLOv8 improved fruit fly detection compared to older models Ahmed *et al.*, 2024).

- **Greece:** A system combining YOLOv10 and ARIMAX predicts aphid levels in greenhouses, using traps and sensors for real-time alerts (Kapeta *et al.*, 2025).

12. Challenges & Limitations of AI in Pest Detection and Monitoring

- **Limited Data:** High-quality field data is often unavailable, especially in remote farming areas.
- **High Variability:** Diverse farm conditions make it difficult to build universally reliable AI models.
- **Low Transparency:** Complex models are hard to interpret, reducing user confidence.
- **Cost Barriers:** Small farmers struggle with the expense of AI tools and limited technical support.
- **Performance Issues:** Slow or inaccurate predictions can hinder timely pest control.
- **Need for Collaboration:** AI development requires cooperation across many scientific fields.
- **Poor Integration:** Many AI tools do not easily fit into existing pest management practices.
- **Data Privacy Risks:** Farmers may avoid AI due to fears about data misuse.
- **Skill Requirements:** Users need proper training and simple interfaces to use AI effectively.
- **Not a Substitute for Research:** AI supports, but cannot replace, core agricultural research.

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INTEGRATED MANAGEMENT OF ROOT-KNOT NEMATODE (*MELOIDOGYNE* SPP.): A SUSTAINABLE APPROACH FOR CROP PROTECTION



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Abstract

Root-knot nematodes (*Meloidogyne* spp.) are among the most economically important plant-parasitic nematodes, causing substantial yield losses in a variety of crops around the world. Their adaptability, polyphagous nature, and complex survival mechanisms make management extremely challenging. Conventional nematicidal approaches have shown limited long-term success and raise environmental concerns. Therefore, **Integrated Nematode Management (INM)**, which integrates cultural, biological, physical, chemical, and genetic methods, provides an ecologically sound and sustainable approach to nematode suppression. The present review summarizes the biology, distribution, host range, and integrated management strategies of root-knot nematodes based on recent global and Indian studies. The integration of cultural practices such as crop rotation and trap cropping, physical control through soil solarization, biological control through beneficial microorganisms, and judicious use of chemical nematicides has proven most effective. Furthermore, the adoption of resistant cultivars and integrated pest management (IPM) modules offers long-term protection. Collectively, INM offers a resilient pathway for mitigating nematode-induced crop losses while safeguarding soil health and biodiversity.

Keywords: Root-knot nematode, *Meloidogyne* spp., Integrated Nematode Management (INM), Biological control, Crop rotation, Soil solarization, IPM.

1. Introduction

Plant-parasitic nematodes (PPNs) represent one of the biggest threats to global agriculture. Among them, the root-knot nematodes (*Meloidogyne* spp.) are mostly destructive due to their wide host range, adaptability and persistent survival structures. The genus *Meloidogyne* was first established by Goeldi (1892) and later revised by Chitwood (1949), who recognised *M. incognita*, *M. javanica*, *M. arenaria*, and *M. hapla* as major species. More than 2,000 plant species, including pulses, vegetables, ornamentals and fruit crops, are infected by these nematodes (Khan *et al.*, 2014).

In India, *Meloidogyne* species were first reported by Barber (1901) in tea plantations. Currently, 14 species are recorded across various agroclimatic regions (Vashisth *et al.*, 2024). The nematodes cause characteristic gall formation on roots, disrupting nutrient and water transport and leading to severe yield losses. With global climate change expanding their distribution, the management of these microscopic pests has become a critical concern.

2. Biology and Survival Mechanisms

The life cycle of root-knot nematodes is complex. It comprises an egg, four juvenile stages (J1–J4), and adult male and female forms (Fig. 1). The infectious stage is known as the second-stage juvenile (J2) that penetrates roots and induces the formation of giant feeding cells. *Meloidogyne* species are remarkable for their ability to withstand harsh environments through a variety of strategies, including cryptobiosis, cold tolerance and protective egg structures, which allow them to stay in soil for years (Onkandia *et al.*, 2014).

3. Detection and Diagnosis

Traditional diagnostic approaches include root gall assessment, microscopic identification of perineal patterns, and host differential tests. Recent advancements employ molecular techniques like PCR-based identification and DNA barcoding for species differentiation, enhancing accuracy and early detection (Onkandia *et al.*, 2014).

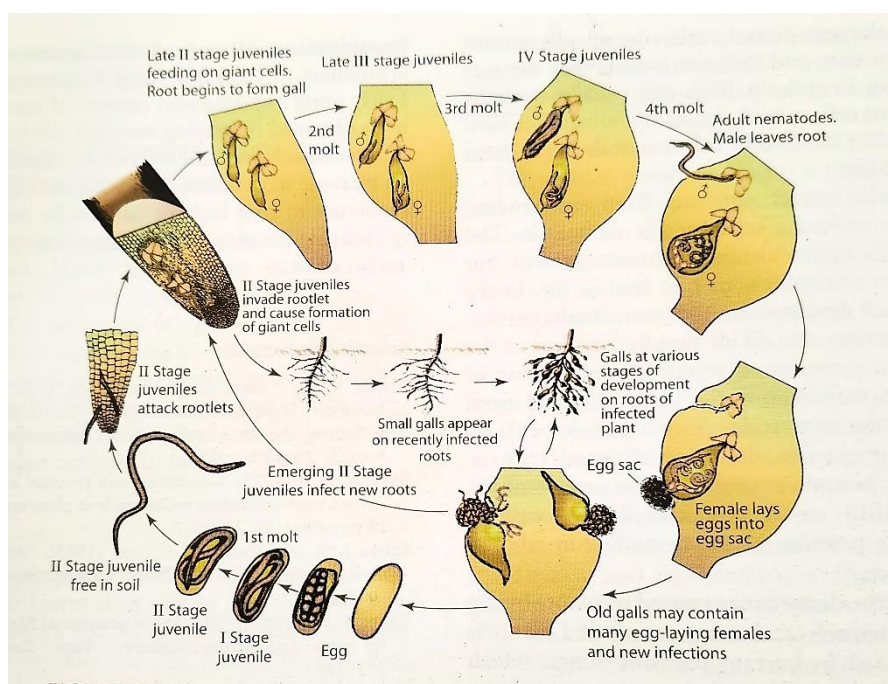


Fig. 1: Life cycle and parasitic behavior of Root-knot Nematode

4. Integrated Nematode Management (INM): Concept and Principles

Integrated Nematode Management (INM) refers to the combined and compatible use of multiple nematode control strategies to reduce pest pressure below the economic threshold in an ecologically sustainable manner (Abhishek and Shiwangi, 2024). The key principles of INM are:

- Multiple Practices:** Integration of cultural, biological, physical and chemical control methods.
- Synergistic Effects:** Integration enhances control efficacy beyond that of single methods.
- Sustainability:** Environmentally safe, economically viable and socially acceptable approaches.

5. Components of Integrated Management

5.1 Cultural Control

Cultural practices form the foundation of INM. Crop rotation with non-host or poor-host crops significantly reduces nematode buildup. Rotation of cowpea (AVCP 1) – onion (GAWO 1) – vegetable cowpea (AVCP 1) effectively minimised the root-knot index in pulses (Patel *et al.*, 2024). Trap crops such as sesame, American cucumber, and sorghum also attract and suppress juvenile nematodes (Samara, 2022). Additionally, biofumigation with mustard or wild radish residues and the use of organic amendments like neem or castor cakes further reduce soil nematode populations.

5.2 Physical Control

The process of "soil solarisation," which involves covering moist soil with sheets like transparent or black polyethene, raises soil temperature and kills nematode eggs and juveniles. Omotosho and Ajayi (2024) demonstrated that black polyethene (100 µm) significantly reduced nematode populations under field conditions.

5.3 Biological Control

Biological agents provide a safe and sustainable alternative to chemical nematicides. Beneficial bacteria such as *Pseudomonas stutzeri*, *Achromobacter alloverae*, and *Bacillus subtilis* (1×10^8 cfu/ ml) suppressed *Meloidogyne javanica* and *Meloidogyne incognita* populations in tomato and eggplant (Dhayal *et al.*, 2023).

Fungal biocontrol agents like *Trichoderma harzianum*, *Pochonia chlamydosporia* and *Verticillium chlamydosporium* demonstrated significant reductions in egg hatching and juvenile survival (Simanjuntak *et al.*, 2025).

5.4 Chemical Control

Modern nematicides such as Fluazaindolizine (1.1 kg a.i./ha) and Fluopyram 34.48 SC (100 ppm) have shown high efficacy with lower environmental toxicity. Fluopyram also inhibits egg hatching and juvenile development (Vetrivelkalai *et al.*, 2025). However, their use should be need-based and integrated with non-chemical methods for sustainability (Groover and Lawrence, 2021).

5.5 Host Resistance

The development and utilisation of resistant cultivars remain one of the most effective management options. Okra genotypes evaluated by Thakur *et al.* (2025) in Punjab showed moderate to high resistance under both summer and rainy seasons. Tomato cultivars possessing the Mi-1 gene confer durable resistance to several *Meloidogyne* species.

6. Integrated Approaches and Field-Level Success

Integrated Pest Management (IPM) modules combining biological and physical tactics have yielded excellent results. In Maharashtra, the combination of soil solarisation, neem cake (500 g/m²), *Trichoderma harzianum* (50 g/m²) and *Glomus intraradices* (50 ml/m²) significantly reduced *Meloidogyne incognita* populations in pomegranate fields (Binage *et al.*, 2025). These integrated systems improve soil fertility and microbial activity while minimising nematode-induced crop losses.

7. Conclusion

Root-knot nematodes continue to challenge agricultural sustainability worldwide. While chemical control offers quick relief, it cannot be relied upon alone. The **Integrated Nematode Management** approach—integrating cultural, biological, physical, and chemical strategies provides a resilient, environmentally safe, and cost-effective solution. Through research-backed integration and farmer-oriented adoption, INM can transform nematode management into a model of sustainable crop protection.

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Clove Bean: Reviving a Forgotten Vegetable of India



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Abstract

India, endowed with diverse agro-climatic regions, supports a wide range of vegetable crops and ranks as the second largest vegetable producer globally. Despite this achievement, challenges of food and nutritional insecurity persist, particularly among vulnerable populations. Expanding vegetable production through horizontal land expansion is no longer feasible; hence, attention must shift toward underutilized and underexploited vegetable crops that can fit into existing cropping systems. Clove bean (*Ipomoea muricata* (L.) Jacq.), a lesser-known member of the family Convolvulaceae, represents one such promising crop. Cultivated mainly for its edible fruits and thickened pedicels, clove bean combines ease of cultivation, nutritional richness, medicinal value, and adaptability across diverse environments. This article presents a comprehensive popular account of clove bean, covering its origin, distribution, botany, nutritional and pharmaceutical properties, cultivation practices, and future potential, highlighting its role in strengthening nutritional security and sustainable agriculture in India.

Keywords: Clove bean; *Ipomoea muricata*; underutilized vegetable; nutritional security; medicinal properties; crop diversification; sustainable agriculture.

Introduction

India is the second-largest producer of vegetables in the world, contributing about 12.1 % of global vegetable production, second only to China, yet malnutrition and hidden hunger remain major concerns. According to the Global Hunger Index, India continues to fall under the “alarming” category, underscoring the urgent need to improve both food availability and diet quality. Vegetables, rich in vitamins, minerals, dietary fibre, and protective phytochemicals, play a critical role in combating micronutrient deficiencies. However, reliance on a narrow range of commonly cultivated vegetables limits dietary diversity.

With limited scope for expanding cultivable land, enhancing vegetable production must rely on diversification and intensification within existing systems. Underutilized vegetables often locally adapted, resilient, and nutritionally dense offer immense untapped potential. Many of these crops have been traditionally used by rural and tribal communities but remain neglected in mainstream agriculture and research. Among them, clove bean (*Ipomoea muricata*) stands out as a versatile, hardy, and nutritious vegetable deserving wider recognition and adoption.

Origin, Distribution, and Nomenclature

Clove bean (*Ipomoea muricata* (L.) Jacq.; $2n = 30$) belongs to the family Convolvulaceae. The species is native to tropical America but has spread widely across warmer regions of South and Southeast Asia, including India, Sri Lanka, Myanmar, China, Nepal, and Japan. In India, it is cultivated as a minor vegetable crop and occasionally as an ornamental plant due to its attractive nocturnal flowers.

The crop derives its English name “clove bean” from the resemblance of its thickened pedicel to cloves of the spice tree *Syzygium aromaticum*. It is known by different vernacular names across India: Michai (Hindi and Bengali), Garayo (Gujarati), Gariya (Marathi), Kattutali and Mukkattikkay (Tamil), and Nithya Vazhuthana (Malayalam). In Tamil Nadu, it is also popularly referred to as “Mookuthi avarai.”

Botanical Description

Clove bean is an annual, slender, climbing vine that can grow several metres high when supported on trellises, fences, or bamboo stakes. The plant is characterized by its vigorous growth habit and minimal susceptibility to insect pests (Fig. 1).

Stem

The stems are herbaceous and rough, owing to the presence of numerous minute, speculate protuberances arising from the epidermis. These features aid in climbing and anchorage.

Leaves

Leaves are simple, smooth, soft, and entire. The leaf base is cordate with rounded lobes, while the apex tapers into a short caudex. The blades are light green with palmately netted venation, measuring 4–9 cm in width and 6–10 cm in length. Petioles may extend up to 10 cm.



Fig. 1. Clove bean plant morphology

Inflorescence and Flower

Inflorescence is axillary, bearing one to few flowers. Each flower is bisexual and borne on a peduncle slightly shorter than the petiole. The corolla is actinomorphic, funnel-shaped, campanulate, and pink to purple in colour (Fig. 2). A unique feature of clove bean is its nocturnal flowering habit, with blossoms opening at night.



Fig. 2. Floral Morphology of Clove bean

Fruit and Seeds

The fruit is a thin-walled capsule that dehisces by valves. It is ovoid, with a diameter of 0.8–1.5 cm and a length of 2–3 cm (Fig. 3). Each fruit weighs about 2–3 g.



Fig. 3. Variations in Clove bean pods

Seeds

Each fruit contains two to four smooth, black seeds (Fig. 4). The thickened pedicel, along with tender fruits, constitutes the edible portion of the crop.



Fig. 4. Clove bean seeds

Nutritional Value: A Small Vegetable with Big Benefits

One of the most compelling reasons to promote clove bean is its impressive nutritional profile (Table 1). Despite being underutilized, it is rich in essential nutrients required for human health.

Table 1: Nutritional composition of clove bean (*Ipomoea muricata*) per 100 g edible portion

Nutrient	Content
Protein	1.0–1.5 g
Phosphorus	120–150 mg
Iron	0.13–0.19 mg
Calcium	200–220 mg
Vitamin C (Ascorbic acid)	30–40 mg
Crude fibre	0.67–3.33 %

The relatively high calcium and vitamin C content make clove bean valuable for bone health and immune function. Dietary fibre aids digestion and helps prevent lifestyle-related disorders. Inclusion of such vegetables in daily diets can contribute significantly to nutritional security, especially in rural and resource-poor communities.

Medicinal and Pharmaceutical Importance

Beyond nutrition, clove bean possesses notable medicinal properties that have been recognized in traditional systems of medicine. Different plant parts viz., seeds, stems, leaves, and milky latex are used for therapeutic purposes.

Traditional uses include treatment of chronic and gangrenous wounds, cuts, blisters caused by burns, and various skin ailments. Seeds have been reported to exhibit both analgesic and antiseptic properties. Phytochemical investigations have identified indolizidine alkaloids such as ipalbicine, ipalbidine, ipalbinium, and ipomine in the seeds. Among these, ipalbidine is particularly associated with analgesic activity.

Antimicrobial and antifungal compounds have also been isolated, supporting the plant's use in managing infections. In China, leaves are used to relieve stomach aches, while seeds are employed in treating trauma. In the Philippines, the plant is traditionally used as a remedy for snake bites. In India, the milky juice is refined and used as a hair tonic by women and also for coagulating rubber sap.

Cultivation Practices

One of the major advantages of clove bean is its simplicity of cultivation and adaptability to diverse environments.

Climate and Soil

Clove bean can be grown from sea level, as seen along the western coasts of Kerala, up to elevations of about 1700 m in the Himalayan region. It thrives well in tropical and subtropical climates and can be cultivated year-round, as it is not season-bound. Well-drained soils with moderate fertility are ideal.

Propagation and Sowing

The crop is propagated through seeds. A seed rate of 6–7 kg per hectare is recommended. Seeds are sown at a spacing of 1.0 m × 0.6 m to allow adequate vine growth and ease of management.

Manures and Fertilizers

Application of farmyard manure (FYM) at 10 t/ha helps improve soil structure and nutrient availability. The recommended fertilizer dose is 35:50:25 kg/ha of N: P₂O₅: K₂O. Balanced nutrition supports vigorous growth and higher yields.

Aftercare and Training

Clove bean requires minimal aftercare. During the rainy season, it can be grown under rainfed conditions with little or no supplemental irrigation. As a climbing vine, it benefits from support systems such as bamboo stakes, trellises, or fences, which facilitate better canopy management and fruit quality.

Pest and Disease Incidence

A notable highlight of clove bean is its relative freedom from major insect pests and diseases, reducing the need for chemical plant protection measures and making it suitable for low-input and organic farming systems.

Harvesting and Yield

Tender fruits along with their thickened pedicels are harvested about 60–70 days after sowing. Harvesting at the right stage ensures better taste and texture. The crop duration ranges from 150 to 170 days.

Yield per plant varies between 2.5 and 4.5 kg, depending on management practices and environmental conditions. Average yield per hectare ranges from 5 to 6 tonnes. With improved varieties and better agronomic practices, productivity could be enhanced further.

Culinary Uses and Popularity

Clove bean is widely appreciated in regional cuisines, particularly in Kerala and parts of Tamil Nadu. The tender fruits and pedicels are used to prepare a variety of dishes such as fries, thoran (upperi), and curries (Fig. 5). The vegetable is valued for its mild flavour, pleasant texture, and ability to absorb spices well.



Fig. 5. Local cuisines prepared using clove bean

Despite its culinary versatility and ease of preparation, clove bean remains confined largely to local markets and home gardens, highlighting the need for greater awareness and promotion.

Scope for Improvement and Future Prospects

In spite of its importance, clove bean remains underexploited, with a lack of high-yielding and superior quality varieties. This necessitates systematic crop improvement programmes. Assessing genetic variability, heritability, genetic advance, and trait associations among available genotypes is essential before undertaking large-scale selection and breeding efforts.

Promotion of clove bean aligns well with current priorities of sustainable agriculture, climate resilience, and nutritional security. Its adaptability, low input requirement, pest tolerance, and multipurpose uses make it an ideal candidate for inclusion in diversified cropping systems, kitchen gardens, and nutrition-sensitive agriculture initiatives.

Conclusion

Clove bean (*Ipomoea muricata* (L.) Jacq.) exemplifies the hidden potential residing in underutilized vegetable crops. With its rich nutritional profile, medicinal value, ease of cultivation, and adaptability across diverse

agro-ecological regions, it offers a promising solution to address challenges of food and nutritional insecurity. Reviving and mainstreaming such forgotten vegetables through research, extension, and awareness can broaden the vegetable basket, enhance farmers' livelihoods, and contribute to sustainable and resilient food systems in India. The time is ripe to rediscover clove bean and recognize its rightful place among the valuable vegetables of the future.

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India's First 'Gene-Edited' Sheep Turns One: A Milestone in Biotechnology



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In December 2023, India celebrated the first anniversary of its groundbreaking achievement in biotechnology - the birth of the country's first **gene-edited sheep**. This scientific milestone is not only a major leap forward for India but also signifies the growing potential of gene-editing technologies, such as **CRISPR-Cas9**, in agricultural and medical biotechnology. This article explores the technology behind gene editing, the significance of this achievement, and the broader implications for livestock improvement, healthcare, and ethical concerns.



Tarmeem's muscle mass is already about 10% greater than that of her normal twin sister, and this difference may become more pronounced as she grows older.

India's first gene-edited sheep has marked its first birthday, and scientists confirm that its health remains completely normal. The landmark achievement was accomplished by researchers at Sher-e-Kashmir University of Agricultural Sciences and Technology (SKUAST) in Jammu and Kashmir.

The sheep, born on December 16, 2024, has been named 'Tarmeem', an Arabic word meaning modification or editing. Tarmeem currently lives in a secure and private enclosure at the university's Srinagar campus, alongside her normal (non-edited) twin sister.

How Tarmeem Was Created Using CRISPR

According to a BBC report, Tarmeem was developed using CRISPR gene-editing technology, a method that allows scientists to precisely cut and alter specific genes in DNA, much like molecular scissors.

Dr Suhail Magray, one of the researchers involved, explained that embryos were extracted from a pregnant sheep, and the myostatin gene, which restricts muscle growth, was deactivated. These embryos were then kept under controlled laboratory conditions for two to three days before being implanted into another female sheep. After a natural gestation period of around 150 days, the lamb was born.

Health Status and Muscle Growth Findings

Professor Riaz Shah, the project's lead investigator and Dean of the Veterinary Faculty, stated that at one year of age, Tarmeem's physical, biochemical, and physiological parameters are entirely normal. He added that Tarmeem's muscle mass is already about 10% greater than that of her normal twin sister, and this difference may become more pronounced as she grows older. However, the sheep remains under continuous monitoring to assess its long-term health and lifespan. The research team has also sought financial support from the government to continue extended testing and observation.

Seven Years of Research and Repeated Setbacks

Developing India's first gene-edited sheep took the eight-member scientific team seven years. Professor Shah revealed that early attempts met with repeated failures. Out of seven IVF procedures, five resulted in live births and two ended in miscarriages, but gene-editing succeeded in only one case: Tarmeem. He said the process has now been standardised, raising hopes that future success rates will be significantly higher.

Addressing Kashmir's Mutton Shortage

Researchers believe this breakthrough could help tackle the severe shortage of mutton in the Kashmir Valley, where annual consumption stands at approximately 60,000 tonnes, while production meets only about half that demand. SKUAST Vice Chancellor Professor Nazir Ahmad Ganai pointed out that land and water resources are

shrinking while the population continues to grow. He said gene-editing could increase sheep body weight by up to 30%, enabling higher meat production from fewer animals.

The Birth of India's First Gene-Edited Sheep

India's first gene-edited sheep was born in December 2022 at the **ICAR-Central Sheep and Wool Research Institute** in Rajasthan. The ewe, named *Himani*, was edited using the cutting-edge CRISPR-Cas9 technology, which allows for precise alterations to the DNA of living organisms. Himani's birth marked a significant achievement for India in the field of genetic engineering and put the country at the forefront of agricultural biotechnology in Asia.

What Is Gene Editing?

Gene editing refers to the process of making precise alterations to an organism's DNA to achieve desired traits. The most popular and widely used technique is **CRISPR-Cas9** (Clustered Regularly Interspaced Short Palindromic Repeats), a natural defense mechanism in bacteria that can be adapted for gene modification in plants, animals, and humans.

In the case of Himani, the gene-editing aimed at **enhancing her wool quality and disease resistance**, which are crucial for improving sheep farming. The editing involved changing specific genes related to wool production, aiming for higher yield and better quality fiber.

How Does CRISPR-Cas9 Work?

CRISPR-Cas9 works like a molecular scissors that can cut DNA at specific locations. Here's how the process works:

1. **Identification of Target Gene:** Scientists first identify the gene responsible for a specific trait, such as wool quality or resistance to disease.
2. **DNA Cutting:** Using the CRISPR-Cas9 system, they introduce a guide RNA that directs the Cas9 protein to a specific part of the DNA, where it makes a precise cut.
3. **DNA Repair:** The cell attempts to repair the DNA cut. Scientists can then introduce a new piece of genetic material that alters the gene in a beneficial way.

In Himani's case, scientists edited genes that improve wool growth, making the sheep more valuable to farmers in terms of fiber production.

Why Is This Important?

1. **Enhanced Agricultural Productivity:** By improving wool production and disease resistance, gene editing can boost the productivity of sheep farming, which is vital for India's rural economy.
2. **Sustainability:** Gene-edited sheep could be less susceptible to diseases, reducing the need for chemical treatments and making farming practices more sustainable.
3. **Medical Potential:** The technology could potentially be used to improve the health and disease resistance of livestock, reducing the use of antibiotics and improving overall animal welfare.
4. **Global Impact:** This technology puts India on the map as a leader in agricultural biotechnology, opening up opportunities for global collaborations in gene editing for livestock improvement.

Key Methodology Steps:

The research, conducted by scientists at Sher-e-Kashmir University of Agricultural Sciences and Technology (SKUAST) in Srinagar, focused on the myostatin gene, which acts as a natural brake on muscle growth. By editing this gene, researchers were able to enhance muscle mass.

1. **Gene Target:** Scientists focused on the **myostatin gene (MSTN)**, which normally limits muscle development.
2. **Tool:** They used the advanced **CRISPR-Cas9 system**, which acts like "molecular scissors" guided by RNA to cut DNA at a specific location.
3. **Editing Process:**
 1. Fertilized eggs from a local Merino sheep were collected.
 2. The CRISPR-Cas9 complex was used to **knock out or disrupt the myostatin gene** in these embryos.
 3. Edited embryos were cultured and then implanted into surrogate mothers.

Outcome: The resulting lamb, Tarmeem, had significantly increased muscle mass (around 10% more at one year, expected to increase further) and normal health, paving the way for potential solutions to India's mutton shortage.

Significance: This approach is distinct from traditional GMOs as it modifies existing genes without adding foreign DNA, potentially easing regulatory hurdles and offering a precise, faster route to improved livestock.

The Ethical Debate: What Are the Concerns?

While gene editing holds immense promise, it also raises ethical questions:

- **Biodiversity Risks:** Modifying the genetics of livestock could lead to unintended consequences, such as reduced genetic diversity, which may make animals more susceptible to new diseases.
- **Animal Welfare:** Some critics argue that gene editing might lead to unintended side effects that could harm the animals involved.
- **Regulatory Issues:** As gene-edited organisms become more widespread, there is a need for clear and robust regulations governing their use to ensure that they do not pose a risk to public health or the environment.

India's Regulatory Landscape for Gene Editing

India currently has a framework for biotechnology, which includes the **Genetic Engineering Appraisal Committee (GEAC)**, which oversees the use of genetically modified organisms (GMOs) in agriculture. However, gene editing, especially CRISPR-Cas9, is still a gray area in many countries, including India. As the technology advances, the Indian government is expected to update regulations to keep pace with scientific developments while addressing safety concerns.

Potential Future Applications

The success of India's first gene-edited sheep is just the beginning. In the future, this technology could be expanded to improve other livestock, such as cows and poultry. Beyond agriculture, gene editing could play a role in human medicine, with researchers looking at CRISPR-Cas9 for potential therapies for genetic disorders.

Other Possible Applications:

- **Crops:** Gene editing could be used to create drought-resistant crops or plants with improved nutritional profiles.
- **Biopharming:** The use of gene-edited animals to produce therapeutic proteins or antibodies for human use.
- **Environmental Conservation:** Gene editing could be used to create more resilient species capable of adapting to climate change.

Conclusion

The birth of India's first gene-edited sheep is a significant milestone in the country's scientific and agricultural journey. As CRISPR and other gene-editing technologies continue to evolve, they hold the potential to revolutionize not just agriculture but also healthcare and environmental conservation. However, it is crucial to proceed with caution, ensuring that ethical and regulatory concerns are addressed in the quest for innovation. India's progress in this area signals a promising future for biotechnology, and as the country continues to lead in genetic research, it could play a key role in shaping the global future of sustainable agriculture.

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HACCP Horizons: Mapping the Future of Food Safety



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INTRODUCTION

In today's interconnected world, food travels faster and farther than ever before. A single shipment of unsafe food can cross borders, reach supermarkets and end up on dinner tables across continents within a day. This means that even a small lapse in safety can have massive consequences from widespread illness to economic losses and damaged trust in brands. That's why systems like **HACCP (Hazard Analysis and Critical Control Points)** are not just important, they're essential. They act as a protective shield, catching risks before they spread and ensuring that what reaches your plate is safe, reliable and trustworthy.

What is HACCP?

HACCP, which stands for **Hazard Analysis and Critical Control Points**, is a preventive system designed to ensure food safety by identifying and controlling potential risks throughout the food production process. Instead of relying only on testing the final product, HACCP focuses on monitoring each stage of food handling from raw materials to processing, storage and distribution to catch problems before they occur. The system begins with a hazard analysis, where possible biological, chemical or physical dangers are identified. Then, critical control points are established, which are specific steps where these hazards can be prevented, eliminated or reduced to safe levels, such as cooking temperatures or packaging checks. By setting clear limits, monitoring procedures and corrective actions, HACCP creates a structured safety net that ensures food remains safe and consistent. Globally recognized as the gold standard in food safety management, HACCP not only protects consumers from illness but also builds trust in the food industry by guaranteeing that every bite is safe and reliable.

The Origins of HACCP

HACCP (Hazard Analysis and Critical Control Points) was first developed in the 1960s by NASA, working with food companies to ensure that astronauts had absolutely safe food during space missions. In space, even the smallest contamination could be life-threatening, so a strict preventive system was needed. This approach focused on identifying hazards before they occurred and controlling them at critical points in the food process.

Over time, HACCP proved so effective that it was adopted by the food industry worldwide. It became the **gold standard of food safety**, recognized by governments, international organizations and businesses across the globe. Today, HACCP is used everywhere from seafood factories to dairy plants, restaurants and supermarkets.

"From space missions to supermarket shelves, HACCP has traveled far protecting astronauts in orbit and families at dinner tables alike."

Principles of HACCP

1. **Conduct a Hazard Analysis:** Identify possible biological, chemical or physical risks in food production. Focus on where problems could occur and how to prevent them.
2. **Determine Critical Control Points (CCPs):** Find the exact steps where hazards can be controlled or eliminated. Examples include cooking, cooling or packaging stages.

3. **Establish Critical Limits:** Set measurable safety limits like temperature, time or pH. These limits define what is safe and what is unsafe.
4. **Establish Monitoring Procedures:** Create methods to check if critical limits are being met. This may include regular testing, observation or recording.
5. **Establish Corrective Actions:** Plan what to do if monitoring shows a limit is not met. Corrective steps ensure food safety is restored immediately.
6. **Establish Verification Procedures:** Confirm that the HACCP system is working effectively. Verification may involve audits, reviews or additional testing.
7. **Establish Record-Keeping and Documentation:** Keep detailed records of hazards, CCPs, limits and actions. Documentation proves compliance and supports continuous improvement.

Why HACCP Matters Today

In today's world, food travels across countries and continents, making safety harder to control. Globalization of the food supply means that one unsafe batch can quickly affect thousands of people worldwide. Climate change adds new risks by altering growing conditions and increasing the spread of harmful bacteria, while new pathogens continue to emerge and challenge food systems.

HACCP provides a structured safety net that helps producers identify hazards early, set control points and prevent problems before they reach consumers. This builds trust between businesses and the public, showing that food is handled with care and responsibility. Real-world examples prove its value: outbreaks have been prevented in industries like seafood and dairy and entire sectors have transformed their practices to meet HACCP standards.

HACCP is not just a regulation — it is the foundation of modern food safety, protecting both global trade and everyday meals.

HACCP Horizons: The Future

- **Digital Monitoring & AI in Food Safety**
Modern technology allows real-time monitoring of food processes. AI can quickly detect patterns, predict risks and alert producers before problems occur, making HACCP faster and more reliable.
- **Blockchain for Transparent Supply Chains**
Blockchain creates a digital record of every step in the food journey from farm to fork. This transparency builds consumer trust and ensures that safety checks are visible and verifiable across the global supply chain.
- **Sustainability and Eco-Friendly Practices**
Future HACCP systems will not only focus on safety but also on sustainability. Eco-friendly packaging, reduced waste and greener production methods will align food safety with environmental responsibility.
- **A Living System That Adapts to New Risks**
HACCP is designed to evolve. As new pathogens, technologies and global challenges emerge, HACCP adapts by integrating innovations and updating its controls, ensuring food safety remains strong in the future.

CONCLUSION

In a world where food journeys stretch across oceans and borders, HACCP stands as a guiding light, ensuring safety at every step. It is not simply a rulebook or a regulation it is a promise of protection, a silent guardian that connects farms, factories and families. As technology reshapes the way we produce and consume food, HACCP evolves alongside it, weaving together innovation, sustainability and trust. The true power of HACCP lies in its adaptability: it grows with new challenges, embraces modern tools and continues to safeguard the meals we share. More than a system, it is a commitment to health and confidence, reminding us that safe food is the foundation of a thriving future.

“HACCP is not just about keeping food safe today — it is about shaping a tomorrow where every bite carries the assurance of care, trust and responsibility.”

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Role of the Microbiome in Milk Yield, Nutrition, and Dairy Sustainability



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1. Introduction

Dairy production is commonly assessed using visible indicators such as milk yield, compositional quality, animal health, and economic performance; however, these outcomes are underpinned by a complex and largely unseen biological framework dominated by microorganisms. Microbial communities inhabiting the rumen, feed substrates, feces, milk, and dairy products play central roles in digestion, nutrient transformation, productive efficiency, and environmental impact. Recent advances in microbiome research, metagenomics, and nutritional physiology have established that these microbes are not passive occupants of the dairy system but active regulators of host metabolism and performance. Increasing evidence demonstrates that variation in milk yield among cows, differences in enteric methane emissions, efficiency of fiber degradation, and even the sensory and physicochemical properties of dairy products, such as cheese flavor and color, can often be traced to microbial composition and functional activity. This article emphasizes the collective influence of rumen and dairy-associated microbiota on productivity, sustainability, and product quality by synthesizing results from various scientific studies. It underscores the increasing significance of microbial knowledge in enhancing precision-driven, resource-efficient, and environmentally sustainable dairy production systems.

2. Impact of minerals on fiber digestibility and rumen microbial dynamics

Fiber digestion is a key part of ruminant nutrition because it directly affects how well ruminal fermentation works and how much energy is available for making milk. Neutral detergent fiber (NDF) and acid detergent fiber (ADF) are routinely used to assess forage quality and digestibility; however, accumulating evidence demonstrates that these estimates can be substantially biased by the presence of insoluble ash, particularly silica. Silica enters the rumen through multiple pathways, including soil-contaminated forages, sand bedding in free-stall housing systems, and inadvertent soil ingestion during grazing. Unlike biogenic silica associated with plant tissues, non-biogenic silica remains insoluble during detergent fiber analysis, leading to artificially inflated NDF and ADF concentrations in digesta and fecal samples and, in some cases, generating implausibly low or even negative estimates of fiber digestibility. Because microbial degradation of structural carbohydrates underpins volatile fatty acid production, energy supply to the cow, and milk synthesis, inaccuracies in fiber digestibility assessment can misguide ration formulation and distort evaluations of ruminal microbial efficiency. Correcting fiber fractions to ash-free NDF and ADF therefore enhances the accuracy of rumen digestibility estimates and reduces unexplained inter-animal variability, strengthening the reliability of nutritional evaluation and feeding strategies.

3. Rumen Microbial Determinants of High Milk Yield in Dairy Cattle

Dairy cows do not respond uniformly to identical diets, and growing evidence indicates that differences in milk yield are closely associated with distinct rumen and fecal microbial configurations. High-producing cows consistently harbor microbial communities that are compositionally and functionally different from those of low-producing animals, often characterized by lower bacterial richness and evenness but a more specialized ecosystem optimized for metabolic efficiency rather than microbial diversity per se. These high-yielding animals typically exhibit an increased relative abundance of Proteobacteria, a concomitant reduction in Bacteroidetes and methanogenic archaea, and an enrichment of genera such as *Butyrivibrio* and *Lachnospira*, which are closely linked to fiber degradation and butyrate production. Such taxonomic shifts are accompanied by pronounced alterations in ruminal metabolic pathways, including enhanced unsaturated fatty acid biosynthesis, steroid metabolism, and more efficient energy partitioning toward milk synthesis. Together, these observations support

the concept that milk production is partially driven by the rumen microbiome and demonstrate the importance of microbial profiles as functional biomarkers for dairy productivity and feed efficiency.

4. Methionine supplementation and its effects on rumen microbial stability

Methionine is widely regarded as the first-limiting amino acid in high-producing dairy cows, particularly during the periparturient period when voluntary feed intake declines while metabolic demands for milk synthesis increase. Rumen-protected methionine (RPM) has therefore been developed to minimize ruminal degradation and ensure adequate post-ruminal methionine supply to the host. More than 90% of RPM successfully avoids the rumen, but a small amount does reach the rumen microbiota, which has led to interest in its possible effects on microbes. Current evidence indicates that this limited exposure does not disrupt rumen microbial community structure and may even exert beneficial effects on specific functional groups during the prepartum period. In particular, increases in key cellulolytic bacteria such as *Fibrobacter succinogenes* have been observed, with no adverse impacts on major fermentative populations. These findings are especially relevant for transition cow nutrition, as they demonstrate that precise amino acid supplementation can be achieved without compromising ruminal microbial stability. More broadly, they emphasize the value of adopting a host–microbiome perspective in dairy nutrition, in which dietary strategies are designed to support both microbial functionality and animal performance rather than viewing rumen microbes as barriers to nutrient utilization.

5. Inter-individual variation in the bovine microbiome

Even when cattle share the same diet, environment, age, and breed, we frequently observe significant inter-individual differences in fecal microbial composition. High-resolution studies employing full-length 16S rRNA gene sequencing have consistently identified a conserved core microbiota common across individuals, alongside substantial variability in the relative abundance of specific taxa. This variability cannot be adequately explained by external factors such as diet, sex, or housing conditions, pointing instead to a dominant role for host-associated determinants, including genetic background, early-life microbial colonization patterns, and long-term host–microbe interactions. Such individual-level differences in microbial structure have important functional consequences, as they help explain variation in feed efficiency, heterogeneity in enteric methane emissions, and inconsistent responses to dietary interventions. These observations highlight the biological importance of microbiome-driven individuality in cattle and endorse the developing notion of microbiome-informed animal selection and precision livestock management strategies.

6. Microbial drivers of enteric methane emissions and mitigation potential

Enteric methane emissions constitute a major environmental challenge in dairy and beef production systems, and metagenomic evidence has additionally established that cattle with high methane outputs possess rumen microbiomes that are both compositionally and functionally distinct from those of low-emitting animals. High methane producers typically exhibit an increased abundance of methanogenic archaea, particularly members of the genus *Methanobrevibacter*, alongside a reduced representation of hydrogen-utilizing bacterial groups such as Succinivibrionaceae that compete for reducing equivalents and redirect hydrogen away from methanogenesis. Consistent with these taxonomic patterns, functional gene profiling reveals a two- to threefold enrichment of methanogenesis-associated genes in high-emitting cattle, highlighting the strong link between microbial functional capacity and methane production. Importantly, the close correspondence between methane output and microbial gene abundance presents new opportunities for mitigation, including microbiome-based animal screening, the integration of low-methane phenotypes into breeding programs, and the development of targeted nutritional strategies that modulate ruminal hydrogen flow. Together, these findings indicate that effective methane mitigation extends beyond conventional dietary interventions and increasingly represents a challenge of microbial ecosystem engineering within the rumen.

7. *Arthrobacter* and its role in the microbial ecology of milk

Microbial influences within dairy systems extend beyond the rumen, as milk itself represents a dynamic and functionally diverse microbial ecosystem. Among the microbial taxa frequently encountered in dairy environments, members of the genus *Arthrobacter* illustrate the dual roles that non-starter bacteria can play in dairy production. *Arthrobacter* species are common inhabitants of raw milk and are often used as indicators of hygienic conditions, reflecting their remarkable adaptability to cold storage and nutrient-limited environments.

While certain species are associated with spoilage, others perform valuable technological functions, including participation in cheese rind development, the formation of color and flavor in smear-ripened cheeses, and the production of industrially relevant enzymes such as β -galactosidase. This functional duality highlights an important conceptual shift in dairy microbiology, moving beyond the traditional view of non-starter microorganisms as purely undesirable contaminants toward a more nuanced perspective that recognizes their potential as functional contributors under controlled conditions. Harnessing such microbial capabilities through targeted management strategies offers promising opportunities to enhance both the quality and value of dairy products.

Table 01: Microbial Roles Across the Dairy Production Chain

Microbial System	Key Microbes	Primary Role	Practical Implication
Rumen fiber digestion	<i>Fibrobacter</i> , <i>Butyrivibrio</i>	Cellulose and hemicellulose breakdown	Improved feed efficiency
High milk yield phenotype	Proteobacteria, Lachnospiraceae	Energy and VFA optimization	Higher milk production
Methane production	Methanobrevibacter	Hydrogen utilization	Environmental footprint
Fecal microbiota	Firmicutes, Bacteroidetes	Gut health, pathogen shedding	Food safety
Milk microbiota	<i>Arthrobacter</i> spp.	Spoilage or flavor development	Quality control and cheese making

8. Conclusion

The collective evidence synthesized in this review highlights a central conclusion that microbial communities are integral to dairy productivity, efficiency, and long-term sustainability. By regulating key processes such as fiber digestion, milk synthesis, enteric methane emissions, and the sensory and technological attributes of dairy products, microbes function as biological regulators throughout the dairy production continuum. As a result, future dairy systems are expected to increasingly rely on microbiome-informed nutritional strategies, precision feeding approaches, microbial signatures as tools for animal selection, and targeted modulation of rumen microbial ecosystems. Through the integration of microbiology with nutrition, genetics, and management practices, dairy science is entering a transformative phase in which microorganisms, once considered incidental, are being recognized and harnessed as essential assets for sustainable and efficient dairy production.

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Soil Sponge: The Power of Green Manure



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Introduction

Across the world, farmers are confronting a prevalent issue that soils no longer hold water the way they once did. From intensively farmed regions of Europe and North America to rainfed and irrigated systems of India, declining soil structure has reduced the soil's ability to absorb, store, and release water efficiently. This issue is becoming more apparent in India due to unpredictable monsoons, periods of heavy rainfall followed by dry spells, and growing irrigation expenses. A deeper problem, the loss of soil's sponge-like function, is indicated by fields that crack during dry spells and lose water following heavy rains. Restoring this function is essential to climate-resilient agriculture, and green manuring provides a tried and tested, locally and globally adaptable approach. The sponge-like behaviour of soil under green manure and cover crops is depicted in Figure 1.

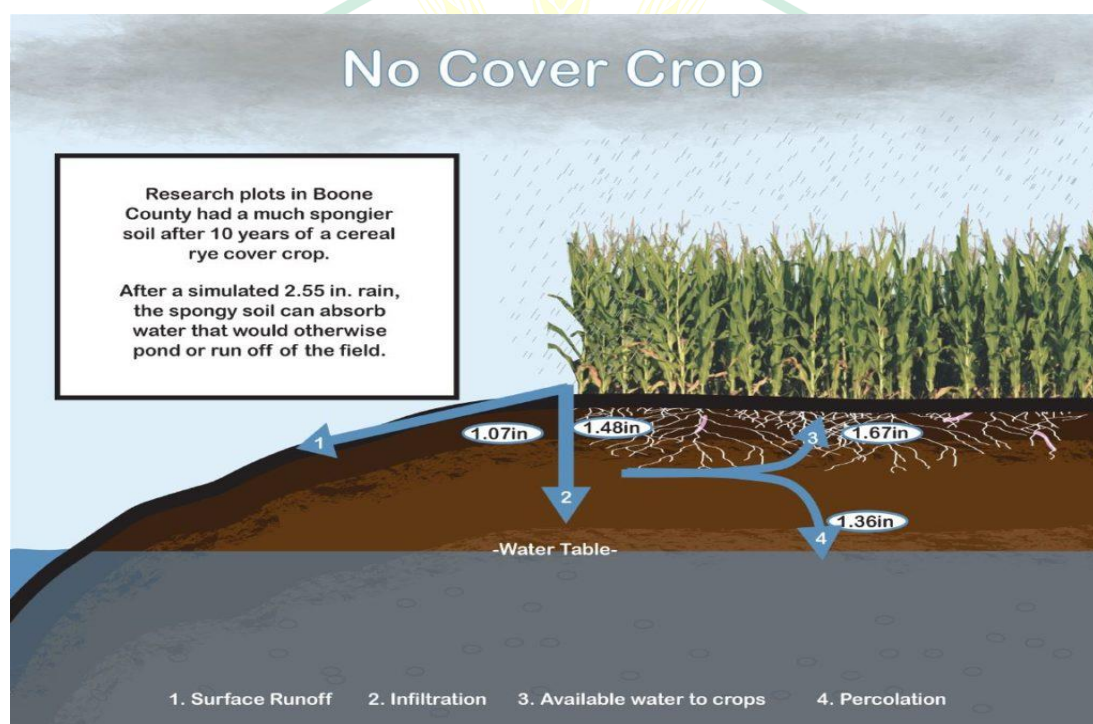


Figure 1. Influence of cover crops on soil water movement and sponge behaviour (Source: USDA-NRCS and Iowa State University Extension)

What Does It Mean for Soil to Act Like a Sponge?

Rainfall is quickly absorbed by a soil sponge, which then stores the moisture in its pore spaces before releasing it gradually to plant roots. This behaviour relies on the amount of organic matter, biological activity, and soil aggregation. Long-term research conducted worldwide has demonstrated that organic matter-rich soils have a much higher capacity to retain water than degraded soils. This sponge effect controls whether crops survive dry spells between irrigations or rainfall events in Indian agro-ecosystems, particularly red soils, sandy loams, and highly cultivated alluvial soils. Therefore, the soil's sponge-like nature is essential for maintaining yields in the face of shifting environmental conditions rather than a luxury.

Why Are Soils Losing Their Sponge Function?

Through frequent tillage, monocropping, and a strong reliance on mineral fertilisers, intensive agriculture has disturbed soil structure all across the world. Similar patterns can be noticed in India, where soil organic carbon has declined due to burning, residue removal, and continuous cropping without organic inputs. During fallow seasons, bare soils are impacted by raindrop impact, which causes runoff and surface sealing. Soils lose their internal pore network, aggregates disintegrate, and biological activity diminishes over time. Soil undergoes this degradation, changing from a water-absorbing sponge to a compact medium that dries rapidly and resists infiltration.

Green Manure: A Universal Yet Locally Adaptable Solution

Globally, green manuring is implemented as a strategy to enhance the structure and functionality of soil. The basic principle is the same whether dhaincha is incorporated into Indian paddy fields or cover crops are planted in temperate locations. Soil sponge capacity is enhanced by green manure crops in a number of ways. Their roots create channels that improve water infiltration by penetrating dense layers of soil. These roots break down after integration, leaving behind stable pores that serve as water and air conduits. Organic materials from above-ground biomass bind soil particles together to form aggregates.

These aggregates retain their porosity and ability to store moisture since they are resistant to disintegration over cycles of wetting and drying. Crops like sunhemp, dhaincha, cowpea, and sesbania are particularly beneficial for Indian circumstances due to their rapid biomass production and climate flexibility. Legume and mixed cover crop systems have been shown to provide comparable advantages worldwide, demonstrating the universal applicability of green manuring.

New Scientific Insights Strengthening the Soil Sponge Concept

A greater comprehension of how green manure improves the soil's sponge-like activity has been made possible by recent advances in soil science. Research conducted worldwide emphasizes the significance of root exudates in promoting beneficial microorganisms that create binding agents like glomalin, which stabilise soil aggregates. Additionally, research indicates that the combination of grasses and legumes in green manure systems improves microbial diversity and pore continuity. Within a few cropping cycles after the use of green manure, field tests carried out in India under both rainfed and irrigated systems have shown benefits in improving soil organic carbon, moisture retention, and penetration rate.

Green manuring has demonstrated synergistic benefits when combined with conservation techniques like reduced tillage and residue retention, particularly in climate-stressed environments. Researchers can now see root-derived carbon flow and pore architecture in soils thanks to recent advances in isotopic tracking and X-ray micro-computed tomography (Figure 2).

Water, Climate, and Yield Implications

Water management in all agro-ecological zones is directly impacted by the soil sponge function. Around the world, sponge-like soils reduce erosion and runoff during periods of heavy precipitation. This is especially crucial in India during intense monsoon showers, when poor infiltration causes flooding and nutrient losses.

Increased water-holding capacity lowers the frequency of irrigation and stabilises yields by enabling crops to access moisture during dry spells. In years with erratic rainfall, crop success in rainfed agriculture can be determined by improved soil moisture buffering. Improved infiltration lowers waterlogging and increases the effectiveness of fertiliser use in irrigated systems. Increased soil organic carbon helps sequester carbon on a larger scale, which connects green manuring to climate change adaptation and mitigation tactics.

Green Manure Crops in Indian and Global Context

Although the species of green manure differ with geographical region, they serve similar functions. Legumes, grasses, and brassicas are used all around the world to build organic matter and soil structure. While sunhemp and cowpea are extensively utilised in upland and dryland agriculture, dhaincha continues to be a fundamental component of rice-based systems in India. Short-duration legumes function effectively in intensive cropping systems, while *Sesbania rostrata* can be helpful in water-logged areas. Incorporation at blooming (around 40–60 days) optimizes biomass production and soil benefits.

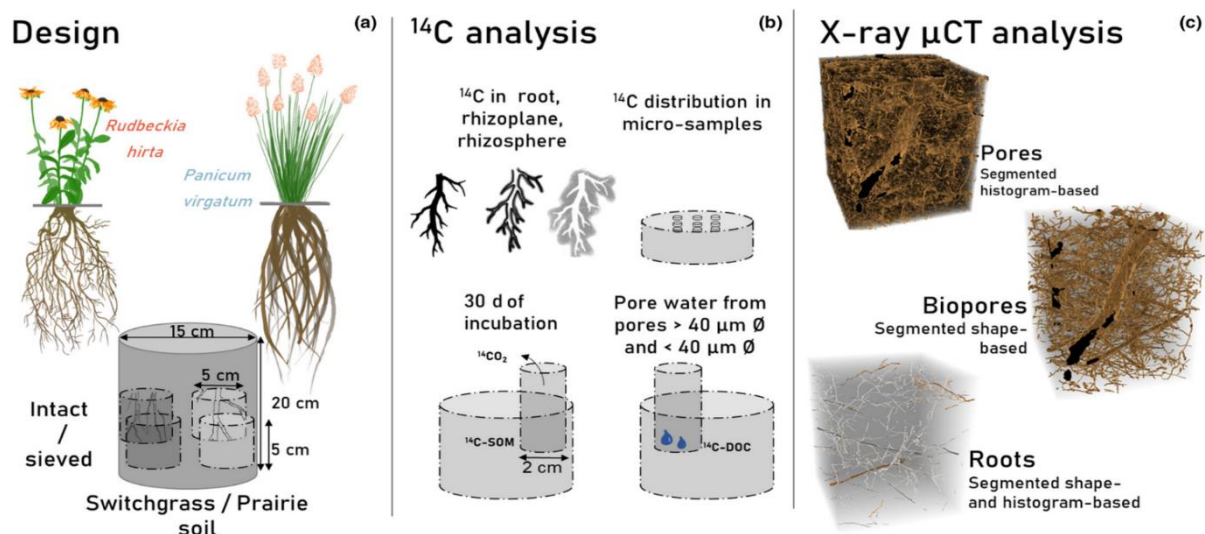


Figure 2: Experimental design and analytical framework illustrating plant–soil systems, ^{14}C tracing of root-derived carbon, and X-ray μCT -based visualisation of soil pores, biopores, and root networks (Source: Kravchenko et al., 2017)



Figure 3: Common green manure crops used in Indian agriculture: (a) Dhaincha (*Sesbania aculeata*), (b) Sunhemp (*Crotalaria juncea*), (c) cowpea, and (d) *Sesbania rostrata*.

Challenges in Adoption Across Scales

Globally, there are challenges in the adoption of green manuring despite compelling scientific data. Due to opportunity costs, labour requirements and delayed economic advantages, farmers frequently hesitate. Adoption is further hampered in India by small landholdings, tight cropping schedules, and restricted access to location-specific guidance. Additionally, severely degraded soils may react more slowly initially, necessitating additional techniques like reduced tillage or organic amendments. To overcome these obstacles, strong extension support,

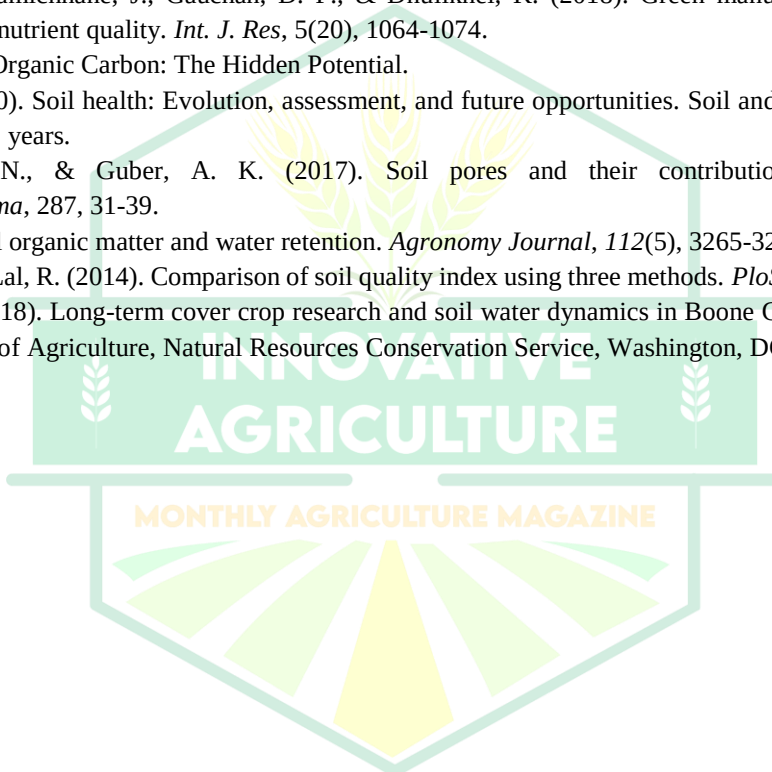
demonstration plots, and policy incentives that view soil health as a long-term investment rather than a temporary input are necessary.

Conclusion

Across the world, sustainable agriculture is based on the idea that soil is a sponge. Rebuilding this sponge function is essential for food security and farm resilience in India, where climatic variability and water stress are becoming more severe. Green manuring stands out as an environmentally sound, economically viable, and scientifically validated technique that connects local farming knowledge with global soil study. Soils can be transformed from water-shedding surfaces to robust, moisture-holding sponges that maintain production both today and in the future by incorporating green manure into cropping systems and integrating it with conventional conservation measures.

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One Flower, Many Shades: The Living Art of *Hibiscus mutabilis*



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Abstract

Hibiscus mutabilis L., known as cotton rose, is a deciduous ornamental shrub native to China and widely cultivated in tropical and subtropical regions for its striking diurnal flower colour change from ivory white to deep pink. This study characterizes its key morphological traits, including palmately lobed leaves with serrated margins and stellate hairs, upright hairy stems and large solitary flowers with a prominent staminal column. Biochemical analysis reveals anthocyanin accumulation, particularly cyanidin derivatives, driving the pigmentation shift via elevated phenylalanine ammonia-lyase activity. These attributes underscore its ornamental value, medicinal potential and ecological benefits in landscapes and biodiversity support.

Keywords: *Hibiscus mutabilis*, Sthalakamal, Morphological traits, Flower colour, *Malvaceae* family

Introduction

Hibiscus mutabilis L., commonly known as **confederate rose, cotton rose, or Sthalakamal**, is a valuable ornamental species belonging to the *Malvaceae* family. Although it carries the names “hibiscus” and “rose,” it is not a true hibiscus or rose, but a close relative within the *Hibiscus* family, which also includes *Gossypium* (cotton). Native to China, *H. mutabilis* is now widely distributed across tropical and subtropical regions of **Asia, Africa, North America and South America** (Zhang *et al.*, 2021). It is extensively cultivated for its **landscape beauty, ecological adaptability and low maintenance requirements** (Ding *et al.*, 2022; Shang *et al.*, 2020). This deciduous or semi-evergreen plant typically grows as a large shrub or small, multi-stemmed tree, reaching up to **4.6 meters in height** with a **canopy spread of approximately 3 meters**. It thrives in a variety of soils, tolerates both full sunlight and partial shade and exhibits strong resilience to drought. Propagation is simple through stem cuttings and the plant establishes quickly in diverse growing environments, making it a popular choice in **garden centers and landscape designs**. The foliage contributes to the plant’s ornamental value, with **large, bright green, deeply lobed leaves** measuring **13-18 cm in length** and covered with fine hairs on the underside. The texture and size of the leaves give the plant a **coarse, eye-catching appearance** in landscape settings. One of the most **striking and unique features** of *H. mutabilis* is its **diurnal flower colour change** (Shanker and Vankar, 2007).

The flowers typically open as **ivory white in the morning**, transition to **light pink by noon** and turn **deep rose or bluish-pink by evening** (Nikolaus and Gert, 1989; Nariyuki, 1973). Due to the independent timing of each flower’s colour transformation, it is common to observe **three distinct flower colours** on the same plant simultaneously. Both **single and double-flowered varieties** are available, with bloom diameters ranging from **8 to 13 cm**. After blooming, the plant forms **round, hairy seed capsules**, which dry and split to release fuzzy seeds resembling cotton balls, hence the common name is “Cotton Rose”. At the biochemical level, the colour-changing behaviour is attributed to the **accumulation of anthocyanin**, especially **cyanidin derivatives**, over the course of the day. Flavonol glycosides such as **isoquercitrin, hyperoside, rutin, quercetin 4'-glucoside and quercimeritrin**, along with **quercetin as the free aglycone**, are present throughout all stages of flower development. Notably, **anthocyanins are absent in the morning petals** but appear by noon and increase significantly by evening. **Cyanidin 3,5-diglucoside** and **cyanidin 3-rutinoside-5-glucoside** have been identified as the primary anthocyanin, while **cyanidin 3-sambubioside** is responsible for the red coloration observed in the later stages. This pigment buildup is closely associated with a rapid increase in **phenylalanine ammonia-lyase (PAL) activity**, which rises up to sevenfold during the early phase of colour development and declines as the flower senesces (Shanker and Vankar, 2007).

Significance of *Hibiscus mutabilis*

1. High ornamental value

It is widely grown as an ornamental shrub due to its large, showy flowers that change colour, making it highly attractive in gardens and landscapes.

2. Medicinal potential

Different plant parts are used in folk medicine for their anti-inflammatory, antimicrobial and soothing properties (Liang *et al.*, 2013).

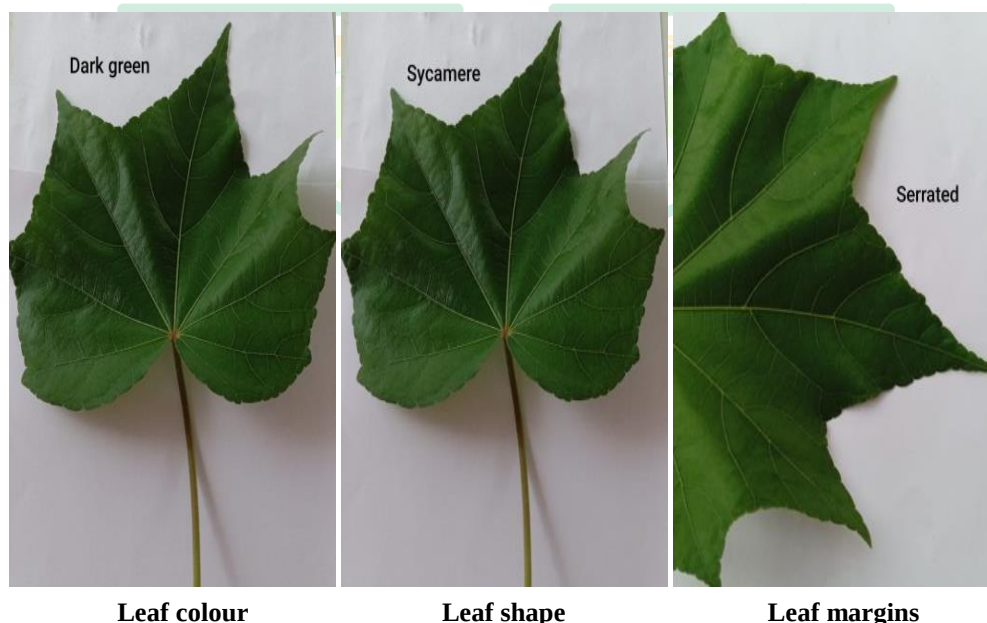
3. Environmental benefits

Being a hardy shrub, *Hibiscus mutabilis* contributes to urban greenery, improves microclimate, supports pollinators like bees and butterflies and aids in biodiversity conservation.

Morphological attributes of *Hibiscus mutabilis*

Leaf characteristics

The leaves of *Hibiscus mutabilis* exhibit a vibrant, dark green coloration on their upper surface, indicative of high chlorophyll content that facilitates effective photosynthesis under bright sunlight. In contrast, the underside appears lighter or whitish-green, a result of the presence of fine, stellate (star-shaped) and glandular hairs. These hairs not only reflect excess light but also help in reducing water loss and deterring herbivores. The leaves are palmately lobed (sycamere), usually comprising three to seven broad, triangular segments that radiate from a central point resembling a hand or maple leaf in structure. Leaf margins were serrated, giving them a coarse texture and bold visual appeal. The main veins, or ribs of the leaves, are typically green and blend seamlessly with the leaf surface, though they may stand out slightly due to the texture provided by surface hairs. Leaves are arranged alternately along the stems, minimizing overlap and optimizing light exposure, while also enhancing the ornamental appeal of the plant's foliage architecture. The leaf tips are generally acute to acuminate, tapering to a subtle point that accentuates the dramatic shape of the lobes. Venation follows an arcuate pattern, where the primary veins bend and trace the leaf blade's edge. The leaf surfaces are distinctly hairy, especially on the lower side which contributes to the lighter appearance beneath and provides additional environmental resilience. The leaf traits have been clearly illustrated in Figure 1.



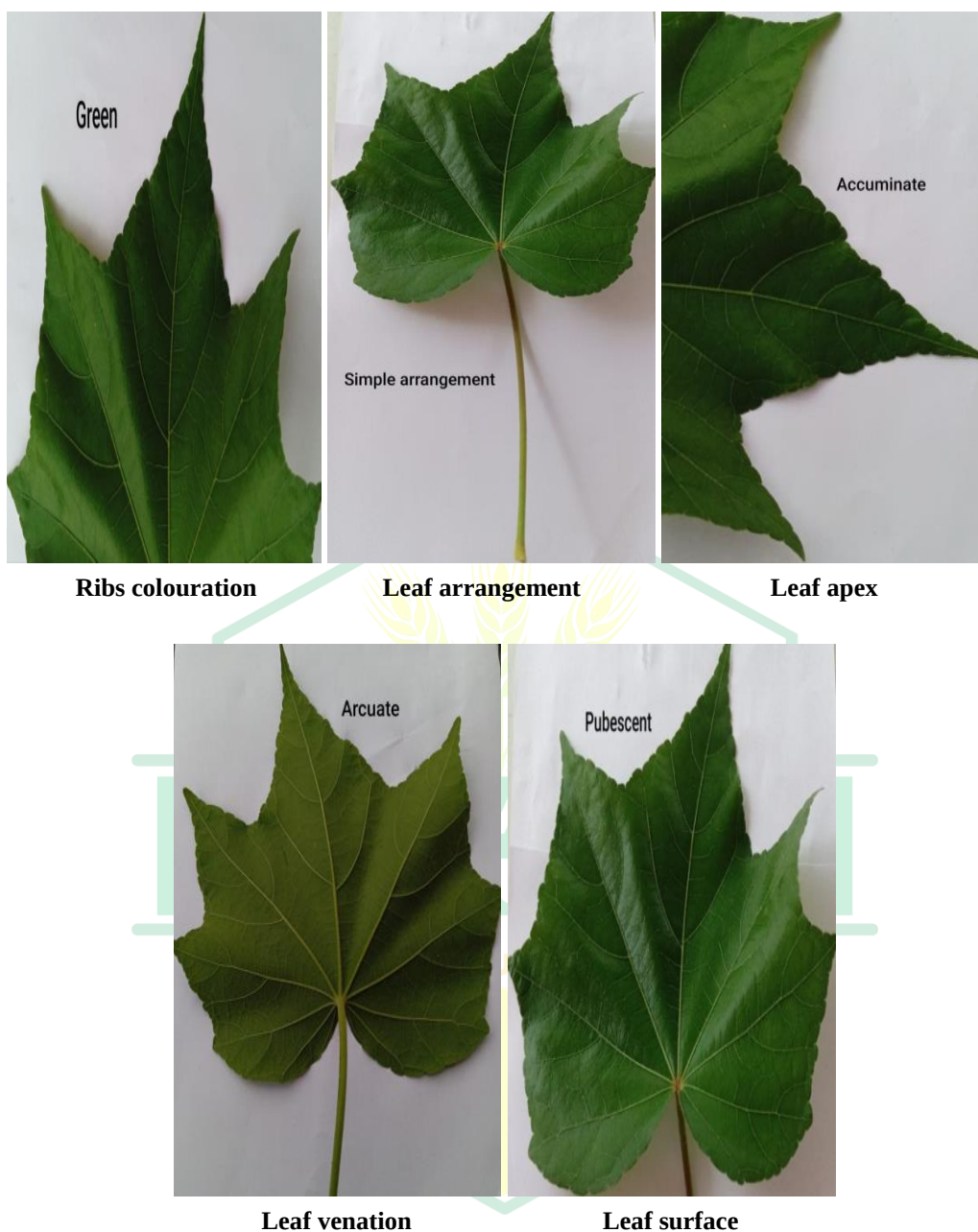


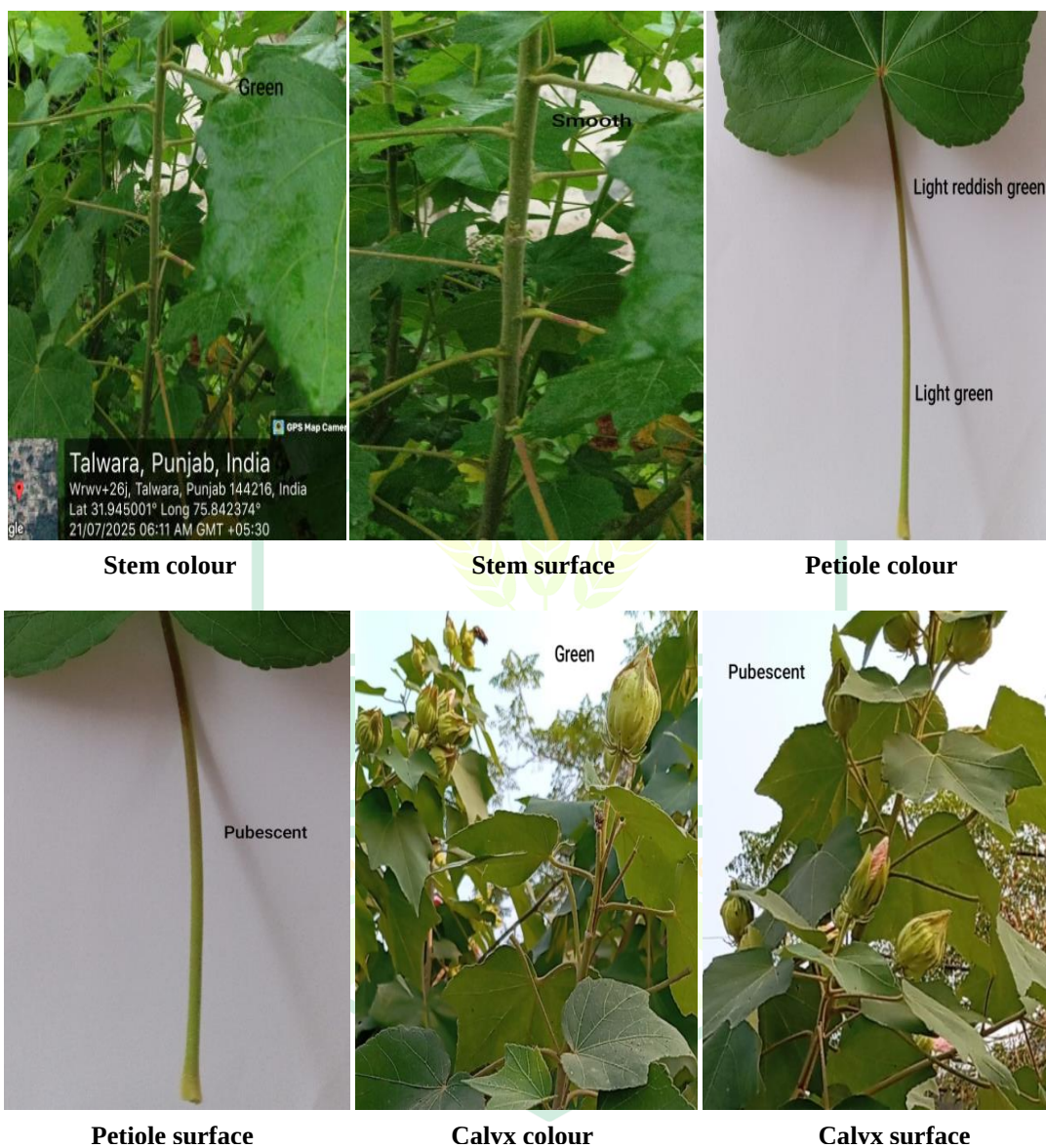
Figure 1. Characteristics of the leaves of cotton rose

Stem, petiole and calyx characteristics

Hibiscus mutabilis is characterized by its strong, upright stems that develop into a heavily branched shrub or small tree, typically reaching heights of 2 to 5 meters and sometimes extending up to 8 meters under favourable growing conditions. The stem is green in colour and are densely coated with fine, star-shaped (stellate) and glandular hairs, giving them a soft, woolly feel and a slightly silvery sheen. This hairy covering plays a protective role, minimizing water loss and deterring insect pests. As the plant ages, the stems become increasingly woody and resilient, with the older branches losing much of their pubescence and developing a firmer texture. The petioles, which attach the leaves to the stem, are relatively slender yet sturdy, providing strong support to the large, lobed leaves while allowing flexibility. Petiole colour is characterized by light reddish green from upper side and light green from lower side. These petioles also bear fine hairs, consistent with the texture of the leaf undersides and aid in reducing

transpiration. The calyx colour is green and surface is marked by sparse hairs. These characteristics of the stem, petiole and calyx are visually represented in Figure 2.

Figure 2. Characteristics of the stem, petiole and calyx of cotton rose



Flower characteristics of cotton Rose

The flowers of *H. mutabilis* are strikingly large and typically borne singly on long stalks (peduncles) emerging from the axils of the leaves. A distinctive trait of this species is the progressive colour change of its blossoms throughout the day, starting as white or light pink in the morning and gradually turning a deeper pink or red by evening. **This floral colour transition has been illustrated clearly in Figure 3.** This dramatic shift not only adds ornamental value but also serves to attract various pollinators, including bees and hummingbirds. They have a broad, cup-like shape composed of five wide, overlapping petals with a soft, velvety feel. The flower's reproductive structure features a prominent central column made up of fused stamens encircling the style and stigma, a hallmark of *Hibiscus* species. Some cultivated forms may bear double flowers, with multiple layers of petals, further increasing their decorative appeal. The floral structure along with petal arrangement has been shown in Figure 4.

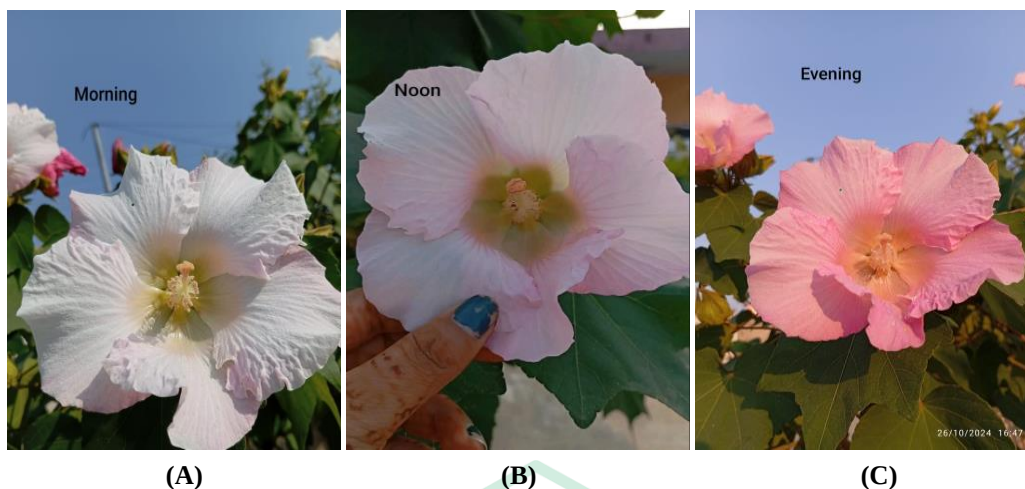


Figure 3. Flower colour of *Hibiscus mutabilis* is (A) Ivory white (left) in the morning (B) light pink (middle) in the afternoon and (C) red (right) in the evening



Flower shape
Figure 4. Flower shape of *Hibiscus mutabilis*

Conclusion

This morphological characterization of *Hibiscus mutabilis* highlights its adaptability, resilience and unique diurnal flower colour transformation, driven by anthocyanin dynamics and **phenylalanine ammonia-lyase (PAL)** enzyme activity, positioning it as a superior ornamental species. The plant's large lobed leaves, hairy stems and petioles and showy blossoms with cup-shaped petals enhanced its landscape utility while offering low-maintenance propagation *via* cuttings. Beyond aesthetics, its folk medicinal uses for anti-inflammatory properties and environmental roles in urban greening, pollinator support and microclimate improvement suggest untapped commercial potential. Future research should explore genetic diversity, breeding for enhanced traits and sustainable cultivation to promote its integration in horticultural entrepreneurship and conservation efforts in subtropical agro ecosystems.

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Bio-Cementation: Transforming Soil Stabilization through Microbial Engineering



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The field of geotechnical engineering is currently witnessing a transition from energy-intensive chemical interventions toward more sustainable, biologically driven solutions. Central to this shift is Microbially Induced Calcium Carbonate Precipitation (MICP), often referred to as bio-cementation. This process utilizes the metabolic activity of specific soil microbes to transform loose, granular substrates into a solidified mineral matrix, effectively mimicking the natural formation of sandstone.

The Biological and Chemical Mechanism

The process of bio-cementation is primarily driven by ureolytic bacteria, such as *Sporosarcina pasteurii*.

The Core Mechanism: Ureolytic Bio-Mineralization

This process is generally executed in several passive, highly controlled stages:

1. **Microbial Introduction:** A solution containing specialized bacteria is injected into the soil matrix. Due to its water-like viscosity, the fluid penetrates even fine-pored soils that would be "grout-locked" by traditional microfine cements.
2. **Nutrient Injection:** A second solution, consisting of urea and a calcium source (such as calcium chloride), is introduced.
3. **Hydrolysis and Precipitation:** The bacteria produce the enzyme *urease*, which facilitates the hydrolysis of urea. This reaction increases the local pH, causing calcium ions to react with carbonate ions.

The resulting calcium carbonate (CaCO_3) crystals precipitate at the contact points between individual soil grains. These mineral bridges effectively "glue" the particles together, turning loose sand into a solidified bio-sandstone without altering the soil's original volume.

Comparative Advantages in Soil Science

Bio-cementation offers several distinct advantages over the mechanical approaches used in traditional grouting, such as permeation or compaction:

- **Superior Penetration:** Due to the low viscosity of the bacterial and nutrient solutions—which are similar to water, the treatment can penetrate fine-pored soils that would otherwise be inaccessible to microfine cement slurries.
- **Structural Integrity without Volume Change:** Similar to permeation grouting, bio-cementation binds particles together without altering the soil's original volume, ensuring that the ground remains stable without the expansion risks associated with compaction grouting.
- **Ecological Preservation:** The process avoids the use of toxic synthetic resins often found in chemical grouting, making it a safer alternative for applications near sensitive groundwater aquifers.

Geotechnical Property Alterations

The scientific objective of this "biological injection" is to transform the soil from a "loose" state to a "cemented" state by increasing the unconfined compressive strength (UCS).

- **Pore-Throat Reduction:** Calcite crystals preferentially form at the "throats" or contact points between soil grains. This significantly reduces the hydraulic conductivity (permeability) of the soil, often by several orders of magnitude, making it an effective barrier against "piping" erosion.
- **Shear Strength Enhancement:** The mineral bridges increase the soil's internal friction angle and cohesion. Research indicates that bio-cemented sands can achieve a UCS ranging from 0.5 MPa to over 10 MPa, depending on the concentration of the urea-calcium "grout" and the treatment duration.

- **Effective Porosity:** Unlike traditional compaction grouting which physically displaces soil particles, MICP maintains the overall volume of the soil matrix while only reducing the "effective" porosity.

Strategic Environmental Applications

Beyond stabilizing foundations for infrastructure, bio-cementation is being adapted for a variety of environmental and geological challenges:

1. **Erosion Control and Piping Mitigation:** In areas where water creates internal "tunnels" or piping through soil profiles, bio-cementation can be used to solidify these voids from the inside out. This strengthens the soil against the erosive forces of moving water without the need for massive excavation.
2. **Subsurface Stabilization for Remediation:** By creating a solidified bio-mineral barrier, this technology can be utilized to construct "grout curtains" that isolate contaminated waste sites, preventing the migration of toxic leachate into clean water supplies
3. **Carbon-Negative Potential:** Current research is exploring how bio-cementation can be integrated with carbon sequestration efforts. As the calcium carbonate crystals form, CO² can be chemically bound into the mineral structure, turning the soil into a permanent subterranean carbon storage bank.

The following conclusion has been revised to utilize a more passive, explanatory tone, focusing on the systemic integration of these technologies into environmental and civil engineering.

Future Prospects of Bio-Cementation (Point-wise Brief)

1. **Low-carbon alternative:** Reduces dependence on Portland cement and lowers CO₂ emissions in soil stabilization.
2. **Sustainable infrastructure:** Supports green construction and climate-smart urban development.
3. **Microbial engineering advances:** Use of optimized or engineered microbes to improve calcite precipitation and performance under harsh conditions.
4. **Synthetic biology applications:** Development of site-specific "designer microbes" for tailored geotechnical solutions.
5. **Scale-up and field use:** Expansion from lab and pilot studies to large-scale, real-world applications.
6. **Standardization:** Creation of design guidelines, performance standards, and regulatory frameworks.
7. **Smart integration:** Combination with geosynthetics, bio-polymers, vegetation, and IoT-based monitoring systems.
8. **Climate resilience:** Application in erosion control, slope stabilization, embankments, and disaster mitigation.
9. **Coastal and land restoration:** Useful for coastal protection and rehabilitation of degraded or contaminated soils.
10. **Economic feasibility:** Lower costs through scaling, local materials, and industrial by-products.
11. **Commercialization:** Growth of startups and industry-academia partnerships offering turnkey solutions.
12. **Circular economy support:** Utilization of waste streams and biologically driven processes.
13. **Soil health improvement:** Enhances long-term soil stability while reducing chemical dependency.

Conclusion: The Integration of Biogeochemical Engineering

It can be concluded that grouting represents a sophisticated intersection of fluid dynamics, chemistry, and pedology. By the systematic treatment of soil not as an inert "dirt" but as a highly engineered and adaptable material, the structural capacity to build taller infrastructures is enhanced, and the protection of global water resources is more effectively managed.

The stability of the built environment is maintained through the silent application of these subsurface interventions³. Furthermore, the climate crisis is proactively addressed through the deployment of carbon-negative grouts and bio-cementation techniques, which facilitate the permanent sequestration of atmospheric CO² into the subterranean mineral profile. Ultimately, the evolution of these injection technologies ensures that the complexities of the porous soil matrix comprising mineral particles, water, and air, are harnessed to support both human infrastructure and ecological preservation.

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Climate-Resilient Cropping Systems for Heat & Drought Stress



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Abstract

Rising temperatures, erratic rainfall, and frequent drought episodes are increasingly threatening agricultural productivity across tropical and semi-arid regions of the world. Farmers are already witnessing shortened crop durations, flower drop during heat waves, and declining water availability in canals and wells. Climate-resilient cropping systems provide a practical pathway to cope with these challenges. Such systems integrate stress-tolerant crop varieties, diversified cropping patterns, soil and water conservation measures, efficient irrigation methods, and timely farm operations. This long extension-style article discusses in detail the principles, field practices, and institutional support required to design and scale climate-resilient cropping systems for heat- and drought-prone environments, with special emphasis on Indian farming conditions.

1. Introduction: Why Climate Resilience Is Needed in Agriculture

Climate change is no longer a distant threat for farmers; it is a present-day reality. Over the last few decades, average temperatures have risen steadily, while rainfall has become more unpredictable. Many regions now experience prolonged dry spells followed by short periods of intense rainfall, which leads to runoff rather than soil moisture recharge. Heat waves during critical crop growth stages such as flowering and grain filling drastically reduce yield in crops like wheat, rice, and maize.

Smallholder farmers who depend on rainfed agriculture are particularly vulnerable. Traditional cropping systems dominated by a single crop and reliant on heavy irrigation or monsoon rains have become risky and unstable. In this context, climate-resilient cropping systems aim to redesign farm practices so that crops can survive and produce even under water scarcity and high temperature stress. These systems are not based on one technology alone but on a combination of biological, agronomic, and institutional interventions working together at the farm level.

2. Understanding Heat and Drought Stress in Crops

Heat stress occurs when temperatures rise above the optimum level for normal crop growth, leading to reduced photosynthesis, pollen sterility, leaf scorching, and accelerated crop maturity. Drought stress results from insufficient soil moisture and causes wilting, reduced leaf area, poor nutrient uptake, and ultimately low biomass and grain yield.

When heat and drought occur together, their impact becomes even more severe. Crops close their stomata to conserve water, which limits carbon dioxide intake and reduces growth. Root systems may fail to access deep moisture in compacted or degraded soils. Therefore, managing soil physical condition, selecting suitable crops, and ensuring timely water supply are central to building resilience against these stresses.

3. What Is a Climate-Resilient Cropping System?

A climate-resilient cropping system is one that maintains acceptable productivity and farm income despite climatic shocks such as heat waves, droughts, or delayed monsoons. Key features of such systems include the use of stress-tolerant crop varieties, diversification through rotations or intercropping, conservation agriculture practices that protect the soil surface, efficient irrigation technologies, and flexible management decisions such as adjusting sowing dates.

These systems also emphasize learning and adaptation. Farmers experiment with new crop combinations, modify planting geometry, or adopt new water-saving methods based on seasonal weather forecasts and extension advice. Over time, these adjustments make the farming enterprise more stable and less dependent on a single crop or rainfall pattern.

4. Crop and Variety Selection for Hot and Dry Environments

Choosing the right crop is the first step toward resilience. Coarse cereals such as pearl millet, sorghum, finger millet, and little millet require less water and tolerate high temperatures better than many fine cereals. Pulses like pigeon pea, cowpea, mung bean, and lentil have deep root systems and can survive intermittent drought while improving soil fertility through biological nitrogen fixation.

In irrigated systems, breeders have developed heat-tolerant and early-maturing varieties of wheat, rice, and maize that escape terminal heat stress. Farmers are encouraged to obtain certified seed of such varieties from agricultural universities or government agencies. Including fodder crops and oilseeds such as mustard or sesame further spreads risk and improves overall farm profitability.

5. Crop Diversification, Rotations, and Intercropping

Diversifying the cropping pattern is one of the most powerful tools for climate adaptation. Crop rotations that include cereals, legumes, and oilseeds improve soil structure, reduce pest and disease build-up, and enhance soil organic matter. Higher organic matter increases the soil's capacity to store water, which is crucial during dry spells.

Intercropping systems, such as sorghum with pigeon pea or pearl millet with cowpea, allow crops with different rooting depths and growth habits to share resources efficiently. If one crop suffers due to drought or heat, the companion crop may still produce a harvest, thereby stabilizing farm income. Traditional mixed cropping systems practiced in many dryland areas of India are now being re-evaluated and improved using scientific recommendations.



Figure 1: Crop Diversification with Millets and Pulses

6. Soil Health Management for Moisture Conservation

Healthy soil acts like a sponge that absorbs rainfall and slowly releases water to plant roots. Continuous application of farmyard manure, compost, green manures, and crop residues increases soil organic carbon and improves aggregation. Better soil structure enhances infiltration and reduces runoff during heavy rains.

Mulching the soil surface with straw, stubble, or leaves lowers soil temperature, reduces evaporation losses, and suppresses weeds that compete for moisture. In conservation agriculture, minimum or zero tillage is combined with residue retention and crop rotations to protect the soil and maintain biological activity. Over time, these practices greatly improve drought tolerance of cropping systems.

7. Efficient Water-Use and Irrigation Management

Water scarcity makes efficient irrigation essential. Micro-irrigation systems such as drip and sprinkler deliver water directly to the root zone and reduce losses through evaporation or deep percolation. Scheduling irrigation

based on crop growth stage rather than calendar days ensures that limited water is used when it gives maximum benefit.

In rice-based systems, practices like alternate wetting and drying can save large amounts of water without sacrificing yield. Laser land leveling improves uniform distribution of irrigation water, while raised-bed planting in wheat or maize enhances drainage and root development. Even simple tools such as tensiometers or soil-moisture feel-and-appearance methods can guide farmers on when to irrigate.



Figure 2: Drip and Sprinkler Irrigation under Drought

8. Rainwater Harvesting and Landscape-Level Interventions

Capturing and storing rainwater is crucial in drought-prone areas. Farm ponds, percolation tanks, check dams, and contour bunds slow down runoff and allow more water to infiltrate into the soil profile. Stored water can provide lifesaving irrigation during prolonged dry spells.

Watershed-based approaches that integrate soil conservation, tree planting on field boundaries, and pasture development on degraded lands improve water availability at the community level. Agroforestry systems, where trees are grown with crops, also moderate field microclimate by providing shade, reducing wind speed, and improving soil organic matter through leaf litter.



Figure 3: Rainwater Harvesting Farm Pond

9. Role of Weather Forecasts, Advisory Services, and Digital Tools

Access to timely climate information greatly enhances farmers' adaptive capacity. Short- and medium-range weather forecasts help decide sowing dates, irrigation timing, and fertilizer application. Mobile-based agro-advisory services and messages from extension agencies translate scientific forecasts into simple field recommendations.

Remote sensing through satellites and drones is increasingly used to detect crop stress early and identify water-deficient patches within fields. Although such technologies may initially be available through service providers or cooperatives, they have great potential to support climate-resilient agriculture in the future.

10. Policy Support and Institutional Linkages

Scaling climate-resilient cropping systems requires supportive policies and strong institutions. Government programs promoting micro-irrigation, soil health cards, crop insurance, and distribution of stress-tolerant seed play a vital role in encouraging adoption. Training programs through Krishi Vigyan Kendras and farmer field schools help build local capacity and confidence.

Linking farmers with markets for diversified crops such as millets and pulses is equally important. Stable prices and assured procurement motivate farmers to shift away from risky monocropping toward more resilient systems.

11. Conclusion

Climate-resilient cropping systems represent a holistic response to the growing challenges posed by heat and drought stress. By integrating tolerant crop varieties, diversified cropping patterns, soil and water conservation measures, efficient irrigation technologies, and climate-informed decision-making, farmers can protect their yields and livelihoods in an uncertain future. Continued research, strong extension services, and enabling policies will be essential to spread these practices widely and ensure long-term sustainability of agricultural production systems.

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Advanced Water Quality Monitoring and Management in Aquaculture Operations



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1. Introduction

The aquaculture industry worldwide has undergone rapid growth in the last thirty years and has transformed into an additional food source and a mainstay of food security of the global seafood industry. To meet the increasing demand, the industry has increasingly undertaken intensification measures that have been characterised by an increase in stocking intensities and an increase in feed per unit area. Though these forms of intensification increase the yield, it also exerts a lot of pressure on the rearing environment. It does not change the basic assumption of successful aquaculture: productivity is determined by the quality of water. Water is not just the environment under which aquatic life lives, water is their life support system, and it affects respiration, feeding efficiency, growth rates, immunocompetence, and reproductive success both directly. In high-density operations, there is a minimal tolerance to error. Even small changes in vital physicochemical parameters can rapidly escalate into disastrous situations, leading to mass death or chronic stress that inhibits the development and promotes the growth of pathogens.

The management of water quality in the past years was based on reactive approaches, periodical manual sampling, and corrective measures. Nonetheless, because of the nature and the speed of modern aquaculture systems, especially Recirculating Aquaculture Systems (RAS), these snapshot methods are insufficient. Real-time monitoring systems with proactive management systems and systems are the current imperative. In this article, the construction of advanced water-quality surveillance is discussed, the key parameters, the technological environment of sensors and data analysis, and how the real-time data can be converted to automated management measures that could be significant in ensuring sustainable and profitable aquaculture activities.

2. Critical Physicochemical Parameters in Intensive Systems

Although there are a large number of parameters that affect aquatic health, there is a set of important parameters that determine the viability of intensive aquaculture activities in the short term. It is essential to know how these variables interact with each other in a bid to manage them.

2.1. Dissolved Oxygen (DO)

Dissolved oxygen is known to be the most important limiting factor in aquaculture. Oxygen is essential to the aerobic metabolism of aquatic life, and the need varies considerably depending on species, size, feeding, exercise and the water temperature. The high-risk window in pre-dawn hours in intensive ponds is as a result of the diel oxygen cycle, which is triggered by algal photosynthesis during the day and total system respiration at night. Chronic hypoxia results in low feed conversion ratios (FCR) and immunosuppression, and acute anoxia is rapidly lethal.

2.2. The Nitrogen Cycle

Total Ammonia Nitrogen (TAN) is the main protein metabolism waste produced in fish. TAN has a temperature- and pH-dependent equilibrium between ionised ammonium (NH_4^+), which is not very toxic, and un-ionised ammonia (NH_3), which is extremely toxic to gill tissue and the central nervous system. In practical biological filtration systems, which are vital in RAS, nitrifying bacteria oxidise ammonia to nitrite (NO_2^-), followed by the oxidation of nitrite to relatively harmless nitrate (NO_3^-). Nitrite itself is also toxic, having the ability to bind to haemoglobin in order to form methemoglobin and therefore lowering the oxygen-carrying capacity of blood (brown blood disease).

2.3. pH and Alkalinity

pH is a measure of the acidity or basicity of water. Whereas the majority of species can withstand the 6.5-9.0 ranges, rapid changes are stressful. More importantly, the toxicity of ammonia depends on the pH; an increase in pH moves the equilibrium to the toxic un-ionised ammonia (NH_3). Alkalinity is the buffering ability of the water towards pH changes and is necessary to stabilise the system, especially high photosynthetic rate, which uses CO_2 and increases pH.

2.4. Temperature

Fish are poikilotherms; their metabolic rate is directly regulated by the temperature of the water. Each species has an optimum thermal range of growth. The limit of these deviations inhibits immune activity and nutrition. Moreover, temperature harms oxygen solubility in that the warmer the water, the lower the oxygen dissolved is at the time when fish metabolic demand is the most intense.

Table 3. Optimal Water Quality Ranges for Intensive Finfish Culture (e.g., Tilapia/Salmonids)

Parameter	Unit	Optimal Range (General)	Critical Limit / Concern
Dissolved Oxygen (DO)	mg/L (ppm)	> 5.0	< 3.0 (Stress); < 2.0 (Mortality risk)
Total Ammonia Nitrogen (TAN)	mg/L (ppm)	< 1.0 (species dependent)	> 2.0 (Chronic stress, depends on pH)
Un-ionised Ammonia (NH_3)	mg/L (ppm)	< 0.02	> 0.05 (Toxic)
Nitrite (NO_2^-)	mg/L (ppm)	< 0.1	> 0.5 (Risk of brown blood disease)
pH	-	6.5 – 8.5	< 6.0 or > 9.0; Daily swings > 0.5
Temperature	°C	Species specific (e.g., 24-28 for Tilapia)	+/- 5°C from optimum
Alkalinity	mg/L CaCO_3	> 50 (Freshwater); > 100 (RAS)	< 20 (pH instability)

3. The Technological Architecture of Advanced Monitoring

The further development of test strips and handheld meters requires a comprehensive technological ecosystem, which is commonly classified as part of the Industrial Internet of Things (IIoT). This architecture consists of three major layers, namely the physical perception layer (sensors), the transmission layer (connectivity) and the application layer (data processing and action).

3.1. The Perception Layer

Any monitoring system is as secure as its sensors are good and strong. The conditions in intensive aquaculture are unfavourable, with biofouling (growth of algae and bacteria on sensor surfaces) and corrosion.

a) Optical DO Sensors: Conventional electrochemical (membrane) DO sensors need constant calibration and the replacement of the membrane, and consume O_2 in the measurement, consequently introducing errors into stagnant water. Modern systems make use of optical dissolved oxygen (LDO/RDO) sensors. The devices are capable of measuring oxygen using the fluorescence quenching method, and have a low maintenance level, stay in calibration over a period of months and are independent of the flow rate and fouling.

b) Ion-Selective Electrodes (ISE): ISEs are used to measure ammonium, nitrate, and pH, and are effective but are prone to drift and require regular two-point calibration to maintain accuracy.

c) Multiparameter Sondes: Multiparameter sondes are used in high-end applications, with multiple sensors mounted in one strong deployment tube, often with mechanical wipers to periodically clean sensor surfaces to avoid biofouling.

3.2. The Transmission Layer

Information gathered by sensors has to be conveyed to a central processing unit. Depending on the size and the location of the farm, connectivity depends on the decision made.

a. Wired Connections: The short distances between sensors and local Programmable Logic Controllers (PLCs) in RAS facilities, and the need to transmit data to automated controls immediately and with the highest reliability, cause wiring of the sensors directly to the PLCs.

b. Wireless LPWAN (LoRaWAN, Sigfox): Low-Power Wide-Area Networks are the best when it is necessary to cover tens of hectares with pond operation. They send small data packets over long distances (kilometres) and a little battery, which is appropriate for remote sensor nodes.

c. Cellular (4G/5G/NB-IoT) and Satellite: Cellular or Satellite backhaul is needed to connect local sensor networks to the cloud, especially when in offshore cages or in other areas with extremely limited connectivity.

3.3. The Application Layer

Raw data are sent to cloud-based solutions, where it is stored, visualised on a dashboard and analysed. This layer converts raw numbers to actionable intelligence.

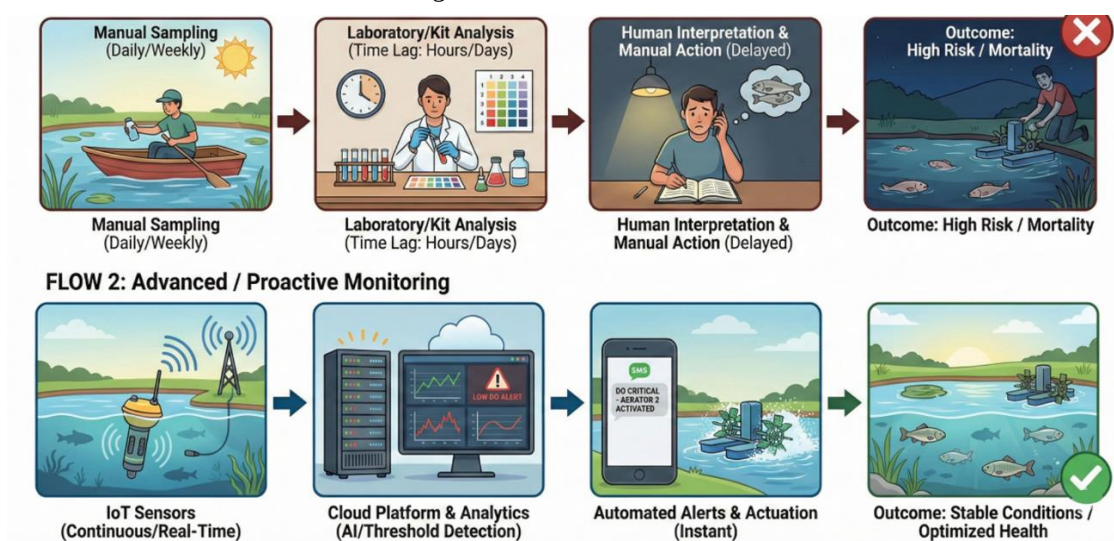


Figure 1. Comparison of Traditional vs. Advanced IoT-Based Monitoring Workflows

4. Data-Driven Management and Automation

The real ROI of the advanced monitoring is not necessarily the purchase of data; however, it is the use of the obtained data to integrate farm management procedures. This kind of automation bridges the gap between recognition and response and optimises the entire work process.

4.1. Automated Actuation Systems

To improve the medical standards, automated actuation systems are required to deliver information about the state of prescription refills and assessments (Steingray, 2013). Farms can add sensor data to programmable logic controllers (PLCs) or intelligent control units, and thus automate important life-support equipment.

a) Aeration Control: A high-tech system turns on aerators below a predetermined setpoint (e.g. 4.5 mg/L) and off when a setpoint is reached (e.g. 6.5 mg/L). The practice helps save a lot in terms of saving energy, which is normally the second-highest operation cost after feed.

b) Feeder Integration: In close relation to temperature and DO is fish appetite. More sophisticated systems may include automated feeders together with water-quality detectors; in case of a decrease in the DO level below a necessary limit or a significant variation in the temperature, feed is automatically turned off to avoid feed wastage and further ammonia bursts.

c) RAS Specific Automation: RAS In recirculating aquaculture systems (RAS), sodium bicarbonate pH sensors control dose pumps to ensure the best environment for nitrifying bacteria. Similarly, oxidation Redox potential (ORP) sensors can be used to regulate the use of ozone injection systems that are used in disinfection and fine-solid elimination.

4.2. Predictive Analytics and Machine Learning

The use of machine-learning algorithms takes place due to the aggregation of historical water-quality data. Instead of simply responding to the violation of the threshold, machine-learning models can also identify minor trends that lead to the emergence of a crisis.

As an illustration, a predictive model may predict the rate of nocturnal decline of DO, water temperature, and biomass data and expect a critical event of hypoxia, which will be experienced at 05:30 PM, at the forecast time of 02:00 AM, and alarm or switch on reserve aeration capacity long before the crash actually occurs. Equally, models can be used to compare the input of feeds with the outcome trends on ammonia to warn the managers about a situation where biofiltration capacity is at variance with stocking density.

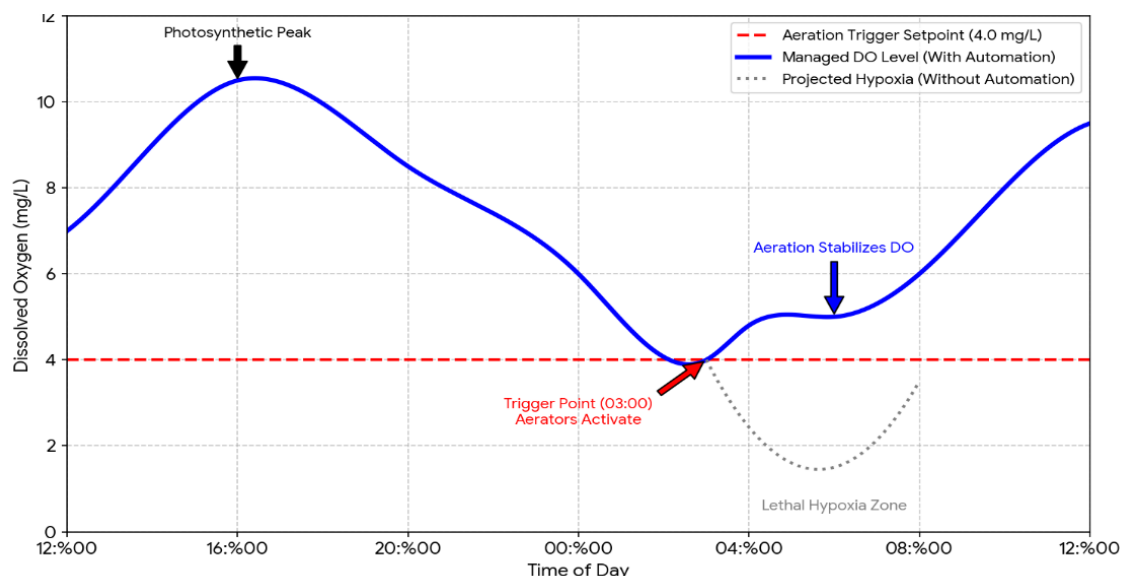


Figure 2. Dissolved Oxygen Cycle and Automated Aeration Response

5. Challenges and Future Horizons

While the benefits of advanced monitoring are manifest, barriers to widespread adoption remain.

5.1. Current Challenges:

- Capital Expenditure (CAPEX):** Capital expenditure is very high to initiate heavy industrial sensors, connectivity technology, and a software platform, especially for small to medium-sized businesses.
- Maintenance and Biofouling:** Although this has been improved through innovations like mechanical wipers, sensors used in nutrient-rich water still need to be cleaned and calibrated. A sensor that is drifted can cause more misinformation than not being there, leading to false confidence.
- Data Overload and Digital Literacy:** It is no use creating terabytes of data, unless one has the experience to process it; there is a skills gap in the industry around effectively handling and using complex data streams.

5.2. Future Horizons:

The next frontier in water quality management involves increasing specificity and integration.

- Real-time Biosensors:** Research and development is currently underway on real-time biosensors with the capability of detecting either a particular pathogen (e.g., *Vibrio* spp.) or stress biomarkers (e.g., cortisol) in the water column, and therefore serve as a malady warning system long before clinical symptoms appear.
- Satellite Remote Sensing:** In large areas of coastal aquaculture, ocean colour satellite imagery is the technology used to identify the harmful algal blooms (HABs) in the proximity of the cage locations to allow producers to stop feeding or place perimeter skirts.
- Integration with Blockchain:** Quality information is already being integrated into blockchain-enabled traceability systems, which enable consumers to check the environmental conditions in which their seafood was raised, which adds a premium value to the product.

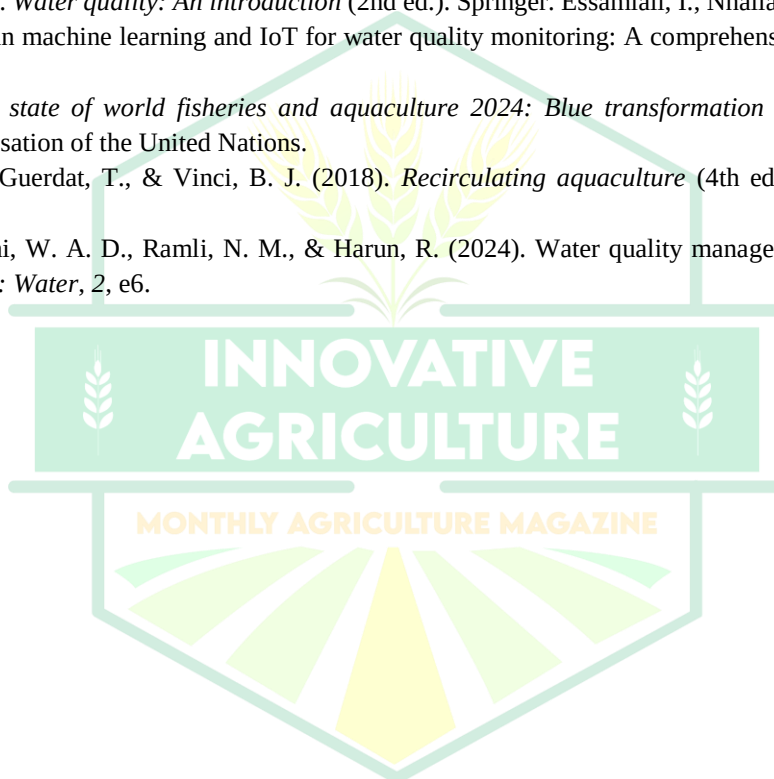
6. Conclusion

An extensive to intensive aquaculture conversion is necessary to meet the needs of an increasing world population, but it further implies an equal transformation in the management activities. The quality of water is the pivot of the success of intensive operations. The use of manual, intermittent surveillance in high-density systems is an outdated approach to risk-management.

Smart water-quality monitoring enabled by sufficient Internet-of-Things (IoT) sensors, real-time connection, and data analytics has become a future-proof luxury to an operational practice. It changes the managerial position of crisis control to optimisation. Although the cost and maintenance issues are still persistent, the further development of sensor devices and machine-learning algorithms is likely to reduce those issues. After all, the mixture of these systems will result in better animal welfare and survival rates and contribute to better energy and feed usage, which, in its turn, will guarantee the environmental sustainability and economic feasibility of the aquaculture sector.

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Advances in Plant Breeding Techniques for Enhancing Quality and Stress Tolerance



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1. Introduction

As the world's agricultural sector faces an uphill task in nourishing a growing population, which is expected to rise to 9.7 billion by 2050, climate change is mounting pressure on agroecosystems. Higher temperatures, changing precipitation patterns, growing salinisation of soils, and the emergence of new pests and pathogens are all posing a threat to crop productivity and food security worldwide. At the same time, customers are becoming more and more rigid in their expectations on the produce with higher nutritional value and longer shelf life, as well as on the quality of processing. The realisation of these demanding consequences will require a paradigm change in crop improvement. Even though traditional breeding of plants has traditionally been used to support agricultural development, the selection process based on phenotype and natural recombination assemblies frequently remains slow enough to remain behind the current demands, particularly when considering complex and polygenic traits, including abiotic stress tolerance and yield stability.

The new generation of breeding has been brought about by the emergence of molecular biology and genomics. Newer methods, which go beyond phenotypic observation and provide the capability of direct genomic manipulation, are providing unprecedented speed, precision and efficiency in the production of better and improved crop varieties. This article is a review of significant developments in plant breeding technologies, specifically Marker-Assisted Selection (MAS) and Genomic Selection (GS), and genome-editing systems, including the CRISPR-Cas9. We review how these advances are being used to increase the quality of the grain and make the crops more resistant to biotic and abiotic stresses to facilitate a more resilient and sustainable agricultural future.

2. The Evolution from Phenotype to Genotype-Based Selection

Traditional breeding methods such as pedigree selection, hybridisation, and backcrossing have helped in the production of high-yield cultivars, and most significantly during the Green Revolution. The approaches rely on the ability to determine better plants through observable phenotypic characteristics under field conditions. Where the trait of interest is highly heritable, and there is only one or a few major genes controlling that trait, the application of phenotypic selection would be cumbersome and less accurate when it comes to complex quantitative traits whose occurrence is controlled by many genes and major interactions between genes and the environment. Besides, it is a time-consuming process that requires 8-12 years of breeding and development of a new variety and can be hindered by linkage drag, as the genes of interest are co-segregated with the desired trait (Acquaah, 2015; Ahloowalia et al., 2004). The limitations of pure dependence on phenotype triggered the inclusion of molecular markers in breeding programmes.

2.1 Marker-Assisted Selection (MAS)

The application of Marker Assisted Selection has been a major improvement in breeding, where breeders are able to select based on traits of interest by using DNA markers closely linked to the genes being targeted. Such a method changes the criterion of selection to the genotype. The first benefit of MAS is that it allows decoupling

selection and environmental effects. Since the genotype of a person is inviolable, screening can be performed when the seedlings are still small, or even on the seeds, without the need to grow the plants before phenotypic analysis. It is specifically beneficial in characteristics that are hard or expensive to quantify, are outpouring in development or need designated environmental conditions to appear, including resistance to distinct pathogens or to abiotic stressors such as salinity (Collard and Mackill, 2008).

MAS has been very useful in characteristics whose regulation is by one or a few dominant genes (oligogenic traits). One such use is gene pyramiding, whereby a series of resistance genes is piled into one cultivar to give broad-spectrum resistance to diseases like bacterial blight and blast in rice (Prabhu et al., 2009). The sensitivity of standard MAS, however, falls in the face of quantitative traits governed by many small-effect quantitative trait loci (QTLs), including yield and drought tolerance, because getting markers on all of the contributing loci is not realistic.

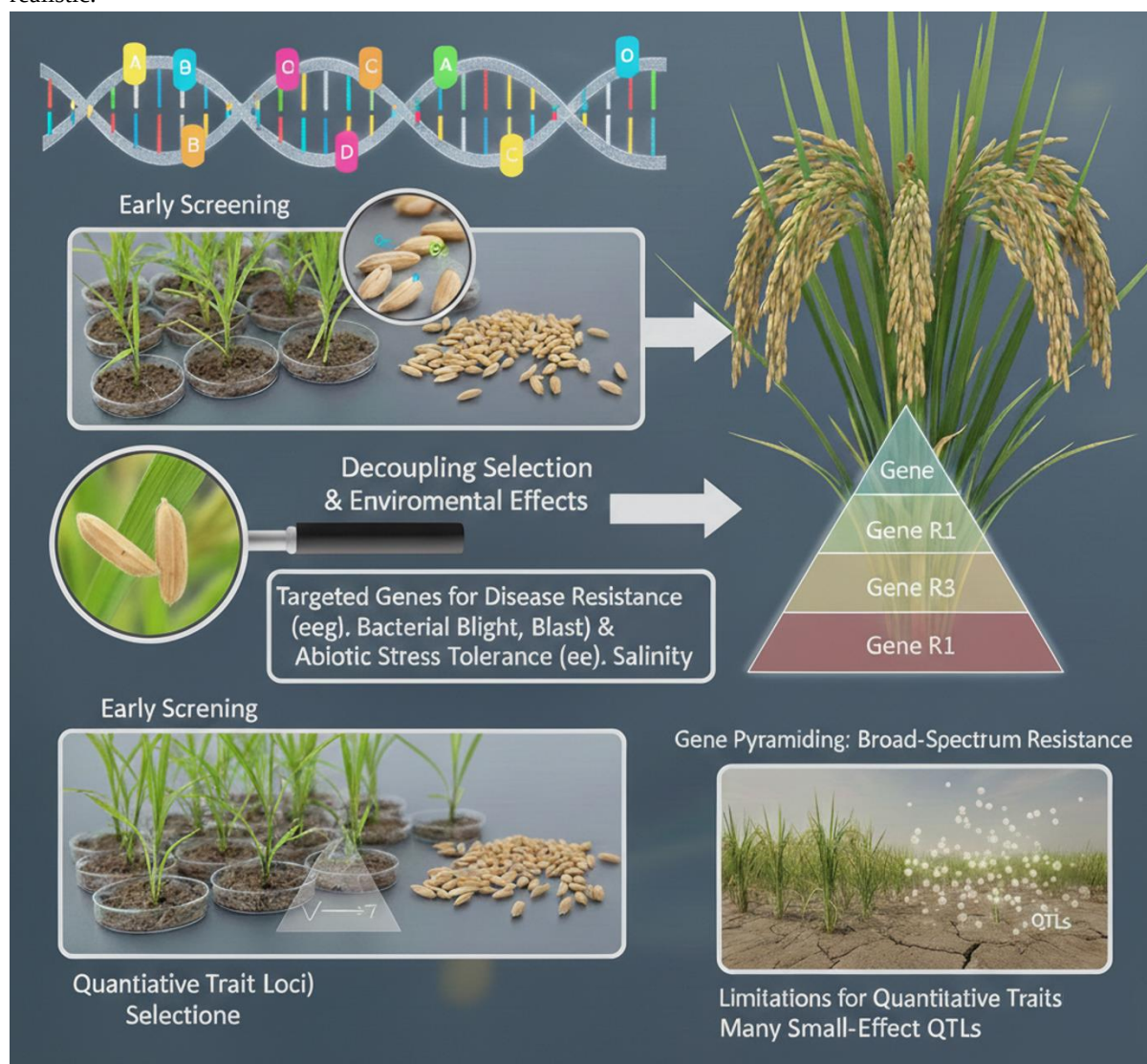


Figure 1. Conceptual Framework of Marker-Assisted Selection (MAS) in Crop

2.2 Genomic Selection (GS)

Genomic Selection was invented to address the shortcomings of MAS with polygenic traits. Whereas MAS uses a limited number of known markers, GS uses genome-wide markers to approximate the breeding value of an individual. It is done by training a statistical model with a reference population having the phenotypic data on the

trait of interest, as well as high-density genotypic data. This model computes the impact of all the markers at the same time to produce a Genomic Estimated Breeding Value (GEBV) of each individual. After validation, the model can forecast the performance of new breeding lines using only the genotypic profile of the lines, and phenotyping in the field is not required (Meuwissen et al., 2001).

GS is a game-changer that is used to enhance complex characteristics that are low in heritability. It predicts genetic merit better than phenotypic selection because it captures the cumulative genetic variation resulting from the use of thousands of markers to predict genetic variation across the genome. The greatest benefit of GS is the dramatic increase in the time required to complete the breeding cycle; breeders can now pick parental candidates to the next generation as soon as the genotypic data is available, and it does not require years of field testing. This is imperative in the creation of climate-resistant crops at a faster rate. The application of GS in major cereals, including wheat and maize, is profitable for improving the quantity of grain and its nutritional value and quantitative resistance to diseases (Crossa et al., 2017; Poland and Rutkowski, 2016). Table 1 gives a comparison of these breeding methods.

Table 4. Comparison of Conventional Breeding, Marker-Assisted Selection (MAS), and Genomic Selection (GS)

Feature	Conventional Breeding	Marker-Assisted Selection (MAS)	Genomic Selection (GS)
Basis of Selection	Phenotype (observable traits)	Genotype (markers linked to specific genes/QTLs)	Genotype (genome-wide markers estimating breeding value)
Primary Target Traits	Highly heritable, simple traits	Oligogenic traits (disease resistance, quality genes)	Polygenic, complex traits (yield, abiotic stress, quality)
Selection Stage	Often mature plant stage; requires a field environment	Seedling stage; independent of environment	Seedling stage; independent of environment
Breeding Cycle Time	Long (requires multiple generations of phenotypic evaluation)	Shorter (early selection reduces generation time)	Shortest (rapid cycling without phenotypic evaluation in later stages)
Cost Effectiveness	High phenotyping costs; low genotyping costs	Moderate genotyping costs; reduced phenotyping costs for specific traits	High initial genotyping costs; significantly reduced phenotyping costs

Note: Adapted from Collard & Mackill (2008) and Crossa et al. (2017).

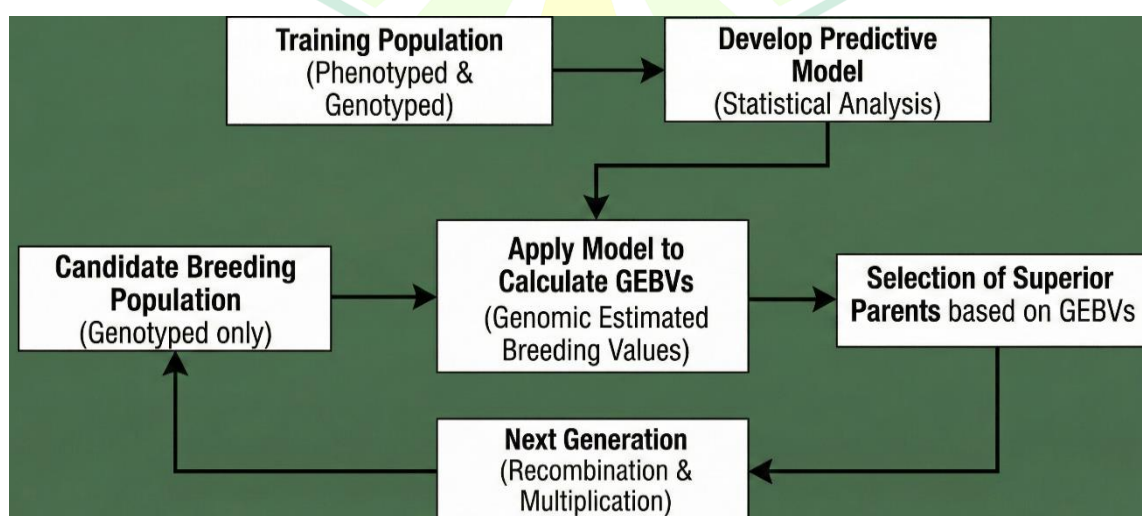


Figure 2. Schematic representation of a Genomic Selection (GS) breeding cycle.

3. Genome Editing

Although the Marker-Assisted Selection (MAS) and the Genomic Selection (GS) can improve the efficiency of utilisation and identification of the already existing genetic variation, the genome-editing technologies provide an opportunity to introduce new genetic variation in a more precise manner. One of these technologies, the CRISPR-Cas9 (Clustered Regularly Interspaced Short Palindromic Repeats/CRISPR-associated protein 9) system, has become a paradigm shift in plant biology due to simplicity, effectiveness, and versatility.

CRISPR-Cas9 is a type of molecule scissor that is directed by a synthetic RNA sequence to a defined locus in the plant genome, where Cas9 nuclease causes a double-strand break. This break is then resolved by endogenous repair machinery of the cell, which can be directed to produce precise mutations (such as insertions, deletions or base replacements) at the site of interest. Unlike traditional genetic engineering, which uses the translocation of foreign DNA between species, CRISPR-Cas9 can be used to alter endogenous genes, and the resulting plants are often indistinguishable from those with naturally occurring mutations. This difference has an important consequence on the systems of regulation in most jurisdictions.

4. Enhancing Biotic Stress Resistance:

Among the most successful applications is the establishment of disease-resistant cultivars by the knockout of the so-called susceptibility genes. Pathogens can also use the host proteins to gain entry, and so by destroying the gene that encodes these proteins, breeders can impart a broad spectrum and sustainable resistance. Indicatively, the alteration in the promoter region of SWEET genes in rice has resulted in bacterial blight-resistant plants that do not affect production (Oliva et al., 2019).

5. Improving Abiotic Stress Tolerance:

It is complicated to improve tolerance to abiotic stresses (drought, salinity and extreme temperature) as various signalling pathways are involved. CRISPR-Cas9 is used to alter the major regulatory genes, such as transcription factors, according to which the plant stress response is organised. The example is the knockout of the OsRR22 gene in rice that has been shown to significantly enhance salinity tolerance (Zhang et al., 2019).

6. Improving Nutritional and Industrial Quality:

Genome editing is an effective tool of biofortification and quality improvement of products. It has been utilised in creating high-amylose rice that has high health value, is able to increase the shelf life of tomatoes by editing the genes that are involved in ripening, and it has also been applied to help in improving the nutritional value of different crops. One such example is the creation of tomatoes that are enhanced with gamma-aminobutyric acid (GABA), which is associated with decreased blood pressure, by editing one of the repressive loci in the gene that produces GABA synthase (Nonaka et al., 2017).

Table 5. Selected Applications of CRISPR/Cas9 for Improving Quality and Stress Tolerance in Crops

Crop	Trait Improved	Gene Target / Mechanism	Reference
Rice	Bacterial Blight Resistance	Editing promoter of <i>OsSWEET11</i> , <i>OsSWEET13</i> , <i>OsSWEET14</i> (susceptibility genes)	Oliva et al. (2019)
Rice	Salinity Tolerance	Knockout of <i>OsRR22</i> (cytokinin type-B response regulator)	Zhang et al. (2019)
Wheat	Powdery Mildew Resistance	Simultaneous editing of three homoeoalleles of <i>MLO</i> (susceptibility gene)	Wang et al. (2014)
Tomato	Enhanced GABA Content	Deletion in C-terminal of <i>SIGAD2</i> and <i>SIGAD3</i> (glutamate decarboxylase enzymes)	Nonaka et al. (2017)
Maize	Drought Tolerance	Editing the promoter of the <i>ARGOS8</i> gene to enhance its expression	Shi et al. (2017)
Potato	Reduced Acrylamide Potential & Cold Storage Sweetening	Knockout of the <i>VInv</i> (vacuolar invertase) gene	Clasen et al. (2016)

7. Conclusion

The contemporary breeding of plants using molecular and genomic technology cannot be ignored to protect the world food system in the changing climate and surging population. Such methods as Marker-Assisted and Genomic Selection have brought breeding to predictive science, allowing facilitation of the effective improvement of simple and complex traits. At the same time, genome editing through CRISPR-Cas9 provides an

accurate platform on which genetic engineering can be performed, allowing one to develop specific traits that were previously unimaginable. These are the most effective methodologies that allow plant scientists and breeders to design high-quality and stress-tolerant crop varieties that are capable of supporting a sustainable and resilient agricultural future more than ever before.

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Animal Welfare Practices in Modern Livestock Production Systems



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1. Introduction

Enhanced livestock production systems in the last 50 years have been mainly shaped by the need to satisfy the nutritional needs of the fast-growing world population. This period of time focused on achieving high yields and feed ratio, which in many cases led to small housing conditions that are more convenient to the managerial needs, instead of meeting the behavioural needs of animals. Modern agriculture, however, is established around a repurposed social contract: modern livestock production is being subjected to an ever-growing scrutiny around animal welfare as a result of the growing scientific knowledge of animal sentience, the changing ethical trends and the increasing consumer consciousness.

Animal welfare is no longer seen as the lack of cruelty or disease only, but it is a multidimensional concept that is physically, physiologically, and psychologically constructed. The current agricultural paradigm accepts the notion that the best production results are often directly connected with high welfare standards. Chronic stress, which comes as a result of sterile conditions or failure to realise natural behaviour, undermines immune systems, decreases reproductive rates, as well as affecting growth rates. Therefore, incorporating sound animal welfare practices is not only an ethical responsibility and initiative, but a pillar of sustainable, efficient, and socially viable animal farming.

2. Evolving Frameworks

In the past, the UK Brambell Committee of the 1960s had provided the basis of assessing animal welfare under the banner of the so-called Five Freedoms. Such freedoms, which alleviate hunger/thirst, discomfort, pain/injury/disease, fear/distress, and provision of the opportunity to express normal behaviour, supplied important background instructions whose main emphasis was put on the prevention of negative conditions.

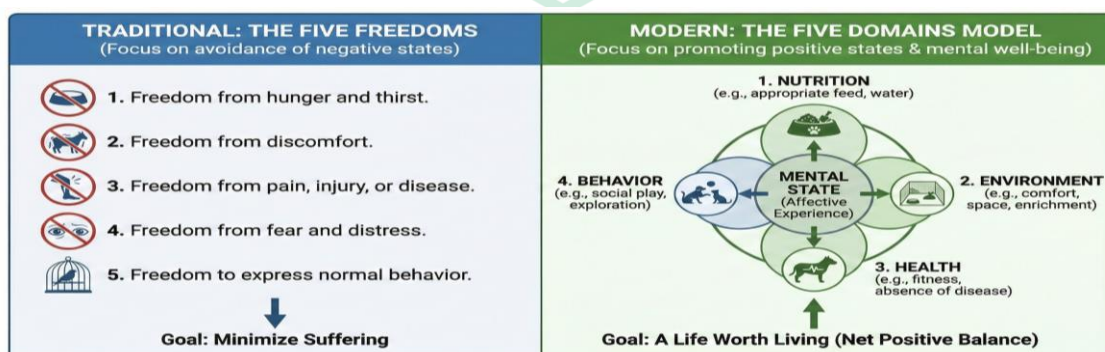


Figure 1. Comparison of Traditional (Five Freedoms) vs. Modern (Five Domains) Animal Welfare Frameworks.

Contemporary welfare science, however, claims that it is not adequate to minimise negative experiences. Modern models have moved to the Five Domains Model, which is promoted by Mellor and others. The model includes four physical/functional domains (nutrition, environment, health, behaviour) entered into a fifth domain: the overall mental state of the animal. More importantly, the Five Domains model focuses on encouraging positive affective states (including comfort, contentment, and playfulness) instead of reducing negative ones alone (Mellor et al., 2020)

This change of theory has practical implications for on-farm assessment. There is a very visible shift to the outcome-based, or animal-based, measures (ABMs), rather than the purely resource-based measures (e.g., stocking density, feeder space). ABMs measure the current condition of the animal (e.g. body condition scoring, lameness scoring, behavioural observations (e.g. stereotypies or positive social interactions). Resource measures are still important requirements of welfare, but ABMs will give conclusive evidence whether the resources have been put into practice to suit the needs of the animals.

Table 6. Comparison of Traditional vs. Modern Welfare Frameworks

Feature	The Five Freedoms (Traditional)	The Five Domains Model (Modern)
Primary Focus	Avoidance of negative states (suffering, deficit).	Promotion of positive states and minimisation of negative ones.
Scope	Mostly physical health and basic biological needs.	Integrates physical health with specific emphasis on mental state (affective experiences).
Assessment Basis	Often resource-based (inputs like space, feed).	Strongly outcome-based (animal-based measures).
Application	Basic compliance baseline.	Continuous improvement strategy.

3. Precision Livestock Farming (PLF) and Welfare Monitoring

Precision Livestock Farming (PLF) is a technology that dramatically increases the scalability of the high-welfare practices of intensive systems. PLF is based on the use of innovative technologies, sensors, cameras, microphones, and artificial intelligence (AI) algorithms, which allow continuous monitoring in real-time of a particular animal or a herd.

Historically, the assessment of welfare used to be based on human observation, which was a labour-intensive, subjective method limited to certain time points. The technologies of PFL provide round-the-clock, non-invasive surveillance, which makes it possible to timely identify welfare violations before they reflect on clinical illness or serious production losses (Berckmans, 2017). As an example, computer vision technology can be used to scan the gait of dairy cattle and identify lameness, an important issue of welfare and economic concern, in its early stages before it can be detected by a human observer. In the same manner, the acoustic method in pig barns is able to differentiate between coughs due to respiratory infection and ambient noise, which initiates early veterinary treatment. Optical flow technology can also be used to track the movement of a flock in poultry to detect problems with thermal comfort or resource allocation.

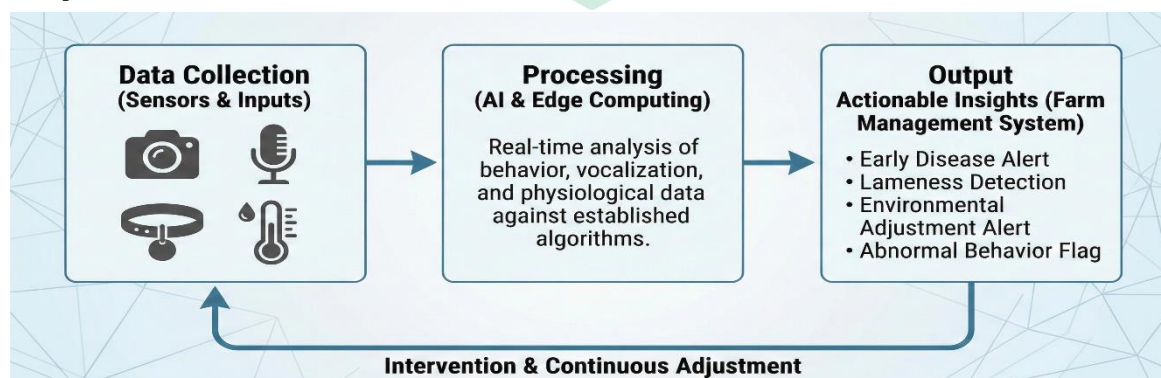


Figure 2. Workflow of PLF in Welfare Monitoring

PLF makes welfare indicators digital, thus turning the management perspective of treatment to prevention. The information gathered using these systems can be incorporated into farm management software, which would give the producers practical information to maximise the environmental factors and the treatment of individual animals.

4. Sector-Specific Innovations and Enrichment

The implementation of contemporary welfare science in livestock industries has significant differences because of the species-specific biological requirements and production conditions.

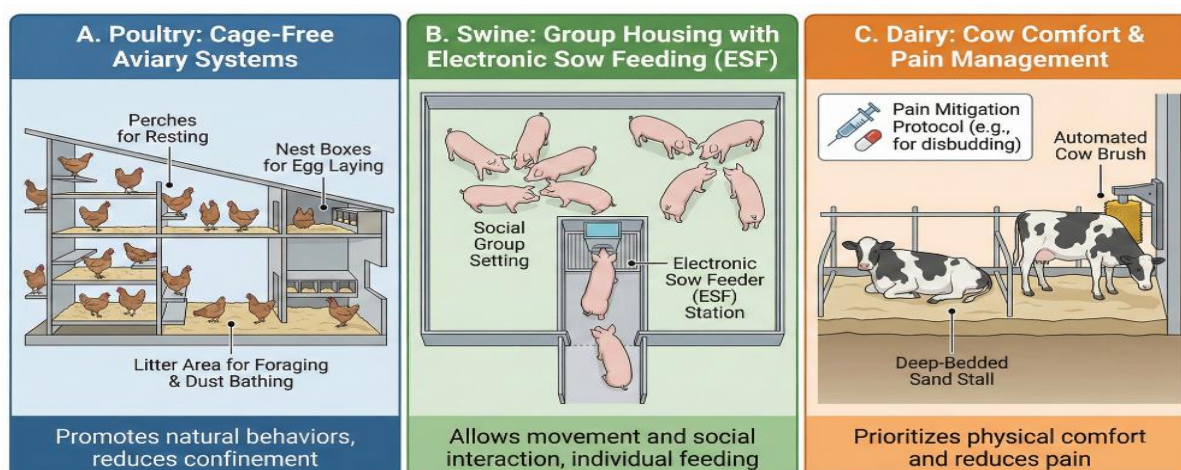


Figure 3. Examples of Sector-Specific Modern Welfare Innovations

4.1 Poultry Production

The worldwide egg sector is experiencing a significant shift from traditional battery cages to the cage-free (aviary or floor) frameworks. Although cage-free systems provide more expression of behaviour, including dusting-bathing, nesting and perching, they bring new welfare issues to be addressed by elaborate management.

The main issue with complex aviaries is that there are chances of fractures in the keel bones as a result of hitting the housing structures during the maneuver. Contemporary system design emphasises the number of ramps and the strategic location of perch to make movement safe. Also, bad environments must be enriched to avoid the injurious feather pecking, a displaced foraging behaviour in barren environments. Foraging can be enhanced by giving friable litter to peck at, and hanging items that would preoccupy the birds and minimise aggression (El-Letey et al., 2000).

The high growth rates in broilers have in the past been linked to cardiovascular problems and leg disorders. Increasingly modern methods make use of slower-growing genetic strains, which are not only more expensive to produce in terms of time but are also much more mobile, less mortal, and more naturally active.

4.2 Swine Production

The welfare issue of swine production has been the central one and is concerned with confinement, namely the gestation stalls of sows in pregnancy and farrowing crates of sows in lactation. Although these systems are supposed to optimise space efficiency and minimise crushing of piglets, the systems have a highly limiting effect on the movement of the sows as well as the normal nest-building behaviour of the sows, which causes chronic stress and stereotypies.

The current production is moving towards where a group of gestating sows are housed with electronic sow feeding (ESF) stations controlling the individual nutrition as a member of a social group. Farrowing crates are being overcome by different forms of pens known as free-farrowing. The designs are temporary confinement during the first days of critical and then grant piglets freedom of movement and expression of maternal behaviours during most of the lactation period (Baxter et al., 2012). In the case of growing-finishing pigs, attention is directed towards environmental enrichment to avoid tail-biting. To act as an outlet to the instinct of rooting and exploration

possessed by the pigs, it is necessary to provide them with manipulable materials, which can be straw, ropes or wood.

4.3 Ruminant Production

In the milk industry, cow comfort is a major issue of consideration. The development of tie-stall into free-stall or bedded-pack barns has increased the freedom of movement of the animals; however, the design of the stalls is one of the most important. Hock injuries and lameness in cattle are predisposed by poorly sized stalls or those poorly bedded. The modern facilities are more concerned with the deep-bedded stalls, mostly filled with sand and rubber flooring in the alleys, to dampen the concussive impacts on the hooves. The use of high-capacity fans and soakers adjusted to temperature-humidity indices (THI) to prevent heat-stress in the animals is a normal practice in high-yielding herds to keep the welfare of the animals during the hot weather.

One such area of improvement in ruminant welfare has been the administration of pain that is given before common husbandry practices, including disbudding of calves (dehorning). Local anaesthetic and non-steroidal anti-inflammatory drugs (NSAIDs) used both concurrently are currently becoming an industry practice and, in most jurisdictions, a regulatory requirement, making it an expression of a zero-tolerance attitude to preventable pain.

Table 7. Key Welfare Challenges and Modern Enrichment Solutions by Sector

Sector	Key Welfare Challenge	Modern System Adaptations & Enrichments
Laying Hens	Behavioural restriction (cages); Keel bone fractures (aviaries); Feather pecking.	Cage-free/aviary systems with ramps; Friable litter, pecking blocks, perches, nest boxes.
Broilers	Leg health/mobility due to rapid growth; Barren environments.	Slower-growing genetics; Straw bales, pecking objects, platforms for perching; Improved lighting protocols.
Swine (Sows)	Confinement stress (gestation/farrowing crates); Lack of nesting behaviour.	Group housing with ESF; Free-farrowing or temporary confinement pens; Nesting materials (straw, paper).
Swine (Growers)	Tail-biting; Aggression due to boredom/crowding.	Manipulable materials (chains, wood, ropes, straw racks); Increased space allowance.
Dairy Cattle	Lameness; Hock injuries; Heat stress; Mastitis.	Deep sand bedding; Rubber flooring; Automated fans/soakers; Cow brushes; Pain mitigation for disbudding.

5. Economic and Ethical Implications

There is always the economic cost of implementing high-welfare systems. Switching to cage-free, lowering stocking ratios, or enriching the environment generally increases the cost of production by adding capital or labour, or making only slight decreases in feed efficiency.

These costs, however, have to be put in perspective considering the economic benefits accrued by improved welfare. Healthier animals require less veterinary treatment and less antimicrobial treatment, have a lower mortality rate and often have a better-quality product, such as lower levels of somatic cells in milk. In addition, the precision livestock farming (PLF) technologies are capable of providing a good payback on investment by streamlining the labour force, which reduces devastating losses by detecting diseases at an early stage.

Ethically, the agricultural sector is under a so-called social licence. Continued prevalence of intensive livestock production will be dependent upon proven dedication to animal welfare, which is compatible with the current societal values. Any lack of welfare issues puts the industry at risk of reputation, regulatory oversight and a denial of market entry as the big food retailers progressively require high welfare procurement policies as a component of their corporate social responsibility (CSR) policies.

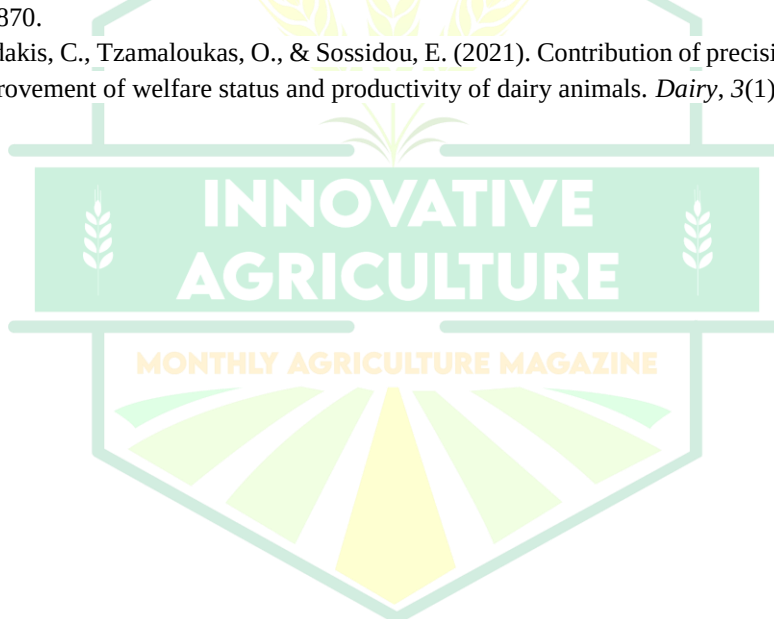
6. Conclusion

Animal welfare has ceased to be a fringe benefit to livestock production, and it is an inherent part of modern sustainable farming. The change of the Five Freedoms into the Five Domains is also an indication of the growing understanding of science that animals need more than just to survive to experience positively: they also need environments where positive experiences can be achieved.

Precision livestock farming, alongside sector-specific housing innovations and additions mean that the stakeholders have the tools to address welfare at scale and monitor it. As much as economic issues may come with such a system change, the future viability of the livestock industry is pegged on the ability to compromise productive efficiency and ethical responsibility. The proposed areas of future development will be the ability to refine the algorithms of PLF in order to better evaluate positive affective states and to further incorporate welfare indicators into holistic sustainability measurements.

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Building Climate-Smart Food and Dairy Systems for Nutritional Security



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India today stands at a critical crossroads. On one hand, it must feed and nourish a population of over 1.4 billion; on the other, it faces growing climate uncertainty marked by erratic monsoons, rising temperatures, frequent droughts, floods, and heat stress. Climate change is no longer a distant threat—it is already reshaping how food is grown, processed, distributed and consumed. In this changing scenario, ensuring nutritional security requires a fundamental transformation towards climate-smart food and dairy systems. Food security alone is no longer sufficient. The challenge before India is to ensure safe, nutritious, affordable, and climate-resilient food, with dairy playing a central role in nutrition, livelihoods, and rural resilience.

1.1 Climate Change and the Nutrition Challenge

Climate change directly affects the availability, quality, and diversity of food. Reduced crop yields, nutrient loss in soils, water scarcity, and increased pest and disease pressure threaten the nutritional value of staple foods. Studies show that elevated temperatures and CO₂ levels can reduce protein, zinc and iron content in cereals and pulses - nutrients that are already deficient in large sections of the population.

At the same time, climate stress affects livestock productivity. Heat stress reduces milk yield, fertility, and animal health, impacting both income and nutrition. For millions of Indian households, milk is the most reliable source of high-quality protein, calcium, and micronutrients. Protecting dairy systems is therefore critical for national nutritional security.

1.2 Climate-Smart Food Systems: A System's Approach

Climate-smart food systems go beyond farm-level interventions. They integrate production, processing, storage, distribution, and consumption ensuring resilience at every stage.

1.2.1 Climate-Resilient Crops and Diversification

Indian agricultural research institutions under ICAR have developed drought, flood and heat-tolerant varieties of rice, wheat, millets, pulses, and oilseeds. Promoting nutri-cereals such as millets rich in fibre, iron, and calcium not only enhances nutrition but also reduces climate risk due to their low water requirement and high stress tolerance.

Government initiatives like the National Food Security Mission (NFSM) and POSHAN Abhiyaan increasingly recognize the importance of crop diversification for nutrition and resilience.

1.2.2 Ecologically Sustainable Farming Practices

Climate-smart practices such as conservation agriculture, crop residue management, organic amendments, and efficient water use improve soil health and nutrient availability. Healthy soils are the foundation of nutritious food.

1.3 Food Science and Nutrition: Protecting Value Beyond the Farm

Climate resilience must extend beyond production to **food processing and storage**. Post-harvest losses due to heat, humidity, and poor infrastructure directly reduce food and nutrient availability.

1.3.1 Climate-Smart Food Processing

Food science and technology play a key role in:

- Fortification of staples (milk, flour, oil)
- Value addition to cereals, millets, fruits, and milk
- Developing climate-resilient storage and packaging

- Reducing spoilage and food waste

Fortified milk and dairy products, promoted under government nutrition programmes, are powerful tools to address micronutrient deficiencies.

1.3.2 Cold Chains and Storage

Climate-smart cold chains reduce losses in fruits, vegetables, and dairy, ensuring quality nutrition reaches consumers. Investments under schemes like PM Kisan Sampada Yojana are critical in this regard.

1.4 Dairy Systems: The Nutrition Backbone

India is the world's largest milk producer, and dairy contributes significantly to rural livelihoods, especially for small and marginal farmers and women. Climate-smart dairy systems are therefore essential.

1.4.1 Heat-Resilient Dairy Management

Rising temperatures severely affect dairy animals. Climate-smart interventions include:

- Improved housing with ventilation and cooling
- Heat-tolerant breeds and crossbreeds
- Balanced feeding and mineral supplementation
- Efficient water management

These practices help sustain milk yield and quality even under heat stress.

1.4.2 Climate-Smart Fodder and Feed Systems

Fodder scarcity is a major climate-related challenge. Promoting drought-tolerant fodder crops, silage making, hydroponic fodder, and crop-livestock integration ensures year-round feed availability and stable milk production.

1.4.3 Low-Emission and Resource-Efficient Dairy

Improved feed efficiency, manure management, and biogas units reduce greenhouse gas emissions while generating renewable energy and organic manure—benefiting both climate and farmers.

1.5 Research and Innovation Imperatives

Indian research institutions are central to building climate-smart food and dairy systems. Programs like NICRA (National Innovations in Climate Resilient Agriculture) demonstrate how integrated approaches—combining crops, livestock, water, and nutrition can reduce vulnerability at the village level. Emerging technologies such as climate-based decision support systems, AI-enabled nutrition planning, precision dairy management and digital traceability in food supply chains are opening new pathways for resilience and efficiency.

1.6 Communication: Turning Science into Nutrition Security

Research and technology achieve impact only when effectively communicated. Farmers, dairy producers, processors, and consumers must understand and adopt climate-smart practices.

1.6.1 Weather based Farm Advisory Services

IMD's **Gramin Krishi Mausam Sewa (GKMS)** links weather forecasts with crop and livestock advisories, helping farmers take timely decisions that protect both yield and nutritional quality.

1.6.2 Digital Platforms and Outreach

Mobile apps, SMS alerts, community radio, KVK networks, and Farmer Producer Organisations (FPOs) play a vital role in spreading climate-smart food and dairy practices.

1.6.3 Consumer Awareness and Behaviour Change

Nutrition security also depends on informed consumers. Promoting climate-friendly diets—rich in millets, pulses, fruits, vegetables, and dairy—supports both health and sustainability.

1.7 Integrating Policies for Climate and Nutrition

India has a strong policy ecosystem that must work in convergence:

- **National Mission for Sustainable Agriculture (NMSA)**
- **National Dairy Plan and Rashtriya Gokul Mission**
- **POSHAN Abhiyaan**
- **PMFBY and PMKSY**

Aligning climate resilience with food and nutrition policies ensures maximum impact.

1.8 Looking Ahead

Building climate-smart food and dairy systems requires:

- A shift from yield-centric to nutrition-centric agriculture
- Strong integration of crops, dairy, and food processing
- Continued investment in research and innovation
- Robust communication and extension systems
- Active participation of farmers, women, youth, and consumers

Climate resilience must be viewed not as a cost, but as an investment in national health, livelihoods, and sustainability. In an era of climate uncertainty, nutritional security cannot be left to chance. Climate-smart food and dairy systems offer a powerful pathway to protect both people and the planet. By harmonizing resilient agriculture with advanced food science, dairy technology and strategic communication, India can convert climate adversity into an engine of opportunity viz., delivering healthier diets, fortified rural livelihoods, and truly sustainable development. The transition from climate-smart fields to nutritious plates is not merely a scientific or policy ambition; it stands as a defining national imperative for the future.



Artificial Intelligence and Machine Learning Applications in Agronomy



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1. Introduction

Agriculture is experiencing an immense shift due to the digital technologies implementation, which can be called Agriculture 4.0. Artificial Intelligence (AI) and Machine Learning (ML) are the leaders of this revolution that transforms the conventional agronomic systems into data-driven, precise, and efficient ones. Agronomy, the science of managing soil and producing crops, is a science that will beneficially gain out of these improvements since it is faced with unknown global challenges. Both the pressure of the growing global population, which is projected to reach almost ten billion in 2050, and the complex effects of climate change require a paradigm shift to more sustainable and productive agricultural systems that will optimise resource utilisation and reduce footprint effects on the environment.

The term AI, which can be broadly defined as the ability of a machine to simulate intelligent human behaviour, has several subfields. One of its key subdivisions is Machine Learning, which consists of the creation of algorithms to allow computers to acquire patterns based on data and make predictions or choices without being programmed to perform a particular task. These technologies are very useful in the analysis of large and complicated data that are being gathered in different formats, such as satellite images, unmanned aerial vehicles (UAVs), on-site soil and weather sensors, and past records of crops within the context of agronomy. Using this big data, AI, and ML models can find the latent insight, automate the intricate decision-making procedures and give farmers and agronomists recommendations to be taken in a manner that is more precise than ever before. This paper is a systematic review of the main uses of AI and ML in agronomy, including precision agriculture, monitoring of crop health, resource management, and prediction of yield, and also the challenges and future opportunities.

2. Precision Agriculture through Remote Sensing and Data Integration

Precision agriculture is one that seeks to control the variability of fields so as to maximise efficiency and yield. This approach has made the interconnection between remote sensing technology and machine learning algorithms one of the pillars. Current satellite constellations and UAVs have multispectral, hyperspectral, and thermal cameras that produce massive amounts of geospatial data that can measure the temporal and spatial heterogeneity of agricultural landscapes. The traditional ways of analysing this imagery used to be usually manual, time-consuming and subject to human error. ML algorithms, especially deep learning models like Convolutional Neural Networks (CNNs) and ensemble models like Random Forests (RFs), have shown greater abilities when it comes to processing these complex datasets in an array of agronomic tasks.

Land-use classification and crop mapping are two of its major applications. The precise maps of the types of crops and their spatial distribution are critical in agricultural planning, distribution of resources and estimation of yield at regional levels. Deep learning architectures are able to automatically identify agricultural fields against the rest of the land use and identify particular crop varieties with high precision by learning based on spatial patterns and context of high-resolution imagery. In addition, tracking vegetation indices like the Normalised Difference Vegetation Index (NDVI) in time enables ML models to determine the growth rates of crops, their health, and to identify the regions of stress due to nutrient deficiency or water shortage. This field-level, granular

data enables farmers to apply variable-rate technology (VRT) to apply inputs, including fertilisers, pesticides, and water, accurately and therefore minimise waste and environmental damage and maximise crop production.

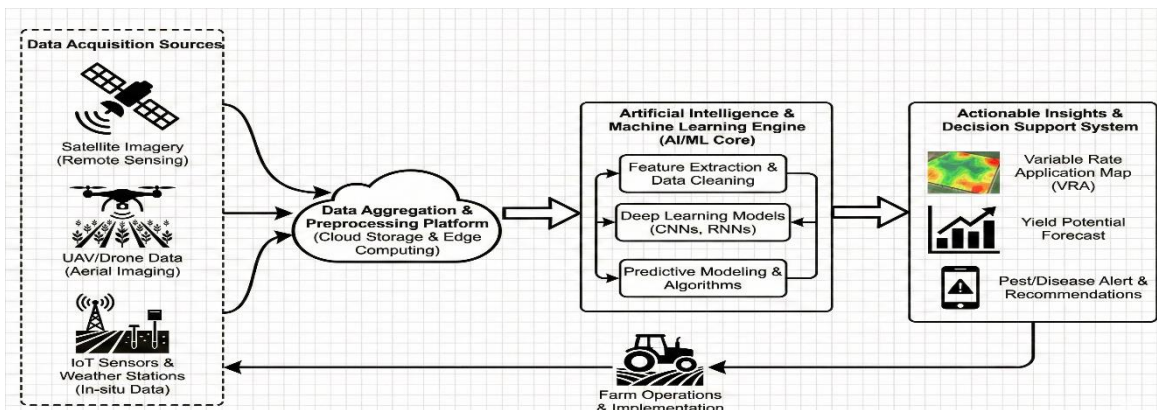


Figure 1: Conceptual Data Flow in AI-Driven Precision Agriculture

3. Crop Disease and Pest Detection Using Computer Vision

Plant diseases and pests are some of the biggest threats to international food security, leading to a high level of losses in annual yields. The conventional disease-detecting systems are still based on manual surveillance using trained agronomists who make use of manual scouting, which is labour-intensive and subjective and in most cases is unable to monitor extensive areas with the frequency of taking early action. One of the branches of AI that can help machines read and comprehend visual images in the real world is computer vision, which provides a groundbreaking solution to automated and early detection of health problems in crops.

Using the method of deep learning, especially CNN, computer vision algorithms can be trained on large collections of image data with healthy and diseased leaves of plant species (stems, fruits). These models are trained to identify minute visual and texture as well as patterns of certain pathogens or pest infestations, which otherwise would not be visible to the human eye. Indicatively, neural networks that have been trained on image datasets like PlantVillage that include tens of thousands of annotated pictures of leaves on various crops have demonstrated classification accuracy on par with, or even surpassing, human specialists. These artificial intelligence-based systems may be implemented on different platforms, namely smartphone applications to perform diagnosis on the spot for farmers and drone-based imaging systems to scan entire fields. This will enable quick and precise response and will minimise the necessity of spraying pesticides, as well as diminish the threat of large-scale epidemics.

Table 8. Comparison of Traditional and AI-Based Computer Vision Methods for Crop Disease Detection

Feature	Traditional Manual Scouting	AI-Based Computer Vision
Detection Basis	Visual inspection by human experts, relying on visible symptoms.	Automated image analysis using deep learning algorithms to identify visual patterns.
Speed and Scalability	Slow, labour-intensive, and limited by human availability. Difficult to scale to large farms.	Rapid, automated, and highly scalable. Can process thousands of images from drones or phones quickly.
Early Detection	Often detects diseases only after significant visible symptoms appear.	Potential for earlier detection by identifying subtle changes not easily seen by humans.
Accuracy and Consistency	Subjective, prone to human error, fatigue, and varying levels of expertise.	High consistency and accuracy once scientifically validated; not susceptible to fatigue.
Cost	High operational costs due to labour and time requirements.	High initial development cost, but lower long-term operational costs per unit area.
Data Utilization	Reliance on individual knowledge and experience; data is often not digitised.	Leveraging vast datasets for continuous model training and improvement; data is digital and shareable.

4. Smart Irrigation and Water Resource Management

Water scarcity is a serious problem in the world, and agriculture is the biggest user of freshwater resources. Traditional irrigation techniques tend to have a fixed timing scheme or a subjective evaluation that, in turn, results in under-irrigation that causes crop stress, or over-irrigation and wastage of water and energy. Machine learning-driven smart irrigation systems provide a data-centred method of streamlining the use of water.

They are systems that combine real-time information from soil moisture sensors, weather stations (measuring temperature, humidity, precipitation, wind speed), and crop physiological information. This multivariate data is analysed with ML algorithms, e.g. Support Vector Machines (SVM), K-Nearest Neighbours (KNN) or neural networks, to model the soilplant atmosphere interactions. The models can calculate the timing and amount of irrigation by forecasting the need for the soil water content and the crop evapotranspiration. This predictive potential enables independent regulation of the irrigation plans so that crops are only provided the maximum water as demanded. Research has shown that smart irrigation that utilises ML can achieve considerable water-saving (usually 20-30 per cent.), without affecting crop productivity, and thus improving water-use efficiency and water sustainability of agriculture.

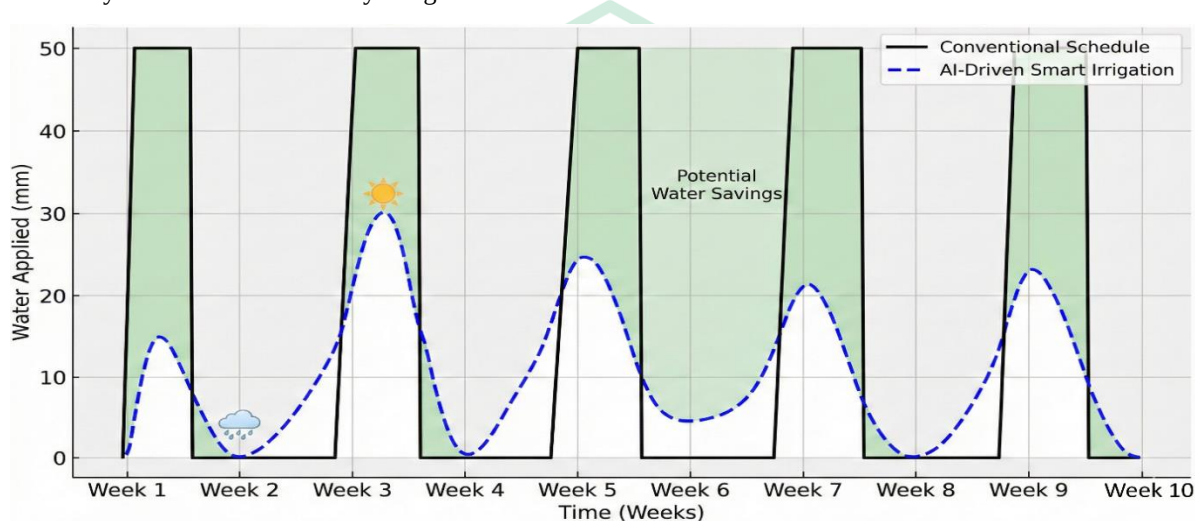


Figure 2. Conceptual Comparison of Conventional vs. AI-Driven Smart Irrigation Schedules

5. Crop Yield Prediction and Improvement

Precise forecasts of crop yield are a central element of food security planning, stability in the commodity market, and the operational decisions deciding the harvest logistics, post-harvest storage, and marketing plans. Crop yield is a complex phenotype that is controlled by several interacting determinants, comprising genotype, edaphic traits, meteorological conditions, agronomic activities and biotic stressors. Traditional yield prediction models are still based on empirical relationships that are simplistic in nature and are often incapable of capturing the non-linear relationships that are inherent in agronomic systems.

Machine learning methods are specifically in a good position to overcome these issues because of their ability to work with high-dimensional data and capture complex and non-linear relationships. Using longitudinal yield records along with a large amount of environmental and management data, the ML algorithms can be trained to give more precise crop yield predictions. These models are useful in determining the regionally specific yield determinants in different climatic conditions, and thus can help farmers to fine-tune their management approaches. Furthermore, artificial intelligence is becoming more and more significant in the breeding of plants. In addition to Mendelian genetics, ML models can be used to interrogate genotypic and phenotypic data in order to identify complex genetic markers that can be associated with desirable traits, including drought tolerance, disease resistance, and increased yield potential. This shortens the breeding cycle and allows more successful parent-line selection and more accurately predicts the results of cross-breeding.

6. Challenges and Future Directions

Despite its great potential, numerous key hurdles have blocked the popularisation of AI and ML in the agronomy domain. The first of these is the limited availability and inadequate quality of data. The creation of strong ML models requires large, heterogeneous, and high-fidelity datasets that have complete coverage of the varied types of crops, soils, and agro-climatic conditions. The scattered nature of agricultural data, the lack of proper standardisation, and the silo-bound nature make the need to rapidly develop open-data initiatives and create standardised data acquisition and distribution protocols a paramount concern.

A second major challenge is the digital divide and infrastructure barriers, especially in the developing world. Poor broadband connectivity, insufficient access to computational resources, and the lack of technical skills are some of the limiting factors to implementing and maintaining AI systems in rural areas. These constraints are made worse by high initial capital costs that sensors, unmanned aerial vehicles and software platforms demand, making them unaffordable to small-holder farmers.

In addition, their opaque nature, primarily of many advanced ML models, particularly deep neural networks, is also an obstacle to trust and use. In order to make decisions, practitioners need clear descriptions of AI-generated recommendations. The creation and implementation of explainable AI (XAI) procedures that provide interpretable evidence is thus important to instil a sense of confidence among users. Responsibility, ownership, and liability in case of AI failures should also be stipulated and implemented as regulatory measures related to data privacy concerns.

In the future, the potential future path of AI application in agronomy is the development of built-in and autonomous systems. This includes AI and robotics coming together to automate field tasks, edge computing being used to perform local data processing and avoid reliance on cloud connectivity, and coming up with more generalisable models that can be trained on to operate in new environments with little retraining. The joint effort of researchers, technology developers, policymakers, and the farming segment will be essential to overcome the existing challenges and realise the full potential of AI to transform the agriculture industry by enabling sustainable growth.

7. Conclusion

Machine Learning and Artificial Intelligence have become the powerful driving forces of innovation in the agronomy sector as they provide it with the opportunity to transform agricultural productivity, sustainability, and resilience like never before. Macro-scale, satellite-based crop surveillance at the macro-scale, through to the micro-scale of plant pathology detection and the fine control of soil moisture, these technologies are driving a paradigm shift in tradition-based, blanket cultivation to the less traditionally-based, data-driven, site-specific cultivation. Despite the problems associated with data quality, infrastructural support, and trust, the endless development of AI algorithms, along with specific investment and enabling policy frameworks, promises the opening of new opportunities in the field of agricultural science. An effective adoption of AI in agronomy is not only a techno-development but also a necessary evolutionary phase in the protection of the world's food systems under the conditions of the 21st century world.

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Carbon Smart Horticulture for Climate Change Mitigation



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Abstract

Horticultural systems represent a critical yet underutilized frontier in climate change mitigation strategies. Carbon smart horticulture integrates climate-conscious production practices, carbon sequestration techniques, and adaptive management to transform fruit, vegetable, and ornamental production systems from carbon sources into carbon sinks. This article examines the scientific principles, practical methodologies, and real-world applications of carbon smart horticulture, demonstrating how strategic management of soil organic matter, perennial crops, agroforestry integration, and reduced-emission technologies can simultaneously enhance productivity, profitability, and planetary health. With horticulture occupying approximately 20 million hectares globally and contributing 25% of agricultural value, the sector's transition toward carbon neutrality represents both an urgent necessity and an extraordinary opportunity.

Keywords: Carbon Sequestration, Climate-Smart Agriculture, Soil Organic Carbon, Horticultural Systems, Greenhouse Gas Mitigation, Agroforestry

1. INTRODUCTION: THE HORTICULTURAL PARADOX

Horticulture finds itself at a paradoxical junction in the 21st century. On one hand, intensive horticultural production systems—greenhouses, orchards, vineyards, vegetable farms—are substantial contributors to greenhouse gas (GHG) emissions through fossil fuel consumption, fertilizer manufacture, refrigeration, and transportation (Hillier et al., 2009). The carbon footprint of a single kilogram of tomatoes grown in a heated greenhouse can exceed 9 kg CO₂-equivalent (CO₂e), comparable to many industrial processes.

On the other hand, horticultural systems possess unique characteristics that position them as powerful climate change mitigation tools:

1. **High Biomass Production:** Fruit trees, berry crops, and perennial vegetables sequester significant carbon in woody tissues and extensive root systems (Montanaro et al., 2017).
2. **Intensive Management:** Unlike extensive grain systems, horticultural operations receive regular inputs and attention, enabling rapid adoption of carbon-enhancing practices.
3. **High Economic Value:** Premium prices for horticultural products justify investments in sustainability infrastructure that would be economically prohibitive in commodity agriculture.
4. **Consumer Connectivity:** Direct farm-to-consumer relationships in many horticultural sectors create market demand for carbon-neutral products.

Carbon smart horticulture emerges as the systematic approach to redesigning horticultural production through the lens of carbon management. Defined by Lal et al. (2011) as "the deliberate manipulation of agricultural systems to enhance carbon sequestration while maintaining or improving productivity," this paradigm shift requires rethinking everything from cultivar selection to post-harvest handling.

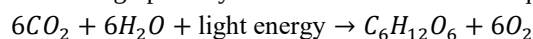
The stakes are substantial. Agriculture contributes approximately 24% of global GHG emissions (IPCC, 2019), yet holds the technical potential to sequester 2-4 gigatons of CO₂ annually through improved management (Paustian et al., 2016). Horticultural systems, with their intensive management and long-lived perennial crops, can contribute disproportionately to this potential.

2. THE CARBON CYCLE IN HORTICULTURAL SYSTEMS

Understanding carbon smart horticulture requires mastery of the carbon cycle within agricultural contexts. Unlike natural ecosystems that tend toward carbon equilibrium, managed horticultural systems experience constant carbon flux.

2.1 Carbon Inputs

Carbon enters horticultural systems through photosynthesis. The fundamental equation:



Captured carbon is allocated to:

- **Harvested products** (leaves, fruits, tubers): This carbon exits the system, representing a "neutral" flow as it was recently atmospheric.
- **Crop residues** (prunings, roots, unharvested biomass): Potential soil carbon input.
- **Root exudates**: Direct carbon transfer to soil microbial communities.
- **Perennial woody tissue**: Long-term sequestration in tree crops and vines.

2.2 Carbon Outputs

Carbon leaves horticultural systems through:

- **Soil respiration**: Microbial decomposition of organic matter (majority pathway)
- **Harvested biomass removal**: Fruits, vegetables, flowers exported from field
- **Erosion**: Physical loss of carbon-rich topsoil
- **Leaching**: Dissolved organic carbon movement through soil profile
- **Combustion**: Burning of crop residues (direct CO₂ emission)

2.3 The Carbon Balance Equation

For any horticultural system, the soil carbon balance can be expressed:

$$\Delta SOC = C_{input} - C_{output} - C_{respiration}$$

Where:

- **ΔSOC** = Change in soil organic carbon stock
- **C_{input}** = Carbon additions (residues, amendments, root turnover)
- **C_{output}** = Carbon removals (harvest, erosion, leaching)
- **C_{respiration}** = Microbial decomposition losses

Carbon smart management maximizes C_{input} while minimizing C_{output} and C_{respiration}.

3. FOUNDATIONAL STRATEGIES FOR CARBON SMART HORTICULTURE

The transition to carbon smart horticultural production rests on six foundational pillars:

3.1 Soil Organic Carbon Enhancement

Soil represents the largest terrestrial carbon reservoir, containing approximately 1,500 gigatons of carbon—more than the atmosphere and vegetation combined (Lal, 2004). In horticultural soils, organic carbon levels of 2-5% are common in well-managed systems, compared to 1-2% in annual cropping systems.

Key Practices:

Organic Amendment Application: Compost, aged manure, biochar, and cover crop residues increase soil C stocks. Meta-analysis by Aguilera et al. (2013) demonstrates that organic amendments increase SOC by 0.5-0.8 tons C per hectare per year in Mediterranean horticultural systems.

Biochar Integration: Pyrolyzed organic matter (biochar) is highly recalcitrant, with mean residence times exceeding 1,000 years. Application at 10-20 tons/ha can sequester 3-5 tons CO₂e annually while improving water retention and nutrient availability (Lehmann & Joseph, 2015).

Reduced Tillage: Conventional tillage accelerates organic matter decomposition by exposing protected carbon to microbial attack. No-till and strip-till systems in vegetable production reduce CO₂ emissions by 30-40% compared to moldboard plowing (Novara et al., 2019).

3.2 Perennial Crop Systems

Annual horticultural crops (vegetables, flowers) require annual soil disturbance, limiting carbon accumulation. In contrast, perennial systems (orchards, vineyards, berry plantations, asparagus) build carbon continuously.

Carbon Sequestration Rates:

- **Apple orchards:** 2-4 tons C/ha/year (Scandellari et al., 2016)
- **Olive groves:** 1.5-3 tons C/ha/year (Nieto et al., 2010)
- **Vineyards:** 1-2 tons C/ha/year in biomass + 0.5-1 ton/ha/year in soil
- **Citrus plantations:** 3-5 tons C/ha/year (Martínez-Alcántara et al., 2012)

3.3 Agroforestry Integration

Alley cropping (vegetables or flowers between tree rows) and **multi-strata systems** (combining canopy trees, understory shrubs, and ground crops) maximize volumetric carbon capture. Horticultural agroforestry systems can sequester 5-10 tons C/ha/year while diversifying farm income (Nair et al., 2009).

Example: Coffee grown under shade trees (traditional "coffee forest") sequesters 95 tons C/ha in biomass, compared to 30 tons C/ha in sun coffee systems (Soto-Pinto et al., 2010).

3.4 Precision Resource Management

Inefficient resource use generates emissions without productivity benefit:

Precision Irrigation: Soil moisture sensors and deficit irrigation strategies reduce energy consumption for water pumping by 20-30% while maintaining yield (Romero et al., 2012).

Targeted Fertilization: Synthetic nitrogen fertilizer production is energy-intensive (1.2 kg CO₂e per kg N), and excess application leads to nitrous oxide (N₂O) emissions—a GHG 298 times more potent than CO₂. Precision nutrient management based on tissue testing and soil analysis can reduce N application by 25% without yield loss (Tilman et al., 2002).

3.5 Renewable Energy Integration

Protected horticulture (greenhouses, high tunnels) requires substantial heating in temperate climates. Carbon smart alternatives include:

- **Geothermal heating:** Ground-source heat pumps
- **Biomass boilers:** Combustion of carbon-neutral pruning waste
- **Solar thermal collectors:** Passive greenhouse heating
- **Combined heat and power (CHP):** Efficient conversion of biogas from farm waste

These technologies can reduce greenhouse heating emissions by 60-90% (Gruda et al., 2019).

3.6 Carbon-Efficient Post-Harvest Systems

Post-harvest handling, storage, and transportation represent 30-50% of horticultural carbon footprints. Strategies include:

- **Local marketing:** Reducing food miles
- **Energy-efficient cold storage:** LED lighting, variable-speed compressors, high-efficiency insulation
- **Modified atmosphere packaging:** Extending shelf life to reduce food waste (which itself is a carbon source)

4. MEASUREMENT AND VERIFICATION

Credible carbon management requires robust quantification. Unlike afforestation projects with well-established methodologies, horticultural carbon accounting faces unique challenges due to high spatial heterogeneity and annual cropping cycles.

4.1 Soil Carbon Measurement

The Depth Question: Most protocols measure SOC to 30 cm depth, but many horticultural practices (deep tillage, tree roots) affect carbon stocks to 60-100 cm. Failure to account for subsoil carbon leads to underestimation of sequestration potential.

Sampling Intensity: Due to spatial variability (CV often 30-50%), minimum sampling densities of 1 core per 0.5-1 hectare are required for statistically robust estimates (Goidts & van Wesemael, 2007).

Equivalent Soil Mass Method: Simple depth-based sampling can introduce error when bulk density changes over time. The equivalent soil mass approach (comparing carbon stocks in the same mass of soil, rather than the same depth) provides more accurate change detection (Ellert & Bettany, 1995).

4.2 Above-Ground Biomass

Allometric Equations: For tree crops, destructive sampling is impractical. Instead, allometric models relate easily measured parameters (trunk diameter, canopy volume) to total biomass carbon. Species-specific equations have been developed for major horticultural crops (Montanaro et al., 2017).

4.3 GHG Flux Measurements

Eddy Covariance Towers: These micrometeorological stations measure real-time CO₂ exchange between the crop canopy and atmosphere at the field scale. While expensive, they provide the "gold standard" for net ecosystem carbon balance (Baldocchi, 2014).

Chamber-Based Methods: Portable flux chambers measure soil CO₂, CH₄, and N₂O emissions at point locations. Spatially distributed measurements provide field-scale estimates through geostatistical interpolation.

TABLE 1: Carbon Sequestration Potential of Major Horticultural Systems

Horticultural System	Soil Sequestration (tons C/ha/year)	Biomass Accumulation (tons C/ha/year)	Total Sequestration (tons C/ha/year)	Time to Equilibrium (years)
Annual Vegetables (Conventional)	0 to -0.5 (often net loss)	0 (all harvested)	-0.5 to 0	N/A (constant disturbance)
Annual Vegetables (No-Till + Cover Crops)	0.3 to 0.8	0	0.3 to 0.8	15-25
Berry Plantations (Blueberry, Raspberry)	0.5 to 1.2	0.8 to 1.5	1.3 to 2.7	10-15
Vineyards (Mature)	0.3 to 0.7	0.6 to 1.2	0.9 to 1.9	15-30
Apple/Pear Orchards	0.8 to 1.5	1.5 to 3.0	2.3 to 4.5	20-40
Citrus Groves	1.0 to 2.0	2.0 to 3.5	3.0 to 5.5	25-50
Olive Groves (Traditional)	0.6 to 1.2	0.8 to 1.8	1.4 to 3.0	30-80
Horticultural Agroforestry	1.5 to 3.0	3.5 to 7.0	5.0 to 10.0	40-100

Note: Rates vary substantially based on climate, soil type, and management intensity. Values represent well-managed systems with active carbon enhancement strategies. Negative values indicate net carbon loss. Sources: Compiled from Lal (2004), Montanaro et al. (2017), Nieto et al. (2010), Nair et al. (2009).

5. CASE STUDIES: CARBON SMART HORTICULTURE IN PRACTICE

5.1 The Carbon-Positive Vineyard: Napa Valley, California

A 40-hectare premium wine estate in Napa Valley implemented a comprehensive carbon smart program:

Interventions:

- Conversion to organic viticulture (eliminating synthetic fertilizer emissions)
- Cover crop mixes (legumes + grasses) in row middles year-round
- Compost application at 10 tons/ha every 3 years
- Solar panels providing 80% of winery electricity
- Electric tractors for vineyard operations

Results (5-year monitoring):

- Soil organic carbon increased from 1.8% to 2.6% (0-30cm depth)
- Net sequestration: 3.2 tons CO₂e/ha/year
- Total estate emissions: 1.1 tons CO₂e/ha/year
- Net carbon balance: -2.1 tons CO₂e/ha/year (carbon negative)

Economic outcome: Carbon-neutral certification commanded 15% price premium for wine, providing 3:1 return on investment for carbon program (Steenwerth et al., 2015).

5.2 Biochar in Tropical Vegetable Production: East Africa

Smallholder vegetable farmers in Kenya tested biochar produced from agricultural waste:

Protocol:

- Biochar application: 15 tons/ha (one-time)
- Crop: Cabbage-tomato rotation
- Comparison: Conventional fertilizer vs. biochar + 50% fertilizer

Outcomes:

- Biochar plots sequestered 6.8 tons C/ha (stable fraction)
- Yield increase: 28% (due to improved water retention)
- Fertilizer cost reduction: 45%
- N₂O emissions decreased by 52%

This demonstrates carbon sequestration can align with food security and farmer profitability goals (Kimetu et al., 2008).

5.3 Climate-Smart Citrus: Spain's Regenerative Model

A consortium of citrus growers in Valencia transformed conventional plantations:

System redesign:

- Biodiversity corridors (native trees) along field boundaries
- Drip irrigation with fertigation (precision nutrient delivery)
- Biological pest control (eliminating pesticide manufacturing emissions)
- Mulching with shredded pruning residues instead of burning
- Sheep grazing in orchards (reducing mowing fuel use, adding manure)

Results (10-year study):

- Soil carbon stocks increased 1.4 tons C/ha/year
- Biomass carbon in trees and hedgerows: +2.8 tons C/ha/year
- Operational emissions reduced 65%
- Net carbon balance shifted from +3.5 tons CO₂e/ha/year (source) to -1.8 tons CO₂e/ha/year (sink)

Additional benefit: Enhanced pollinator habitat increased fruit set by 12% (Aguilera et al., 2020).

6. TECHNOLOGICAL ENABLERS

6.1 Precision Agriculture Technologies

Soil Carbon Sensors: Portable visible-near infrared (vis-NIR) spectrometers can predict SOC content in seconds, enabling high-density spatial mapping of carbon stocks for monitoring purposes (Viscarra Rossel et al., 2006).

Remote Sensing: Satellite imagery (Sentinel-2, Planet Labs) provides temporal NDVI data correlating with biomass accumulation. Machine learning models translate NDVI trajectories into carbon stock estimates (Gómez et al., 2016).

Decision Support Systems: Software platforms (e.g., Cool Farm Tool, COMET-Farm) calculate whole-farm carbon footprints and model the impact of management changes, guiding farmers toward carbon-optimal practices.

6.2 Controlled Environment Agriculture (CEA) Innovations

Vertical Farms: Indoor LED-grown vegetables can achieve yields 10-30 times higher per square meter than field production. When powered by renewable electricity, carbon intensity per kilogram can be lower than transported conventional produce (Kozai et al., 2015).

Renewable Energy Greenhouses: Next-generation greenhouses integrate:

- Photovoltaic glazing (semi-transparent solar cells)
- Ground-source heat pumps
- Thermal mass water storage
- LED lighting with dynamic spectral control

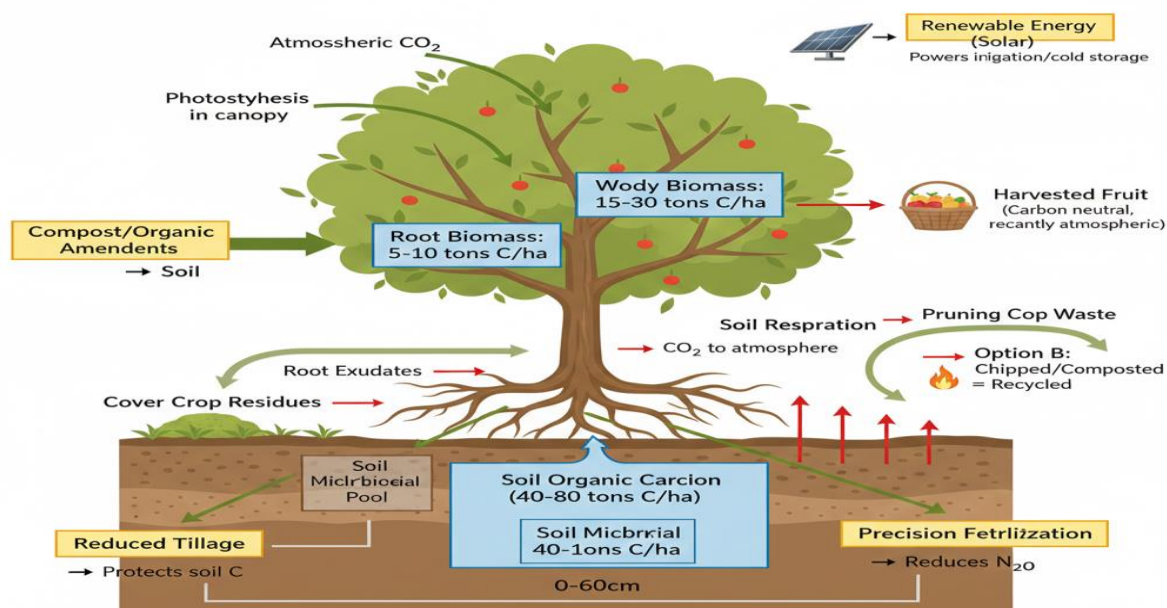
These achieve carbon neutrality in heating-intensive climates.

Table 2: Key Practices in Carbon Smart Horticulture and Their Climate Mitigation Mechanisms

Practice	Primary Mechanism	Estimated CO ₂ e Reduction (tons/ha/year)	Co-Benefits	Implementation Barriers
Compost Amendment (20 t/ha/3yr)	Soil C sequestration, reduced synthetic fertilizer	1.5 - 2.5	Improved soil structure, water retention, nutrient cycling	Availability/cost of compost, transport logistics
Biochar Application (15 t/ha, one-time)	Long-term stable C sequestration	5.0 - 8.0 (amortized over 30yr)	pH buffering, nutrient retention, water holding	High initial cost, production infrastructure
Cover Cropping (Annual veg systems)	Reduced soil erosion, N fixation, C inputs	0.5 - 1.5	Weed suppression, soil health, biodiversity	Management complexity, seed cost
Reduced/No-Till (Vegetable production)	Prevented SOC oxidation	0.8 - 1.2	Reduced fuel use, labor savings, soil structure	Specialized equipment, weed pressure
Precision Drip Irrigation	Reduced pumping energy, less N ₂ O from waterlogging	0.3 - 0.8	Water conservation, disease reduction	Capital investment, technical knowledge
Renewable Greenhouse Heating	Eliminated fossil fuel combustion	5.0 - 15.0	Energy cost stability, marketing advantage	High capital cost, retrofit challenges
Agroforestry Integration	Biomass C accumulation, soil protection	3.0 - 7.0	Diversified income, microclimate regulation	Long establishment period, spatial design complexity
Optimized N Management (soil testing)	Reduced N ₂ O emissions from excess fertilizer	0.4 - 1.0	Cost savings, reduced leaching	Requires technical support, soil testing infrastructure

Note: Values are approximations based on temperate climate conditions and assume best-practice implementation. Actual results vary with site-specific factors. Sources: Synthesized from Aguilera et al. (2013), Paustian et al. (2016), Lal (2004).

Figure 1: The Carbon Flow Diagram in a Carbon-Smart Orchard System



Description for Figure 1: A comprehensive flow diagram showing carbon movement through a fruit orchard system:

Central Element: Stylized fruit tree with visible root system

Carbon Inputs (Green Arrows Pointing In):

- Atmospheric CO₂ (from top) → Photosynthesis in canopy
- Compost/Organic Amendments (from left) → Soil
- Cover Crop Residues (from bottom left) → Soil
- Root Exudates (from roots) → Soil microbial pool

Carbon Stocks (Blue Boxes):

- Woody Biomass (trunk, branches): "15-30 tons C/ha"
- Root Biomass: "5-10 tons C/ha"
- Soil Organic Carbon (0-60cm): "40-80 tons C/ha"
- Soil Microbial Biomass: "1-3 tons C/ha"

Carbon Outputs (Red Arrows Pointing Out):

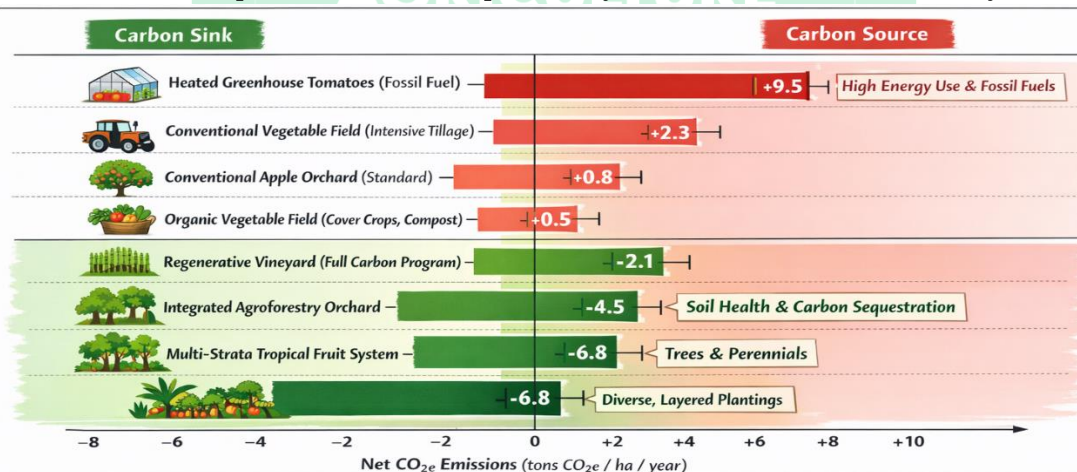
- Harvested Fruit (leaving system to right) - "Carbon neutral (recently atmospheric)"
- Soil Respiration (upward from soil) - "CO₂ to atmosphere"
- Pruning Waste (option A: burned = emission; option B: chipped/composted = recycled)

Management Interventions (Yellow Boxes):

- "Reduced Tillage" → Protects soil C
- "Precision Fertilization" → Reduces N₂O
- "Renewable Energy (Solar)" → Powers irrigation/cold storage

Caption: Carbon dynamics in a carbon-smart orchard showing major flows, stocks, and management intervention points. Arrow thickness represents relative magnitude of flow. Carbon-smart management maximizes inputs (green), maintains stocks (blue), and minimizes losses (red).

FIGURE 2: Comparative Carbon Footprint Analysis of Horticultural Production Systems



Net carbon balance across diverse horticultural production systems. Positive values indicate net GHG emissions (carbon source), while negative values represent net carbon sequestration (carbon sink). Data compiled from Hillier et al., 2009; Gruda et al., 2019; Aguilera et al., 2020; Nair et al., 2009.

Description for Figure 2: A horizontal bar chart comparing net carbon balance (tons CO_{2e} per hectare per year) across different horticultural systems:

Y-Axis: Horticultural system types **X-Axis:** Net CO_{2e} emissions (-8 to +10 tons/ha/year)

- Negative values (left, green zone) = Carbon sink
- Positive values (right, red zone) = Carbon source
- Zero line clearly marked

Systems Shown (from top to bottom):

1. **Heated Greenhouse Tomatoes (Fossil fuel):** +9.5 (deep red)
2. **Conventional Vegetable Field (Intensive tillage):** +2.3 (light red)
3. **Conventional Apple Orchard (Standard):** +0.8 (pale red)
4. **Organic Vegetable Field (Cover crops, compost):** -0.5 (pale green)
5. **Regenerative Vineyard (Full carbon program):** -2.1 (green)
6. **Integrated Agroforestry Orchard:** -4.5 (medium green)
7. **Renewable-Heated Greenhouse (Solar/Geothermal):** -0.8 (pale green)
8. **Multi-strata Tropical Fruit System:** -6.8 (deep green)

Additional Visual Elements:

- Small icons representing each system (greenhouse, tractor, tree, etc.)
- Error bars showing uncertainty ranges
- Annotation boxes highlighting key interventions for top performers

Caption: Net carbon balance across diverse horticultural production systems. Positive values indicate net GHG emissions (carbon source), while negative values represent net carbon sequestration (carbon sink). Data compiled from life cycle assessments and field monitoring studies (Hillier et al., 2009; Gruda et al., 2019; Aguilera et al., 2020; Nair et al., 2009).

7. POLICY AND MARKET MECHANISMS

7.1 Carbon Markets

Agricultural carbon credits are tradable on both compliance markets (e.g., California's Cap-and-Trade) and voluntary markets (e.g., Verra VCS, Gold Standard). Horticultural operations can generate revenue through verified emission reductions.

Challenges:

- **Permanence:** Soil carbon can be reversed by management changes; protocols require long-term monitoring (10-100 years)
- **Additionality:** Must prove that sequestration exceeds "business as usual" baseline
- **Leakage:** Ensuring that emissions aren't simply displaced elsewhere

Current carbon credit prices range from \$5-50 per ton CO₂e, with premium prices for co-benefit projects (e.g., biodiversity, water quality).

7.2 Certification and Labeling

Consumer-facing labels create market differentiation:

- **Carbon Neutral Certification** (e.g., Climate Neutral Certified)
- **Regenerative Organic Certification** (includes carbon criteria)
- **Low Carbon Agriculture** schemes in Europe

Studies show 15-30% of consumers willing to pay premiums for verified low-carbon products (Grunert et al., 2014).

7.3 Government Incentives

Many jurisdictions now offer financial support:

- **Australia's Emissions Reduction Fund:** Pays farmers for verified sequestration
- **EU Common Agricultural Policy:** Carbon farming initiatives
- **USDA NRCS Programs:** Cost-share for conservation practices (many of which enhance carbon)

8. CHALLENGES AND LIMITATIONS

8.1 Measurement Complexity and Cost

Rigorous carbon accounting requires substantial investment in soil sampling, laboratory analysis, and monitoring infrastructure. Small-scale horticultural operations may lack resources for comprehensive measurement.

Solution: Landscape-scale collaborative monitoring, where costs are shared across multiple farms using the same protocols.

8.2 Temporal Delays

Carbon sequestration in perennial systems requires years to decades to reach maximum rates. Farmers face economic pressure for immediate returns, creating misalignment with long-term carbon goals.

Solution: Blended finance models combining carbon credit advance payments with traditional agricultural loans.

8.3 Climate Variability

Drought, floods, and extreme heat affect both carbon inputs (reduced plant growth) and outputs (accelerated decomposition). Climate change itself threatens the stability of soil carbon stocks (Lal, 2004).

Solution: Diversified carbon management portfolios combining soil carbon (vulnerable to reversal) with biochar (highly permanent) and agroforestry biomass (moderate permanence).

8.4 Knowledge Gaps

Extension services and agronomic advisors often lack training in carbon management. This limits farmer adoption despite available technologies.

Solution: Integration of carbon literacy into agricultural education curricula and professional development programs.

9. FUTURE DIRECTIONS

9.1 Genomic Selection for Carbon-Efficient Cultivars

Breeding programs are beginning to select for traits that enhance carbon sequestration:

- Deep, extensive root systems
- High root exudate production (feeds soil microbes)
- Enhanced photosynthetic efficiency
- Drought tolerance (maintaining productivity under water stress)

9.2 Microbiome Engineering

Soil microbial communities govern carbon stabilization. Inoculation with beneficial fungi (mycorrhizae) and bacteria can enhance both carbon sequestration and crop productivity (Lehmann et al., 2020).

9.3 Digital Carbon Platforms

Blockchain-enabled supply chains will allow consumers to trace the carbon footprint of individual fruit or vegetable items, creating transparent accountability and premium market access for low-carbon producers.

9.4 Integration with Circular Economy

Horticultural operations will increasingly serve as biological processing hubs—converting food waste into compost, generating renewable energy from crop residues, and closing nutrient loops at landscape scales.

10. CONCLUSION: CULTIVATING A CLIMATE-POSITIVE FUTURE

Carbon smart horticulture represents far more than incremental improvement in agricultural sustainability. It embodies a fundamental reconceptualization of horticultural systems—from extractive production units to regenerative carbon infrastructure.

The evidence is compelling: With strategic management of soil health, crop selection, energy use, and agroecological design, horticultural operations can transition from net GHG emitters to net carbon sinks while maintaining or enhancing profitability. The practices are known. The technologies exist. The economic case is strengthening as carbon markets mature and consumers demand climate-aligned food.

What remains is the challenge of scale. Twenty million hectares of global horticulture, if managed for maximum carbon benefit, could sequester 100-200 megatons of CO₂ annually—equivalent to removing 20-40 million cars from roads. This is not a solution to climate change in isolation, but it is an essential component of the portfolio of actions required.

For horticultural producers, the transition to carbon-smart systems offers a pathway to:

- **Climate resilience:** Healthy soils with high organic matter withstand drought and flood better
- **Market differentiation:** Verified low-carbon products command premium prices
- **Regulatory preparedness:** Anticipating inevitable carbon regulations
- **Legacy:** Building soil health that future generations will inherit

The choice before the horticultural sector is clear: Continue on a trajectory of extractive production with escalating environmental costs, or embrace the regenerative potential inherent in working with living systems. Carbon smart horticulture offers not just a climate solution, but a blueprint for an agriculture that nourishes both people and planet. The fields, orchards, and greenhouses of tomorrow will be judged not only by the quality of their harvest, but by the health of the carbon cycle they steward. The time to cultivate that future is now.

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Climate Change Impacts on Livestock Health and Disease Dynamics



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1. Introduction

The livestock industry is a critical component of the world's agricultural economy and food security, providing vital protein and livelihoods to billions of people. However, the stability of the sector is increasingly being compromised by anthropogenic changes in the global climate regime. Climate change is no longer a projected reality in the future, but its effects, in the form of increasing temperatures of the planet on average, changing rain patterns, and greater frequency and severity of extreme weather events, are actively reorganising agro-ecosystems. One of the most significant consequences of these environmental changes consists of the complex changes in the health of livestock and the complex pattern of infectious diseases. The interaction of climatic and animal health is not simple, and it is controlled by the epidemiological triad, which is the host, agent, and environment.

Climate change can be viewed as a systemic destabiliser of this triad in that it can alter livestock health in two main ways: by directly affecting the physiological status of the animal and by indirectly changing the ecological niches of the pathogens, vectors, and intermediate hosts. Furthermore, the nutritional stress due to the scarcity of resources, especially water and forage quality, plays a role in the reduction of host immunity, which is a result of the climate.

2. Direct Physiological Impacts

Heat stress is the most obvious and the most documented impact of a warming climate on livestock. Livestock species are known to act within known thermoneutral ranges- a window of ambient temperatures where heat generation within the metabolism matches heat loss without the need to consume extra energy. Hyperthermia develops when the environmental conditions, which include high ambient temperature and high relative humidity, surpass the ability of an animal to dissipate heat. A commonly used measure of this risk is the Temperature-Humidity Index (THI). Although thresholds can be species, breed, and productive state specific (e.g., lactating dairy cows are more susceptible to elevated THI than beef cattle because of greater heat production), high THI provokes physiological responses that are universally counterproductive and detrimental to health.

a) Physiological Mechanisms of Heat Stress

Livestock in response to thermal stress have started thermoregulatory processes that include increased rates of respiration (panting), sweating and vasodilation. Such processes use a lot of energy and resources that could be used in other processes like growth, lactation or reproduction, to maintain the temperature and survival.

At the same time, the effect of heat stress on behaviour includes a dramatic decrease in dry matter intake (DMI) to decrease metabolic heat generation generated by fermentation and digestion. This nutritional deficiency also increases the reductions in productivity.

On the cellular level, long-term hyperthermia leads to oxidative stress and triggers the synthesis of heat shock proteins. It impairs the work of the intestinal barrier (leaky gut), allowing the entrance of endotoxins into

circulation and causing systemic inflammation. This inflammatory condition, sustained over time, coupled with a lack of energy, significantly deteriorates the immune system, making animals more vulnerable to secondary infections like bovine respiratory disease complex (BRDC) and mastitis. Thermal stress is extremely sensitive to reproductive parameters. Heat stress in the peri-implanting phase in dairy cattle leads to significant embryonic mortality. High testicular temperatures in the male animals of different species compromise the quality and motility of the semen, which directly influences the fertility of the herd.

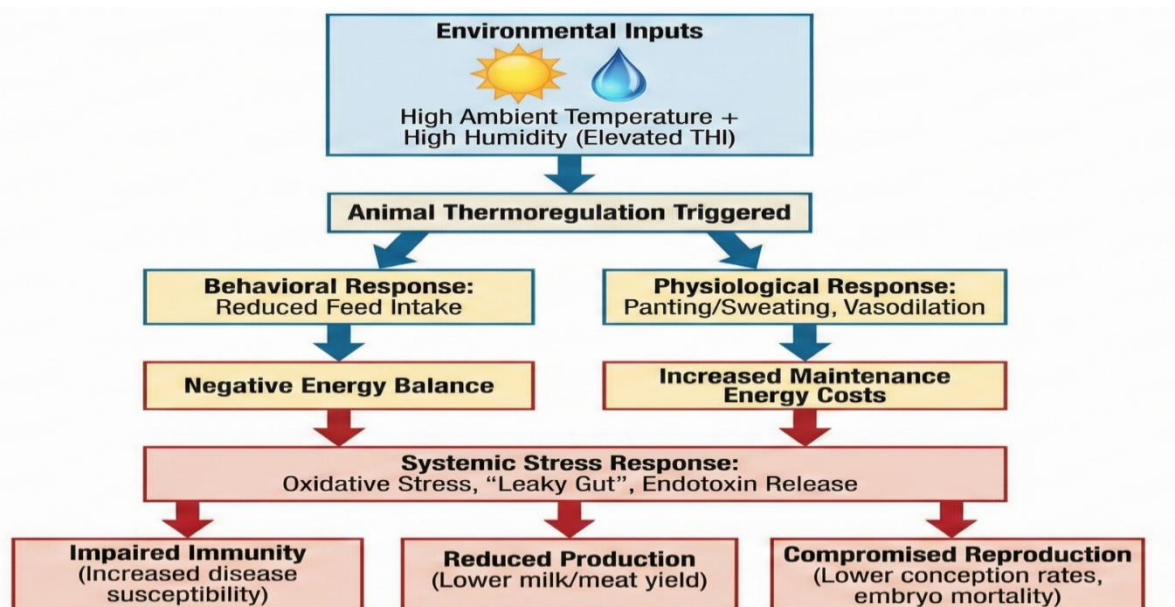


Figure 1. The Cascade of Physiological Impacts of Heat Stress in Ruminants

3. Altered Disease Ecology and Vector Dynamics

The most complex effect of climate change is that it affects the spatial and temporal distribution of infectious diseases, which is especially the case with arthropod vectors (mosquitoes, ticks, midges, and flies). The basic environmental factors, such as temperature, rainfall, and humidity, are important determinants of the survival of the vectors, their reproduction, and their geographical range boundaries.

a) The Expansion of Vector Ranges

The increasing temperatures contribute to the extension of the vectors' habitats towards the north and upwards (altitudinal). Areas that were thought to be too cold to support some vectors are accessible. As an example, the spread of the tick *Ixodes ricinus* northwards in Europe has expanded the range of Lyme borreliosis and tick-borne encephalitis endemic areas. In the same way, warmer winters enhance the overwintering success of the vector population, resulting in greater spring populations.

In Africa, changing rainfall patterns affect the African animal trypanosomiasis (nagana) vectors, the tsetse fly. With the increase in the area covered by arid zones, the tsetse fly belt can move to the previously non-infected lands and cause disease burdens to the inquisitive livestock.

b) Accelerated Pathogen Dynamics

The temperature has far-reaching effects on the pathogen biology of the vector. The extrinsic incubation period (EIP), the duration of time necessary to allow a pathogen to grow within the vector such that it is transmissible to a new host, is reduced at elevated temperatures.

In the case of arboviruses, including Rift Valley Fever (RVF) or Bluetongue virus, the shorter the EIP, the faster vectors will become infectious after feeding on a host. This increases the rate of transmission of diseases, which may trigger explosive epidemics in favourable circumstances. The behaviour is exemplified by Bluetongue disease, which is spread by *Culicoides* midges and has previously been limited to tropical and subtropical areas,

but in the last 20 years, serotypes of Bluetongue have continued to move north into Europe, boosted by rising temperatures that favour the survival of the midges and the proliferation of the virus.

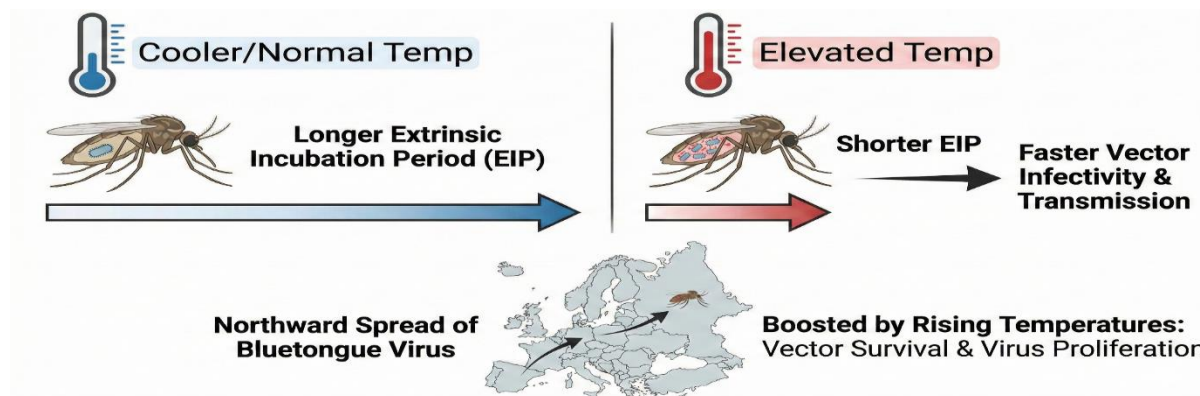


Figure 2. The Impact of Rising Temperatures on Pathogen Dynamics and Vector Spread

c) Precipitation Extremes and Waterborne Zoonoses

Climate change is not just the process of warming, but also the process of increasing the hydrological cycle. Flooding and heavy rain mobilise pathogenic organisms of faecal origin, which contaminate pasture and water bodies, promoting the occurrence of waterborne and pasture-related diseases, including leptospirosis, fascioliasis (liver fluke), and cryptosporidiosis. On the other hand, droughts ensure the presence of pathogens in the scarce water resources, increasing the risk of infection by fomites and direct contact.

Table 9. Key Climate-Sensitive Livestock Diseases and Climatic Drivers

Disease	Primary Species Affected	Pathogen/Vector Type	Key Climate Drivers	Observed/Projected Impacts
Bluetongue	Sheep, Cattle, Goats	Viral / <i>Culicoides</i> midge	Increased temperature; milder winters	Northward expansion into Europe, increased overwintering of vectors, and shorter extrinsic incubation period.
Rift Valley Fever (RVF)	Sheep, Cattle, Goats, Humans	Viral / <i>Aedes</i> & <i>Culex</i> mosquitoes	Extreme rainfall events (El Niño association)	Flooding triggers hatching of infected <i>Aedes</i> eggs, leading to explosive outbreaks in arid regions.
Fascioliasis (Liver Fluke)	Sheep, Cattle	Parasitic flatworm / Aquatic snail intermediate host	Increased rainfall and temperature	Warmer, wetter winters increase snail survival and parasite development, extending the transmission season.
Tick-borne Diseases (e.g., Babesiosis, Anaplasmosis)	Cattle, various	Protozoal/Rickettsial / Ixodid ticks	Temperature increases; humidity changes	Expansion of tick geographical ranges poleward and into higher altitudes; accelerated tick life cycles.
Anthrax	All grazing livestock	Bacterial (<i>Bacillus anthracis</i>) / Soil-borne spores	A cycle of heavy rains followed by severe drought	Heavy rains expose buried spores; subsequent drought forces close grazing to contaminated soil.

4. Indirect Impacts Through Environmental and Nutritional Stressors

Although heat and vectors are direct drivers, climate change also has an indirect impact on the health of livestock by compromising the nutritional environment. The immunocompetence begins with nutrition; any animal that suffers a negative energy or protein balance will be physiologically affected in its ability to withstand infection.

a) Forage Quantity and Quality

Better frequency and intensity of drought events lead to a significant reduction in the biomass of forages, leading to overgrazing and subsequent under-nutritional state. Besides, high levels of carbon dioxide (CO₂) in the air can alter plant physiology. Even though increased CO₂ levels can enhance plant growth through the fertilisation effect, it often causes a nitrogen dilution effect, leading to the development of forage with low crude protein content and low digestibility. Such lower-quality forage can cause livestock grazing to experience subclinical malnutrition, thus lowering its immune responses to vaccines and natural challenges.

b) Mycotoxins and Feed Safety

Climate change is estimated to have an impact on the occurrence of mycotoxins, trophic secondary metabolites produced by fungi on crops and forage. Temperature and moisture play very crucial roles in the growth of the fungus during the growing period, harvesting and storage of the crops. The weather extremes, like drought during growth and heavy rains during harvest, provide the perfect environment for some species of *Fusarium* and *Aspergillus*. Mycotoxin-contaminated feed will cause a continuum of health effects in livestock, including acute toxicity, hepatic damage, chronic immunosuppression and reproductive failure. The risks of mycotoxins are increasingly difficult to predict and handle as climate variability increases.

5. Economic Implications and Food Security

A combination of heat stress and change in disease dynamics and food limitation translates into strong economic effects. Mortality is not the sole cause of economic losses, which also include the indirect costs of diminished productivity: decreased milk production, decreased average weight gain, decreased fertility rates, and veterinary and work costs. Also, outbreaks of diseases often provoke trade bans, destroying the export markets of the countries where the disease spreads. Diseases caused by climate change are an added risk that discourages investment in the livestock industry in prone areas. However, in the end, all these factors pose a threat to food security across the world. The products of cattle rearing contain critical micronutrients for various human populations; a decline in the stability of the livestock system caused by climate affects smallholder farmers disproportionately in developing countries, as they depend on livestock as one of their financial safety nets and food sources.

6. Mitigation And Adaptation Strategies

To deal with the issues of climate change in livestock production, a multidisciplinary strategy addressing the issue of resilience is required.

- a) **Genetic Selection and Breeding:** Breeding schemes should shift the focus from sole productivity to introduce aspects of strength and hardiness. This approach involves the choice of heat tolerance (e.g., the gene of the slick type of hair in cattle, which creates a shorter and greasier hair coat) and genetic immunity to particular diseases or vectors. A very important strategy is the inclusion of locally adapted native breeds, which, in most cases, have high resistance to harsh environments, in the crossbreeding programs.
- b) **Environmental Management and Engineering:** To reduce heat stress, the infrastructure must be invested in. It involves the provision of enough shade, better ventilation of barns and active cooling measures like sprinklers and fans in high-density dairy and poultry farming. Management of pastures should learn to accommodate the changing rainfall patterns, which could be achieved by the use of drought-resistant forage species, with rotational grazing being used to avoid degradation of land.
- c) **Enhanced Disease Surveillance and Veterinary Care:** The dynamic nature of diseases requires strong and alert disease surveillance systems that can detect new or re-emerging diseases in good time. This involves the reinforcement of veterinary care and laboratory facilities on an international basis. The vaccination regimen might require changes in the schedule and frequency in order to match the changing vectors' phenology.

7. Conclusion

Climate change serves as an effective multiplier of risks to the health of the world's livestock, disrupting the known equilibria between hosts, pathogens and environments. Its effects are extensive, as they are realised in direct thermal aggression of the physiology of animals, in the geographic shift of the vectors of diseases, and with the erosion of nutritional bases. The pace of these transformations makes modern farming management practices difficult.

Ensuring the further sustainability of livestock systems in the face of climatic disruption requires an immediate shift of the crisis response mode to proactive adaptation. Such transition involves long term investment in research with climate-resistant genetics, invention of new vaccines against new threats and implementation of One Health methods that recognise the hopeless centrality of animal health, human health and ecological integrity. Inability to adjust to these dynamic changes poses a grave threat to the agricultural economies as well as to nutritional security in the world.

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Climate Smart Agronomic Practices for Sustainable Crop Production



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1. Introduction

Contemporary agriculture faces an unprecedented existential challenge: the requirement to increase total factor productivity to feed an estimated 9.7 billion people by 2050, while simultaneously operating under increasingly erratic climatic conditions and reducing the sector's own significant environmental footprint. The linear model of the Green Revolution, reliant heavily on synthetic inputs, intensive tillage, and genetic uniformity, is proving insufficient and, in some cases, deleterious under new climate regimes characterized by prolonged droughts, extreme precipitation events, and shifting pest pathogen dynamics. Climate-Smart Agriculture (CSA), as conceptually anchored by the Food and Agriculture Organization (FAO), provides the necessary framework to navigate this complexity. CSA is not a monolithic technique but an integrated approach aimed at achieving three simultaneous objectives:

- 1. Sustainable Productivity:** Increasing agricultural yields and incomes without degrading the resource base.
- 2. Adaptation and Resilience:** Reducing vulnerability of agricultural systems to climate-related risks and shocks.
- 3. Mitigation:** Removing greenhouse gas (GHG) emissions where possible, particularly through soil carbon sequestration and improved nitrogen efficiency.

2. The Biophysical Imperative for Change

The urgency for adopting CSAPs stems from the observable degradation of the biophysical environment supporting agriculture. Conventional intensive tillage has accelerated the loss of soil organic carbon (SOC), resulting in reduced water-holding capacity and increased susceptibility to erosion. Furthermore, the inefficient application of nitrogen fertilizers acts as a primary driver of nitrous oxide (N₂O) emissions, a GHG with a global warming potential nearly 300 times that of CO₂ over a century.

Data gathered through the early 2020s indicates that major staple crop yields (maize, rice, wheat) are already experiencing stagnation or decline in low-latitude regions due to heat stress during anthesis and grain-filling periods. The business-as-usual agronomic model is ill-equipped to buffer these shocks. Therefore, a transition toward regenerative and resilient systems is no longer optional; it is an agronomic imperative for national food security strategies.

3. Core Climate Smart Agronomic Practices (CSAPs)

The translation of CSA principles into practice involves a diverse toolbox of agronomic interventions adapted to specific agro-ecological zones.

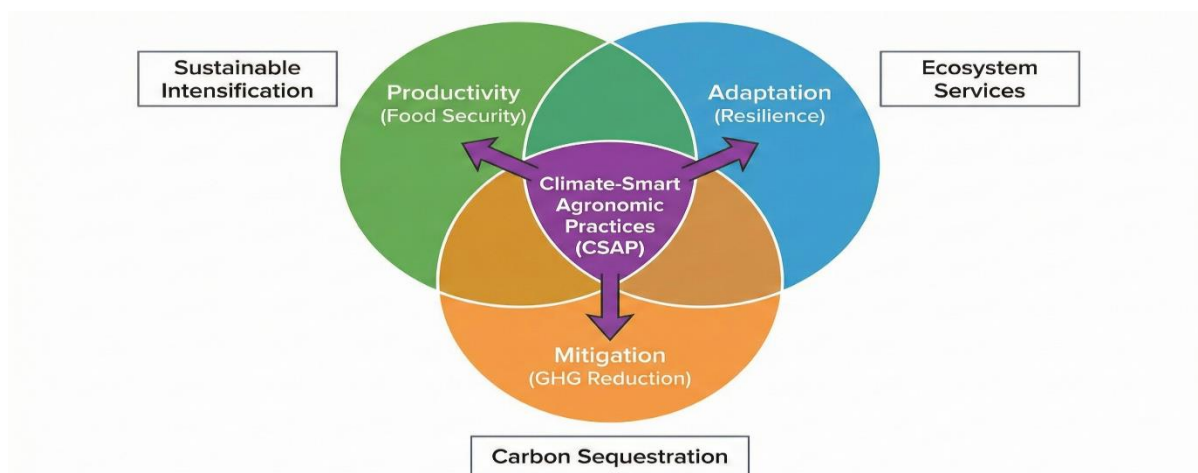


Figure 1. The Three Pillars of Climate-Smart Agriculture Intersection

3.1 Conservation Agriculture (CA) and Soil Health Restoration

Conservation Agriculture is the cornerstone of climate-resilient farming. It marks a paradigm shift from soil degradation to soil restoration based on three principles: minimum soil disturbance (no-till or reduced-till), permanent soil organic cover (crop residues or cover crops), and species diversification. The mechanism of CA's effectiveness lies in its impact on soil architecture. By ceasing intensive ploughing, fungal hyphae networks remain intact, improving soil aggregation. The maintenance of surface residues reduces soil temperature evaporation, acting as a vital buffer during drought conditions. Crucially, CA systems transform agricultural soils from net carbon sources to net sinks over time, sequestering atmospheric CO₂ into stable pools of soil organic matter.

Table 10. Comparative Analysis: Conventional Tillage vs. Conservation Agriculture

Agronomic Parameter	Conventional Intensive Tillage	Conservation Agriculture (CSAP Approach)	Climate Impact Implication
Soil Disturbance	High inversion ploughing disrupts soil structure.	Minimal; direct seeding ensures structural integrity.	CA reduces oxidative loss of soil carbon; lowers fuel consumption (mitigation).
Water Management	High evaporation and poor infiltration lead to runoff.	High infiltration due to macropores; residues reduce evaporation losses.	CA significantly increases green water availability during dry spells (adaptation).
Soil Organic Carbon (SOC)	Rapid depletion due to oxidation and erosion.	Gradual accumulation; sequestration of atmospheric carbon.	CA acts as a long-term carbon sink (mitigation/resilience).
Soil Temperature	High fluctuation; bare soil absorbs heat.	Moderated by surface residue cover.	CA protects root systems from extreme heat stress (adaptation).
Initial Yield Response	Often higher in short-term (1-2 years).	Variable; potential short-term yield drag followed by long-term stability.	CA offers long-term yield stability over immediate maximization.

3.2 Dynamic Cropping Systems and Agro-biodiversity

Monocultures are inherently vulnerable to climate shocks and pest outbreaks exacerbated by changing weather patterns. CSAPs emphasize reintroducing spatial and temporal diversity into agricultural landscapes.

- a. **Stress-Tolerant Varieties (STVs):** Modern breeding, including recent CRISPR applications validated

in the mid-2020s, has rapidly accelerated the development of cultivars resistant to abiotic stresses. Submergence-tolerant rice (Sub1 gene), drought-tolerant maize, and heat-tolerant wheat varieties are essential tools for adaptation.

- b. Legume Integration and Cover Cropping:** Integrating legumes (e.g., cowpea, lentils) into cereal rotations fixes atmospheric nitrogen biologically, reducing reliance on synthetic N-fertilizers and their associated emissions. Cover crops, planted during fallow periods, prevent erosion and scavenge residual nutrients, preventing leaching into waterways.
- c. Agroforestry Systems:** The strategic integration of trees into cropland (e.g., *Faidherbia albida* in cereal systems) provides microclimatic regulation. Trees reduce wind speed, lower understory temperatures through shading, and access deep soil moisture, while also providing diversified income streams (timber, fruit) that enhance farmer economic resilience.

3.3 Precision Resource Management

Precision agriculture leverages technology to decouple productivity from intensive resource consumption. In a climate-smart context, the focus shifts from mere yield maximization to maximizing crop per drop of water and yield per unit of nutrient.

- **Site-Specific Nutrient Management (SSNM):** Moving away from blanket fertilizer recommendations, SSNM utilizes soil testing, optical sensors (e.g., NDVI readings via drones or satellite), and decision support tools to match nutrient application precisely to crop demand spatially and temporally. This significantly reduces nitrogen losses via volatilization and leaching.
- **Efficient Irrigation Technologies:** In irrigated systems, shifting from flood irrigation to drip or sprinkler systems, often coupled with soil moisture sensors and evapotranspiration modelling, is critical for adaptation in water-scarce regions. Alternate Wetting and Drying (AWD) in rice production is a proven CSAP that reduces water usage by up to 30% and significantly mitigates methane emissions from flooded paddies.

4. Quantifying the Impact

To understand the necessity of these practices, we must examine projections of agricultural performance under varying adoption scenarios.

The divergence between the red line (conventional practices struggling under climate stress) and the blue line (resilience gained through CSAPs) highlights the adaptation gap.

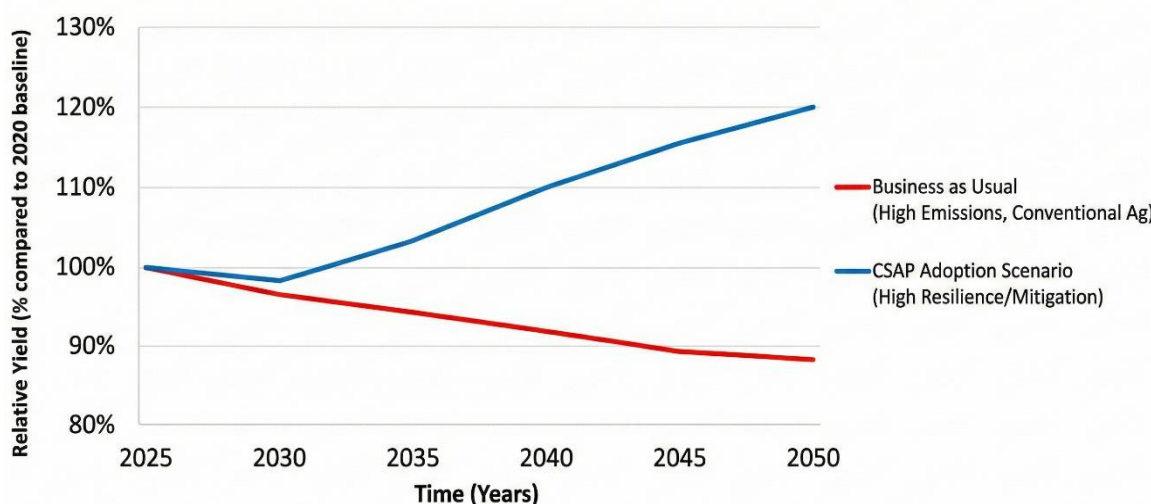


Figure 2. Projected Aggregate Cereal Yield Trends under Climate Change Scenarios (2025-2050)

5. Socio-Economic Dimensions and Adoption Barriers

Despite the proven biophysical benefits, the adoption rate of CSAPs remains suboptimal globally, particularly among smallholder farmers in developing regions. The transition to climate-smart systems is not merely a technical challenge but a profound socio-economic one.

Key Barriers:

1. **Initial Investment and Delayed Returns:** Practices like conservation agriculture often involve an initial yield drag during the soil restoration phase (years 1-3) while requiring upfront investments in specialized machinery (e.g., no-till seeders). Smallholders often lack the financial capital to bridge this gap.
2. **Knowledge Intensity:** CSAPs are generally more knowledge-intensive than conventional farming. Successfully implementing SSNM or integrated pest management requires understanding complex ecological interactions, necessitating robust agricultural extension services, which are often under-resourced.
3. **Land Tenure Insecurity:** Farmers without secure land titles have little incentive to invest in long-term soil health measures like agroforestry or terracing, as they may not reap the future benefits.

Enabling Environments:

Overcoming these barriers requires innovative policy and financial mechanisms. Payment for Ecosystem Services (PES) schemes, where farmers are compensated for sequestering carbon or improving watershed health, are gaining traction. By 2026, verified agricultural carbon credit markets will become more accessible to aggregated groups of small farmers, providing a vital financial incentive for adopting mitigation-focused CSAPs. Furthermore, de-risking mechanisms, such as weather-index insurance, are crucial to encourage farmers to experiment with new crop varieties or planting schedules without fear of catastrophic loss.

6. Conclusion

The convergence of rising food demand and escalating climate instability demands a decisive move away from extractive agricultural models toward regenerative, resilient systems. Climate Smart Agronomic Practices encompassing conservation agriculture, biodiverse cropping systems, and precision technology offer the only viable pathway to secure sustainable crop production through the mid-21st century.

The science supporting CSAPs is robust. The challenge now lies in the scaling mechanisms. Success depends not just on agronomic innovation, but on creating enabling policy environments that recognize and reward farmers not only as producers of food but as stewards of the essential ecosystems upon which our collective future depends. The adoption of these practices is the defining agronomic mandate of our time.

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Digital Soil Mapping: Innovation, Challenges And Future Prospective



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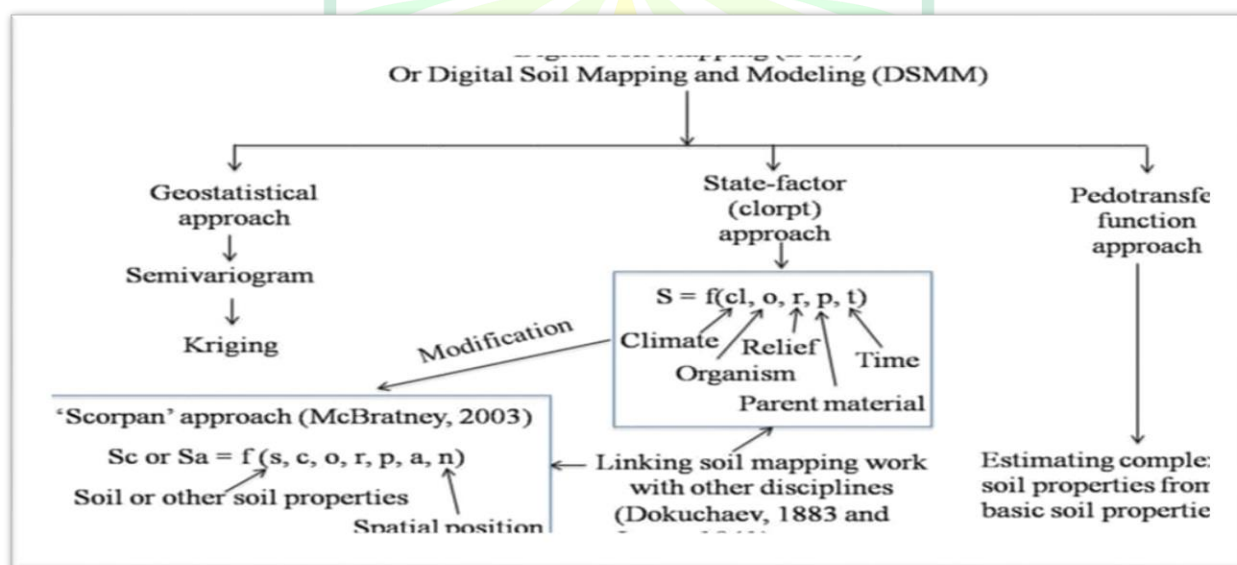
Introduction

Mapping of soil fertility is a practical and effective method to delineate soils into low, medium and high nutrient status. These delineated soils, based on their productivity, can be treated separately for precise application of fertilizer. Digital Soil Mapping (DSM) is the process of predicting and spatially representing soil types and properties across landscapes using a combination of observed soil data, environmental covariates, geostatistical tools and machine learning algorithms. It relies on quantitative models to establish soil-environment relationships and produces continuous, high-resolution and digital maps (McBratney *et al.*, 2003; Grunwald, 2009).

What is Digital Soil Mapping?

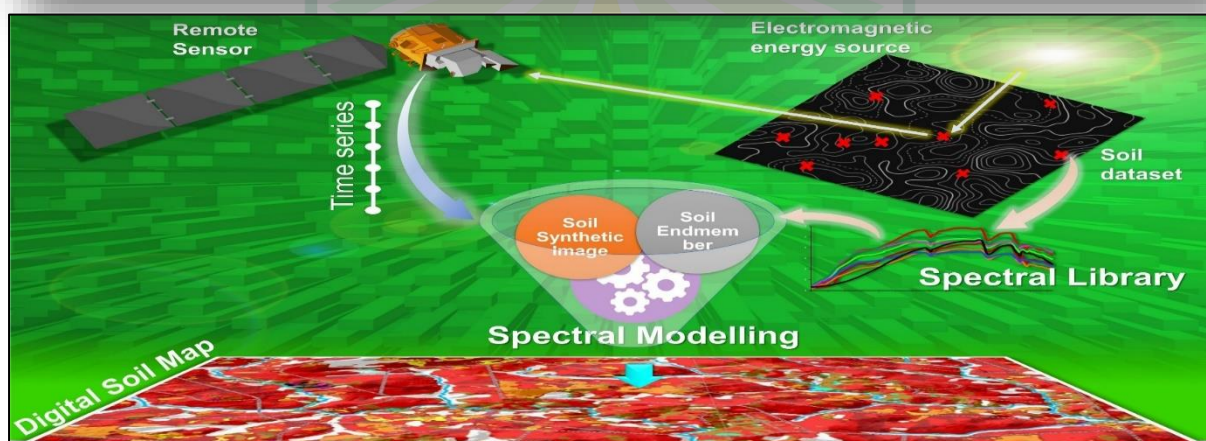
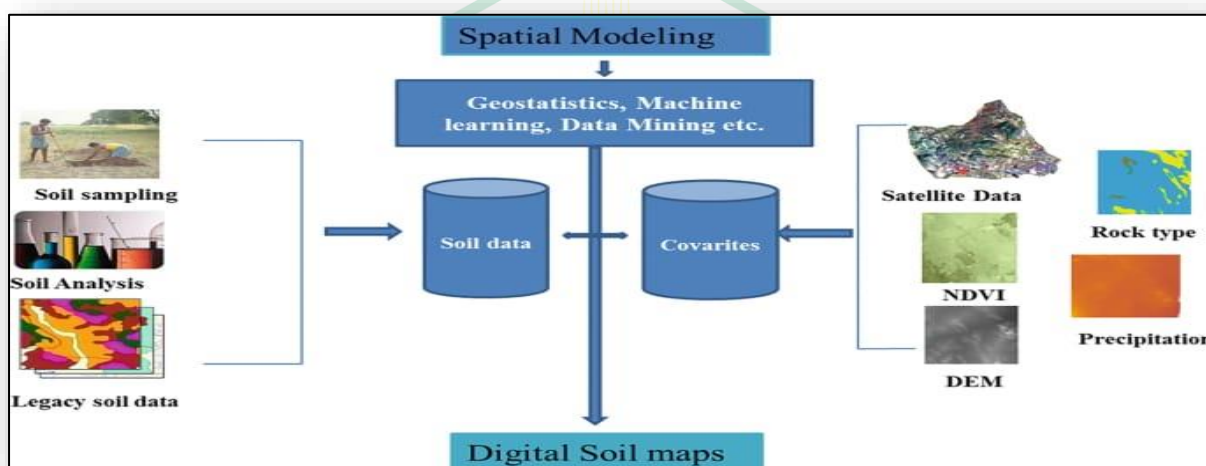
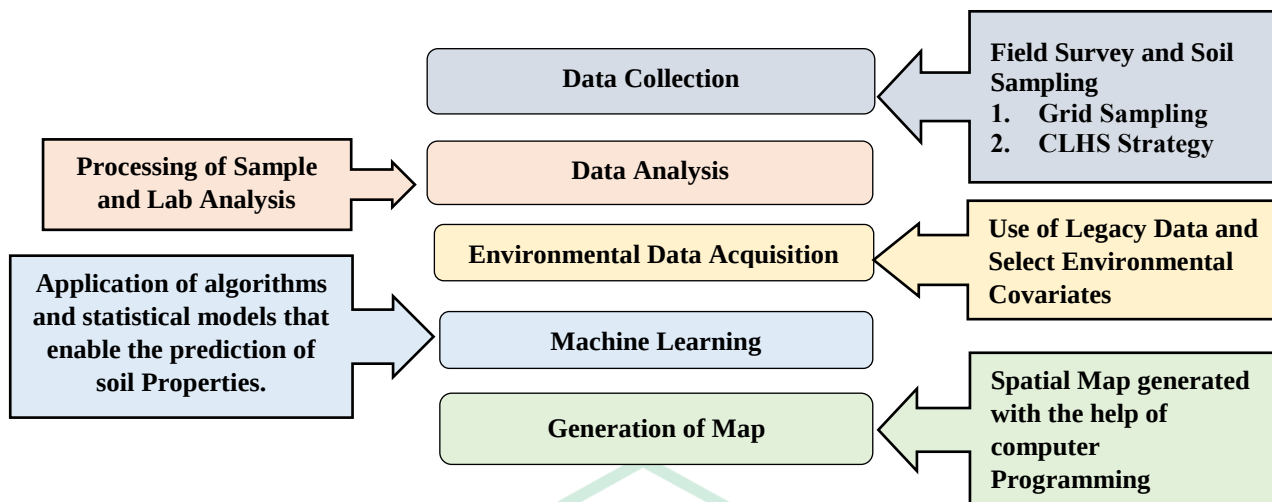
Soil mapping: Soil mapping is the geographical representation showing diversity of soil type and soil representation.

Pedometrics: Application of mathematical and statistical methods for the study of the distribution and genesis of soils.



Digital Soil Mapping: Computer assisted production of digital maps of soil type and soil properties by use of mathematical and statistical models that combine information from soil observation with information contained in explanatory environmental variables.

Process of DSM



Abstract of Digital Soil Mapping Using Multispectral Modeling with Landsat Time Series Cloud Computing (Novais *et al.*, 2021).

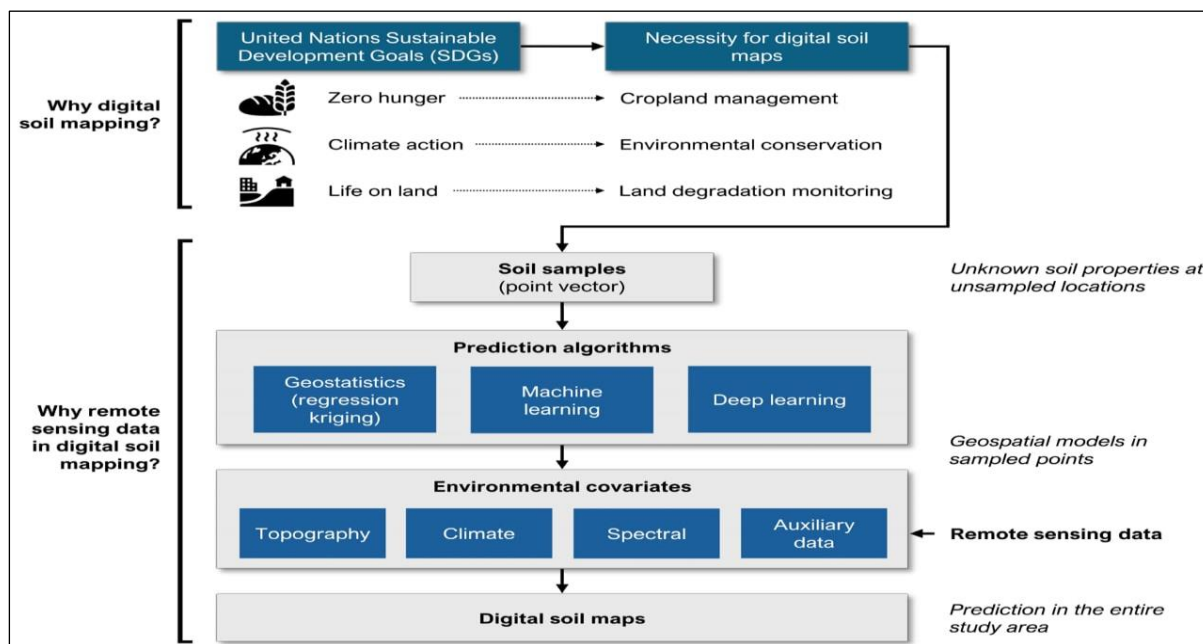
Concept of Digital Soil Mapping (DSM)

DSM operates on the principle that soil properties are spatially dependent and influenced by environmental factors such as elevation, slope, land use, parent material and climate (McBratney *et al.*, 2003).

It applies models like multiple regression, random forest, regression-kriging and machine learning to relate soil observations to these variables, generating high-resolution, reproducible maps with defined accuracy (Hengl *et al.*, 2015).

A key framework in DSM is the SCORPAN model, where soil variation is a function of Soil properties, Climate, Organisms, Relief, Parent material, Age and Nearby observations (McBratney *et al.*, 2003).

- Advances in geostatistics and machine learning enable DSM to interpolate soil data (e.g., via kriging) and predict soil variability across landscapes (Grunwald, 2009).
- It represents a major shift from subjective mapping to objective, model-based predictions suited for precision agriculture and environmental planning (Minasny *et al.*, 2013)



Basic Principle of Digital Soil Mapping (DSM)

- The fundamental principle of **Digital Soil Mapping (DSM)** is that **soil properties and classes at any location are spatially dependent and can be quantitatively predicted based on their relationship with measurable environmental covariates**.
- DSM operates on the concept that “**similar environments produce similar soils**” meaning that locations with comparable environmental conditions tend to have similar soil properties.
- A widely accepted framework supporting this principle is the SCORPAN model, where soil variation is expressed as a function of:

This principle ensures that DSM provides objective, reproducible, high-resolution and updatable soil information essential for modern agriculture, environmental management and land use planning (Minasny & McBratney, 2016).

Key Features:

- Integrates field and lab data with environmental covariates.
- Uses statistical, geostatistical and machine learning models.
- Produces continuous, updatable, objective and reproducible soil information.
- Allows mapping of soil attributes (e.g., pH, organic carbon, texture and depth) rather than discrete soil units only.

Technological Backbone:

- Remote Sensing (RS)
- Geographic Information System (GIS)

- Global Positioning System (GPS)
- Digital Elevation Models (DEMs)
- Machine Learning Models (Random Forest, Cubist and SVM)

Conventional soil mapping methods:

Definition:

Conventional soil mapping refers to the traditional approach of delineating and classifying soils through systematic field surveys, profile descriptions, physical and chemical analysis and manual interpretation of aerial photographs or satellite images. Maps are prepared through human expert judgement based on soil-landscape relationships (Soil Survey Staff, 1993).

Process:

1. Extensive field visits for soil sampling and profile observations.
2. Documentation of soil horizon sequence, color, texture, structure and other observable properties.
3. Determination of soil chemical and physical characteristics (e.g., pH, EC, organic carbon and texture).
4. Defining and grouping soils into series, associations or complexes based on observed and lab data.
5. Manual preparation of soil maps at standard scales (e.g., 1:50,000 or 1:250,000) using traditional cartographic techniques

Soil Survey Staff (1993); Minasny *et al.* (2013)

SCORPAN+E Model: Explanation, Features, and Principle

The SCORPAN+E model is an advanced conceptual framework used in Digital Soil Mapping (DSM) for predicting the spatial distribution of soil properties and soil classes.

It builds upon the widely recognized SCORPAN model (McBratney *et al.*, 2003) by integrating an additional component 'E' representing spatial or positional effects or location-based spatial dependence not captured by the other SCORPAN factors.

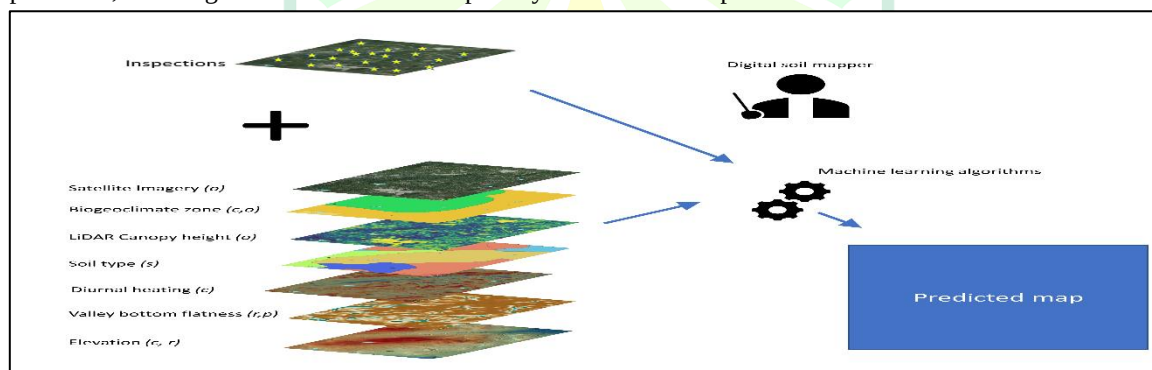
SCORPAN is originally an extension of Jenny's (1941) soil formation factors, expanded for use in digital soil prediction systems.

In its extended form:

The 'E' term captures this through positional or location-based effects, typically modelled by:

- Kriging residuals from the primary predictive model, or
- Spatial autocorrelation measures (e.g., variograms and Moran's I)

This approach ensures that both deterministic environmental influences and stochastic spatial patterns are represented, resulting in more accurate and spatially continuous soil predictions.



Basic Features of SCORPAN+E Model

1. **Incorporates Residual Spatial Dependence**
 - The 'E' term accounts for spatial patterns not explained by environmental covariates, typically captured through geostatistical interpolation (like kriging of residuals).
 - Improves the predictive accuracy and reliability of soil maps.
2. **Flexibility in Data Input**
 - Uses various environmental covariates derived from digital elevation models (DEMs), remote sensing, land use data, and climatic records and along with measured soil property data.

3. Combination of Environmental and Spatial Effects

- Unlike basic SCORPAN, which relies solely on environmental predictors, SCORPAN+E integrates both environmental factors and positional effects of soil data points.

4. Supports Both Categorical and Continuous Soil Mapping

- Suitable for predicting both soil classes (e.g., soil types) and continuous variables (e.g., organic carbon, pH and texture).

5. Compatible with Modern Statistical and Geostatistical Models

- Works well with regression-kriging, random forest and machine learning techniques combined with spatial interpolation of residuals.

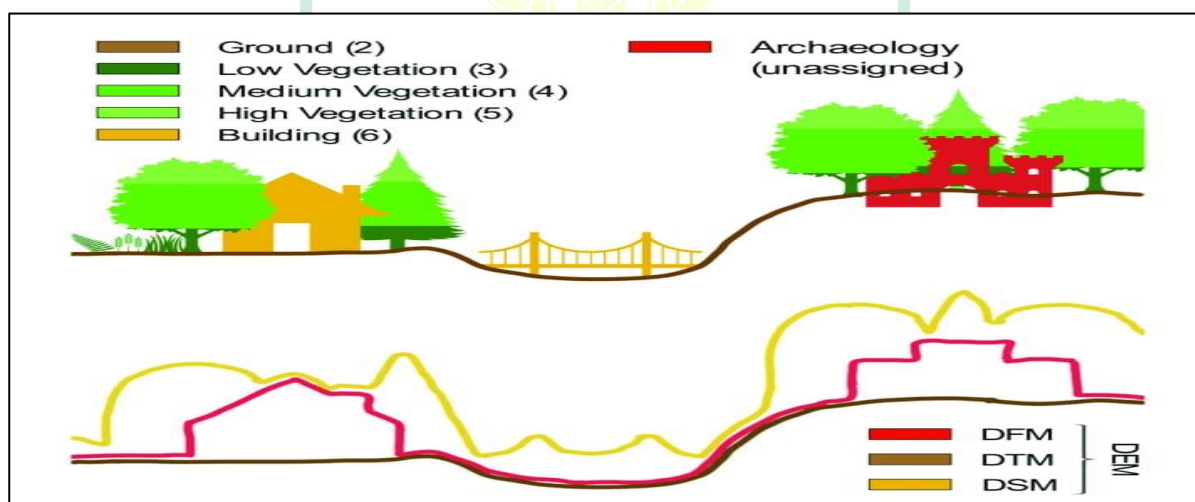
Digital Elevation Model (DEM): Concept, Features, and Role in DSM

What is a DEM?

A Digital Elevation Model (DEM) is a raster-based digital representation of the Earth's surface topography, where each pixel or cell contains a value representing elevation (height above sea level).

DEMs are fundamental datasets in geospatial sciences and are widely used in Digital Soil Mapping (DSM) to derive terrain-related covariates influencing soil formation and variability.

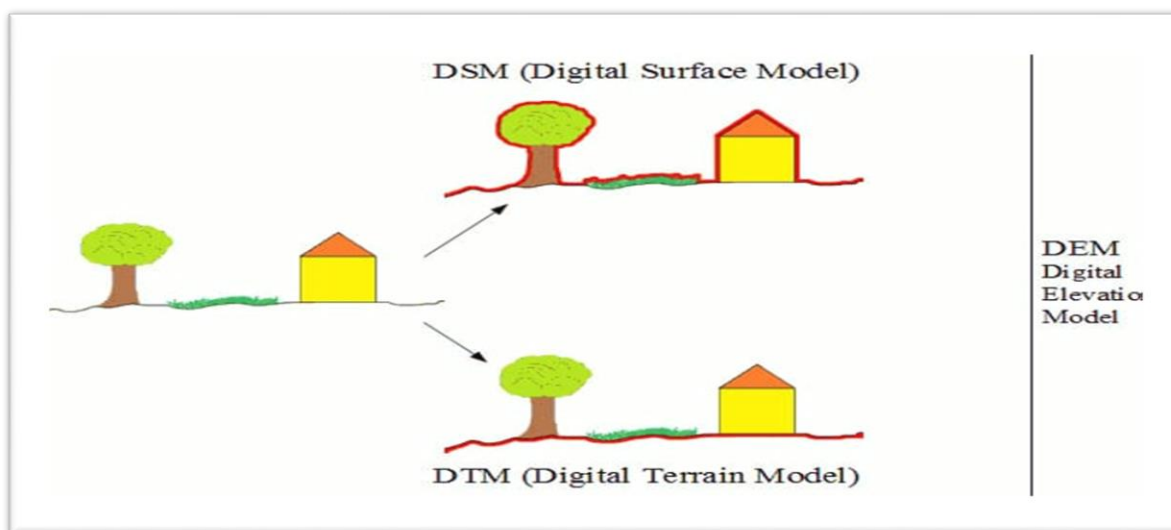
- Satellite-based sensors (e.g., SRTM and ASTER)
- LiDAR (Light Detection and Ranging)
- Aerial photogrammetry



Key Features of DEMs

1. **Grid-based format:** DEMs are structured as raster data, where elevation values are arranged in a regular grid pattern.
2. **High spatial resolution:** Depending on the source, DEMs can have resolutions ranging from 1 m (LiDAR) to 30 m or 90 m (e.g., Shuttle Radar Topography Mission).
3. **Derived Terrain Attributes:** DEMs are used to derive secondary topographic variables (also called terrain attributes), such as:
 - Slope
 - Aspect (direction of slope)
 - Curvature
 - Topographic Wetness Index (TWI)
 - Stream Power Index (SPI)

Elevation variability: These attributes are crucial covariates in DSM models as they directly influence soil moisture, erosion, drainage and soil development processes



What is Kriging?

Kriging is a geostatistical interpolation technique used to predict the value of a variable (e.g. soil property like pH, organic carbon and texture) at unsampled locations based on the values at known sample points, while accounting for the spatial autocorrelation between those sample points.

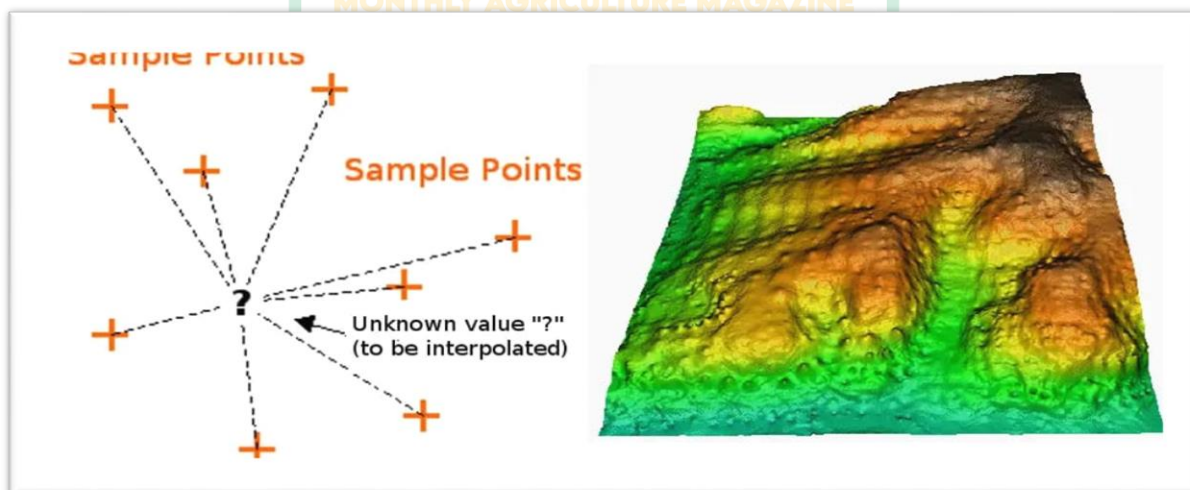
It's named after Danie Krige, a South African mining engineer who developed the method for resource estimation in mining, and was formalized by Georges Matheron in the 1960s as a branch of geostatistics.

Principle of Kriging

Kriging is based on Tobler's First Law of Geography:

"Everything is related to everything else, but near things are more related than distant things."

In spatial data like soils, values of soil properties at locations close to each other tend to be more similar than those farther apart. Kriging models this spatial dependence using a semi-variogram (or variogram), which quantifies how the similarity between two points changes with distance.



Key Components of Kriging

1. Sample data (observed soil property values at known locations)
2. Spatial autocorrelation structure (modelled using a variogram)
3. Prediction model (using weighted averages of nearby points based on their distance and spatial structure)
4. Uncertainty estimation (kriging provides both predicted values and associated error/variance)

Type	Description	Application
Ordinary Kriging (OK)	Assumes a constant unknown mean across the area of interest.	Mapping soil properties where only spatial autocorrelation is considered.
Simple Kriging (SK)	Assumes a known constant mean.	Rarely used in DSM.
Universal Kriging (UK)	Incorporates a deterministic trend (e.g., slope and aspect) and models residuals.	When soil property varies systematically over space.
Regression Kriging (RK)	Combines regression (covariates like DEM and NDVI) and kriging of residuals.	Widely used in DSM to combine environmental predictors and spatial structure.

How Kriging Helps in DSM

Kriging plays a crucial role in DSM by:

1. Spatial Interpolation

When field sampling is limited (common in soil surveys), kriging can predict soil property values at unsampled locations based on nearby sampled data and their spatial structure.

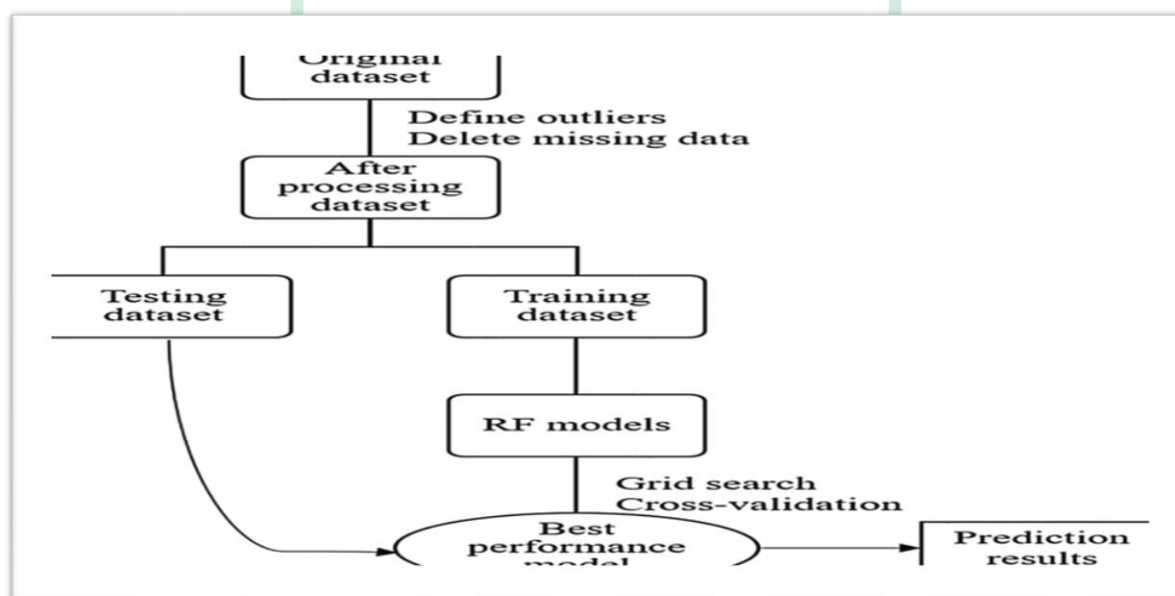
2. Generating Continuous Soil Property Maps

Kriging is used to create high-resolution continuous surfaces (rasters) of soil properties like pH, SOC, clay content and nutrient availability — essential outputs of DSM.

Process Steps of Digital Soil Mapping (DSM):

- Soil Data Collection
- Environmental Covariate Preparation
- Database Integration.
- Model Selection & Fitting
- Spatial Prediction
- Accuracy Assessment
- Map Production and Dissemination

Reference: Hengl *et al.* (2017)



Indian DSM Initiatives

India has progressively adopted Digital Soil Mapping (DSM) techniques for soil resource inventory, monitoring, and sustainable land management.

Major DSM Initiatives in India

◆ Soil Information System (SIS) — NBSS&LUP

- Developed by the National Bureau of Soil Survey and Land Use Planning (NBSS&LUP).
- A comprehensive, spatial soil database integrating soil survey data, environmental covariates (like DEM and remote sensing) and geostatistical models.
- Aims to provide digital soil maps for precision farming, land use planning and soil health management.

◆ Soil Health Card (SHC) Scheme

- Launched in 2015 by the Government of India.
- While largely field-sampling-based, it integrates GIS tools and digital mapping to prepare district and block-level soil fertility maps.
- Promotes DSM techniques for state-level soil information systems.

◆ Digital Soil Resource Mapping Projects (State Level)

- States like Maharashtra, Karnataka, Rajasthan and Tamil Nadu have initiated DSM-based projects for:
 - Land capability mapping
 - Soil fertility zoning
 - Watershed development planning
 - Precision agriculture advisories

◆ Indian Remote Sensing (IRS) Satellite Data Integration

- ISRO and ICAR collaborations have promoted the use of IRS satellite data (LISS-IV and Cartosat DEM) for preparing soil moisture, erosion risk and land degradation maps, applying DSM principles

Future Challenges of Digital Soil Mapping

- Limited Data Availability
- Covariate Selection Issues
- Model Selection and Transferability
- Uncertainty Handling
- Integration with Decision Support Tools
- Temporal Dynamics Monitoring
- Ethical and Data Ownership Issues
- Shortage of Trained Experts
- High Computational Demands
- Lack of Standardization

Conclusion

Digital Soil Mapping (DSM) has emerged as a powerful, modern approach for generating spatially explicit, quantitative soil information using statistical and geospatial techniques. It offers significant advantages over conventional methods in terms of accuracy, maximum area cover, speed and the ability to integrate diverse environmental covariates. DSM supports precision agriculture, land-use planning and natural resource management by delivering detailed, scalable soil maps. However, several challenges such as limited high-quality soil data, model transferability issues, handling of uncertainty, lack of standardization and shortage of trained experts still constrain its widespread application. Addressing these limitations through improved data infrastructure, advanced modelling techniques, capacity building and policy frameworks will be crucial to fully realize the potential of DSM in supporting sustainable agricultural development and land management, particularly in data-scarce regions like India.

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Digital Soil Mapping and its Application in Agronomic Planning



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Abstract

Digital Soil Mapping (DSM) represents a paradigm shift in how we understand, quantify, and manage soil resources for agricultural production. By integrating environmental covariates, statistical modeling, and geospatial technologies, DSM provides high-resolution soil property predictions that are revolutionizing agronomic decision-making. This article explores the principles, methodologies, and practical applications of DSM in modern agronomic planning, demonstrating how this technology enables precision agriculture, optimizes input management, and contributes to sustainable farming systems.

Keywords: Digital Soil Mapping, Precision Agriculture, Variable Rate Application, SCORPAN Model, Agronomic Planning

1. INTRODUCTION: THE SOIL INFORMATION DEFICIT

Agriculture stands at a crossroads. With a global population projected to reach 9.7 billion by 2050, food production must increase by 60-70% while simultaneously reducing environmental impacts (FAO, 2017). The foundation of this challenge—quite literally—is soil. Yet, despite soil being agriculture's most critical natural capital, our knowledge of its spatial distribution remains remarkably coarse.

Traditional soil survey methods, developed in the early 20th century, have served us well. However, these conventional approaches produce categorical maps at broad scales (typically 1:50,000 to 1:250,000), which are insufficient for modern precision agriculture operations requiring meter-scale decisions (Minasny & McBratney, 2016). A farmer operating a variable rate applicator needs to know not just that their field contains "sandy loam," but the precise clay percentage, pH, and nutrient status at 10-meter intervals.

Digital Soil Mapping (DSM) emerges as the solution to this information deficit. Defined by Lagacherie et al. (2007) as "the creation and population of spatial soil information systems by numerical models inferring the spatial and temporal variations of soil types and soil properties from soil observations and knowledge and from related environmental variables," DSM represents the convergence of soil science, statistics, and geospatial technology.

The implications for agronomic planning are profound. With high-resolution soil property maps, agronomists can design site-specific management zones, optimize fertilizer applications, predict crop performance, and manage irrigation with unprecedented precision.

2. THEORETICAL FOUNDATION: THE SCORPAN MODEL

The conceptual foundation of DSM rests on the pioneering work of Hans Jenny (1941), who proposed that soil formation is a function of climate, organisms, relief, parent material, and time. In the digital era, this has been reformulated into the **SCORPAN framework** (McBratney et al., 2003):

$$S = f(s, c, o, r, p, a, n) + e$$

Where:

- S = Soil property or class
- s = Soil (existing soil information)
- c = Climate (temperature, precipitation patterns)
- o = Organisms (vegetation, fauna, land use)
- r = Relief (topography, terrain attributes)

- **p** = Parent material (lithology, geology)
- **a** = Age (time factors)
- **n** = Spatial position (geographic location)
- **e** = Error term

This model provides the theoretical scaffold for DSM. Instead of relying solely on expert interpretation and manual delineation, DSM quantifies the relationship between observable environmental covariates (the right side of the equation) and soil properties (the left side) using statistical and machine learning methods.

2.1 Environmental Covariates: The Data Layer

The power of DSM lies in its ability to leverage vast amounts of spatial data. Modern DSM projects typically integrate:

1. **Remote Sensing Data:** Satellite imagery (Landsat, Sentinel-2) provides spectral information correlated with soil organic matter, iron oxides, and moisture (Mulder et al., 2011).
2. **Digital Elevation Models (DEMs):** High-resolution topographic data enables calculation of derivative terrain attributes such as slope, aspect, curvature, and wetness indices that strongly influence soil formation (Wilson & Gallant, 2000).
3. **Proximal Sensing:** Ground-based sensors (electromagnetic induction, gamma radiometrics, visible-near infrared spectroscopy) provide direct measurements of soil properties across landscapes (Viscarra Rossel et al., 2011).
4. **Legacy Soil Data:** Existing soil profile descriptions and laboratory analyses serve as critical calibration points.

3. METHODOLOGY: FROM DATA TO DIGITAL MAPS

The DSM workflow involves several systematic steps:

3.1 Data Acquisition and Preparation

The process begins with assembling environmental covariates and collecting soil observations. Modern campaigns often employ **conditioned Latin Hypercube Sampling (cLHS)**, a stratified approach that ensures samples represent the full range of environmental conditions present in the study area (Minasny & McBratney, 2006).

3.2 Model Building

DSM employs diverse statistical and machine learning algorithms:

- **Multiple Linear Regression:** Simple but interpretable
- **Random Forests:** Handles non-linear relationships and variable interactions (Hengl et al., 2018)
- **Support Vector Machines:** Effective in high-dimensional spaces
- **Neural Networks:** Captures complex patterns in large datasets
- **Cubist:** Rule-based approach popular in soil mapping (Malone et al., 2009)

3.3 Validation and Uncertainty Quantification

Rigorous validation using independent test datasets is crucial. Metrics such as Root Mean Square Error (RMSE), Mean Absolute Error (MAE), and the coefficient of determination (R^2) quantify prediction accuracy. Importantly, modern DSM also generates uncertainty maps, showing where predictions are more or less reliable (Kempen et al., 2012).

4. APPLICATION IN AGRONOMIC PLANNING

The true value of DSM manifests in its agricultural applications. Below are key domains where DSM transforms agronomic decision-making:

4.1 Precision Nutrient Management

Traditional "blanket" fertilizer applications ignore within-field soil variability, leading to over-application in some areas (economic loss, environmental pollution) and under-application in others (yield limitation). DSM-derived maps of pH, phosphorus, potassium, and other nutrients enable **Variable Rate Application (VRA)**.

Case Example: In a study across Australian wheat fields, Whelan et al. (2009) demonstrated that DSM-guided nitrogen management reduced fertilizer use by 20% while maintaining yield, resulting in significant economic and environmental benefits.

4.2 Water Management and Irrigation Design

Soil texture governs water holding capacity—arguably the most important property for dryland and irrigated agriculture. DSM products showing clay content distribution allow agronomists to:

- Design variable rate irrigation systems
- Identify zones prone to waterlogging or drought
- Optimize drainage system placement
- Schedule irrigation based on soil-specific water budgets

4.3 Crop Suitability and Zone Management

High-resolution soil maps reveal constraints invisible to traditional surveys. Subsoil sodicity, hardpans, salinity, and pH barriers can be mapped continuously, enabling:

- Informed crop selection decisions
- Delineation of management zones for differential seeding rates
- Strategic soil amelioration (e.g., gypsum application only where sodic)
- Precision deep ripping to break compacted layers in specific locations

4.4 Soil Carbon Accounting

With agriculture increasingly participating in carbon markets, accurate quantification of soil organic carbon (SOC) stocks is essential. DSM provides the spatial framework for:

- Baseline SOC stock assessment
- Monitoring changes over time
- Verifying carbon sequestration claims for credit generation (Malone et al., 2014)

Table 1: Comparison of Traditional Soil Survey vs. Digital Soil Mapping

Attribute	Traditional Soil Survey	Digital Soil Mapping
Output Format	Polygon-based soil map units	Continuous raster (grid) predictions
Spatial Resolution	Coarse (1:50,000 - 1:250,000)	Fine (5m - 100m pixels)
Property Information	Qualitative descriptions + limited lab data	Quantitative predictions for specific properties
Update Frequency	Decades (static)	Can be updated annually with new data
Cost per km²	High (labor-intensive fieldwork)	Moderate (technology costs, scales efficiently)
Uncertainty Assessment	Qualitative (expert judgment)	Quantitative (statistical confidence intervals)
Integration with Precision Ag	Limited (boundaries too coarse)	Direct (designed for VRT equipment)
Subsoil Information	Limited profile descriptions	Can predict at multiple depths

5. CASE STUDIES: DSM IN ACTION

5.1 The GlobalSoilMap Initiative

The GlobalSoilMap project (globalsoilmap.net) represents the most ambitious DSM effort to date—a collaborative attempt to map soil properties globally at 100m resolution for standard depth intervals. Arrouays et al. (2017) report that over 70 countries have contributed data, with products already supporting land use planning, climate modeling, and agricultural development in data-poor regions.

5.2 Cotton Production in Australia

In Australia's cotton belt, DSM has been integrated into routine farm management. Wong et al. (2017) documented a case where electromagnetic (EM) surveys combined with strategic soil sampling created clay content maps. These maps guided precision irrigation layout, reducing water use by 15% and increasing fiber quality by minimizing waterlogging in heavy-textured zones.

5.3 Vineyard Terroir Delineation

Premium wine production depends on understanding terroir—the combination of soil, topography, and microclimate. Priori et al. (2014) used DSM to map soil depth, texture, and stoniness in Italian vineyards at 2m

resolution. The resulting maps enabled harvest to be organized by soil-defined quality zones, with premium lots commanding 30% higher prices.

6. TECHNOLOGICAL ENABLERS

Several technological advances have accelerated DSM adoption:

6.1 Satellite Remote Sensing

The free availability of Landsat and Sentinel imagery has democratized access to temporal spectral data. Bare soil periods, captured in time-series analysis, reveal soil properties through spectral signatures (Demattê et al., 2018).

6.2 Unmanned Aerial Systems (UAS)

Drones equipped with multispectral sensors can capture ultra-high resolution imagery (< 5cm pixels), useful for detecting within-field variability and validating ground-based DSM products (Pajares, 2015).

6.3 Machine Learning Algorithms

The rise of accessible machine learning libraries (scikit-learn, TensorFlow, R packages like 'caret' and 'ranger') has made sophisticated predictive modeling available to non-specialists. Cloud computing platforms enable processing of massive datasets that would be impossible on local machines.

6.4 Proximal Soil Sensing

On-the-go sensors mounted on tractors or all-terrain vehicles can collect thousands of soil measurements per day. Viscarra Rossel et al. (2011) provide a comprehensive review showing that visible-near infrared (vis-NIR) spectroscopy can predict over 20 soil properties simultaneously from a single scan.

Table 2: Key Soil Properties Mapped by DSM and Their Agronomic Significance

Soil Property	DSM Prediction Method	Agronomic Application
Soil Texture (Clay %)	EM surveys, gamma radiometrics, vis-NIR	Water holding capacity, trafficability, nutrient retention
pH	Legacy data + relief attributes, vis-NIR	Lime requirement mapping, crop suitability
Organic Carbon	Satellite NDVI, vis-NIR spectroscopy, climate data	Fertility assessment, carbon credit accounting
Cation Exchange Capacity (CEC)	Clay % proxies, vis-NIR, parent material	Nutrient management planning
Available Phosphorus	Legacy samples + topography, yield maps	Phosphorus fertilizer VRA
Electrical Conductivity (EC)	Direct EM measurement	Salinity management, irrigation design
Soil Depth	Gamma radiometrics, topographic indices	Root zone assessment, drainage planning
Bulk Density	Indirect via texture + carbon, compression sensors	Compaction management, tillage decisions

Note: EM = Electromagnetic induction; vis-NIR = visible-near infrared spectroscopy; VRA = Variable Rate Application

7. CHALLENGES AND LIMITATIONS

Despite its transformative potential, DSM faces several challenges:

7.1 Data Quality and Availability

The old computer science maxim "garbage in, garbage out" applies strictly to DSM. Poor quality legacy data, sparse sampling, or outdated environmental layers compromise prediction accuracy (Arrouays et al., 2014).

7.2 Validation and Ground-Truthing

All models require validation with independent field data. This "ground-truthing" remains labor-intensive and expensive, creating a paradox: the areas most in need of DSM (data-poor regions) are least able to afford proper validation.

7.3 Model Interpretability

Complex machine learning models (neural networks, deep learning) may achieve high accuracy but operate as "black boxes." Agronomists and farmers may be reluctant to trust recommendations they cannot conceptually understand (Padarian et al., 2020).

7.4 Scale Mismatch

Environmental covariates (like satellite imagery at 10-30m resolution) may not capture fine-scale variability important for precision agriculture. This can lead to smoothing of critical boundaries or features.

7.5 Temporal Dynamics

Most DSM products represent a snapshot in time, yet soils change—especially properties like moisture, nutrient status, and organic matter. Integrating temporal dynamics into DSM remains an active research frontier (Shi et al., 2020).

8. IMPLEMENTATION GUIDE FOR AGRONOMISTS

For practitioners considering DSM adoption, the following roadmap is recommended:

Step 1: Define Objectives Identify specific agronomic questions: Are you targeting nutrient management? Irrigation design? Crop zoning?

Step 2: Inventory Existing Data Collect all available soil tests, yield maps, elevation data, and imagery for your area of interest.

Step 3: Engage Specialists Partner with soil scientists, GIS analysts, or commercial DSM service providers. Many agricultural consultancies now offer turnkey DSM services.

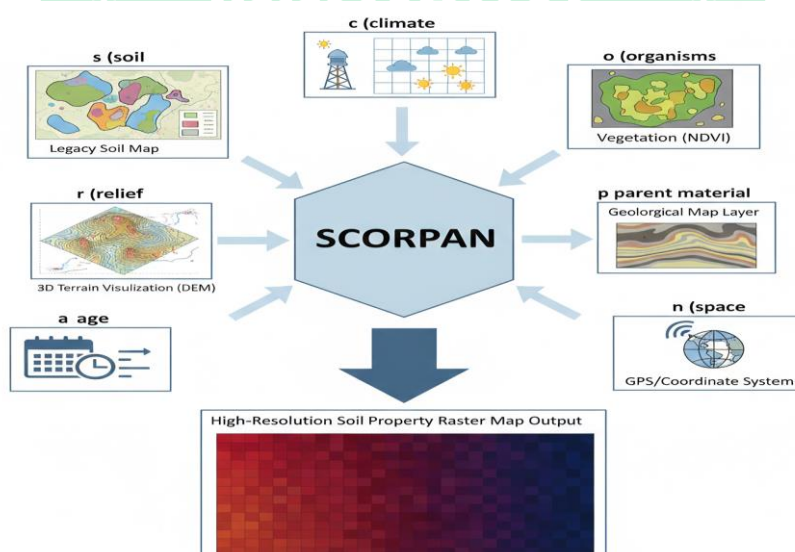
Step 4: Strategic Field Sampling Supplement existing data with targeted field sampling using cLHS or similar design.

Step 5: Model Development and Validation Build predictive models, rigorously validate them, and generate both prediction and uncertainty maps.

Step 6: Integration into Farm Management Systems Export maps in formats compatible with VRT equipment (typically ESRI shapefiles or ISO XML).

Step 7: Monitor and Update Treat DSM as a living system. Update maps as new data (yield, additional samples) becomes available.

Figure 1: The SCORPAN Conceptual Framework for Digital Soil Mapping



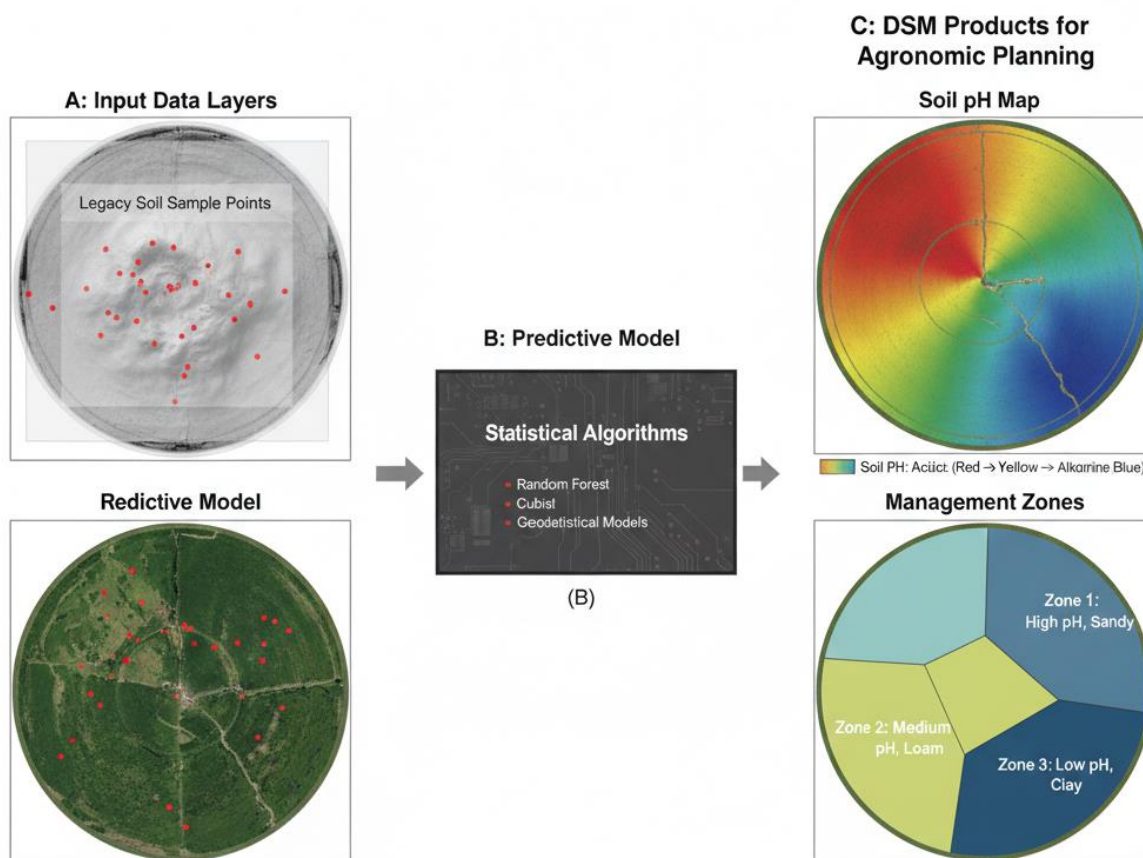
Description for Figure 1: A conceptual diagram showing the SCORPAN model at the center, with arrows pointing to it from surrounding boxes representing each factor:

- **s (soil):** Icon showing legacy soil map
- **c (climate):** Weather station/rainfall grid
- **o (organisms):** Satellite image showing vegetation (NDVI)
- **r (relief):** 3D terrain visualization (DEM)
- **p (parent material):** Geological map layer
- **a (age):** Time/calendar icon
- **n (space):** GPS/coordinate system

From the central SCORPAN model, an arrow points to a high-resolution soil property raster map output.

Caption: The SCORPAN model framework showing how environmental covariates are integrated through statistical modeling to predict soil properties at unsampled locations (adapted from McBratney et al., 2003).

Figure 2: Example DSM Workflow and Output for Agronomic Planning



Description for Figure 2: A three-panel horizontal figure:

Panel A (Left): Input data layers stacked as semi-transparent overlays:

- Sentinel-2 satellite image (RGB composite)
- Digital Elevation Model (hillshade)
- Legacy soil sample points (red dots)

Panel B (Center): The predictive model (represented by a flowchart or "black box" with algorithm names: Random Forest, Cubist, etc.)

Panel C (Right): Output DSM products showing the same field:

- **Top:** Soil pH map (color gradient from red/acidic through yellow/neutral to blue/alkaline)
- **Bottom:** Management zones delineated based on multiple DSM layers, with labels "Zone 1: High pH, Sandy", "Zone 2: Medium pH, Loam", "Zone 3: Low pH, Clay"

Caption: Typical DSM workflow showing integration of multiple data sources (A), predictive modeling (B), and final products used for precision agronomic planning (C).

9. THE FUTURE: EMERGING TRENDS

Several exciting developments promise to expand DSM's impact:

9.1 Real-Time Mapping

Integration of on-the-go sensors with GPS-equipped agricultural machinery will enable real-time soil mapping during field operations, with immediate adjustment of application rates (Adamchuk et al., 2004).

9.2 Deep Learning and AI

Convolutional Neural Networks (CNNs) can analyze soil landscape patterns in imagery, potentially capturing spatial context that traditional models miss (Padarian et al., 2019).

9.3 Fusion with Crop Models

Linking DSM outputs directly to crop simulation models (APSIM, DSSAT) will enable predictive agronomy—forecasting yield under different management scenarios before the season begins (Basso et al., 2016).

9.4 Citizen Science and Crowdsourcing

Mobile apps allowing farmers to contribute soil observations could dramatically increase data density, especially in underserved regions. The "Soil Testing Challenge" initiative in Kenya exemplifies this approach (Vågen et al., 2010).

10. CONCLUSION: A DATA-DRIVEN AGRONOMIC REVOLUTION

Digital Soil Mapping represents far more than a technological upgrade to traditional soil survey methods. It is a fundamental reconceptualization of soil as a continuous, quantifiable, and digitally manageable resource. For agronomic planning, this shift enables unprecedented precision in matching management to soil capability.

The benefits are compelling: reduced input costs, increased yields, minimized environmental impacts, and enhanced resilience to climate variability. As computational power grows, sensor technology becomes more affordable, and machine learning methods mature, DSM will transition from a specialized research tool to a standard component of agricultural practice.

However, realizing this potential requires investment in data infrastructure, training of agricultural professionals, and development of accessible DSM platforms. Policymakers, research institutions, and the private sector must collaborate to ensure that these technologies benefit all scales of production, from smallholder farms to large agribusinesses.

The soil beneath our feet has remained largely invisible to data-driven agriculture. Digital Soil Mapping is changing that reality, one pixel at a time. As we face the challenge of feeding a growing population on a warming planet, seeing—and managing—our soils with digital clarity may be one of agriculture's most powerful tools.

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Ecosystem-Based Fisheries Management: A Paradigm for Long-Term Resource Conservation



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1. Introduction

The world's oceans and freshwater systems face unprecedented pressure from commercial fishing operations, climate change, habitat degradation, and pollution. Traditional fisheries management, which historically focused on single-species maximum sustainable yield (MSY) models, has proven inadequate to address the complex, interconnected challenges of modern marine resource exploitation. The sequential collapse of major fisheries worldwide—from the Grand Banks cod to the Peruvian anchoveta—demonstrates the limitations of reductionist approaches that ignore ecological complexity, trophic interactions, and cumulative anthropogenic impacts. Ecosystem-Based Fisheries Management (EBFM) represents a fundamental reconceptualization of how humanity interacts with aquatic living resources. Rather than treating target species as isolated populations subject to harvest optimization, EBFM recognizes fisheries as integral components of dynamic ecosystems where biological, physical, and human dimensions interact across multiple spatial and temporal scales. This holistic paradigm acknowledges that sustainable fisheries cannot be achieved through species-specific quotas alone, but require comprehensive strategies that maintain ecosystem structure, function, and resilience. The imperative for ecosystem-based approaches has gained international recognition through frameworks including the United Nations Convention on the Law of the Sea, the FAO Code of Conduct for Responsible Fisheries, and the Convention on Biological Diversity. These instruments mandate precautionary management that considers ecosystem integrity alongside resource extraction. This chapter examines the scientific foundations, practical implementation, and conservation outcomes of ecosystem-based fisheries management, offering a comprehensive framework for long-term sustainability of aquatic resources in an era of accelerating environmental change.

2. Conceptual Framework and Foundational Principles

Ecosystem-Based Fisheries Management operates on the premise that sustainable resource use requires maintaining the ecological processes, trophic structures, and habitat integrity that support productive fisheries. This approach transcends the narrow focus on stock biomass and fishing mortality rates that characterized traditional management, instead embracing the full complexity of marine and freshwater ecosystems.

2.1 Core Principles of EBFM

The Food and Agriculture Organization has articulated several foundational principles that distinguish EBFM from conventional approaches. First, management must consider the full range of ecosystem components and their interactions, including non-target species, habitat, water quality, and food web dynamics. This contrasts sharply with single-species management that artificially isolates target populations from their ecological context. Second, spatial management becomes paramount, recognizing that different areas serve distinct ecological functions—spawning grounds, nursery habitats, migration corridors, and feeding areas—that must be protected to maintain population productivity. Third, EBFM embraces the precautionary principle, acknowledging pervasive scientific uncertainty and erring on the side of conservation when knowledge is incomplete. This principle proves particularly critical given the long time lags between ecosystem degradation and observable population declines, the potential for non-linear responses and regime shifts, and the difficulty of reversing ecosystem damage once critical thresholds are crossed. Fourth, adaptive management structures are essential, creating feedback loops between monitoring, assessment, management action, and outcome evaluation that enable continuous learning and adjustment in the face of changing conditions.

2.2 Ecosystem Components and Interactions

Understanding trophic relationships constitutes a central pillar of ecosystem-based management. Fishing operations do not merely reduce target species abundance but propagate effects throughout food webs via predator-prey dynamics, competitive interactions, and functional redundancy. The removal of top predators can trigger trophic cascades, where mid-level consumers increase and subsequently overexploit their prey, fundamentally altering ecosystem structure. The classic example of sea otter extirpation leading to urchin barrens and kelp forest loss illustrates how fishing effects cascade through multiple trophic levels.

Habitat dependencies similarly demand explicit consideration in EBFM frameworks. Many commercially important species exhibit ontogenetic habitat shifts, utilizing different environments across life stages. Destruction of coastal wetlands, mangrove forests, seagrass beds, or coral reefs eliminates critical nursery habitat, imposing recruitment bottlenecks that no amount of fishing effort reduction can overcome. Bottom-contact fishing gears physically degrade benthic habitats, reducing structural complexity that provides refuge for juvenile fish and invertebrates. Ecosystem-based management thus requires spatial protections that preserve essential habitats and limit destructive fishing practices.

3. Contrasting Management Paradigms: Traditional vs. Ecosystem-Based Approaches

The transition from conventional single-species management to ecosystem-based approaches represents more than incremental improvement—it constitutes a paradigm shift in how society conceptualizes fisheries and their governance. Understanding the fundamental differences between these frameworks illuminates why traditional management has failed to prevent overexploitation and ecosystem degradation.

3.1 Single-Species Management Limitations

Traditional fisheries management emerged from agricultural paradigms viewing fish populations as crops subject to harvest optimization. The dominant model, maximum sustainable yield, seeks to identify the population size and fishing mortality rate that maximizes long-term catch without causing stock collapse. This approach assumes equilibrium dynamics, density-dependent population regulation, and isolation of target species from ecological interactions. These assumptions rarely hold in reality. Environmental variability creates non-stationary dynamics where optimal harvest rates fluctuate unpredictably. Species interactions mean that fishing one population affects others through trophic pathways, competitive release, and predator-prey dynamics. Furthermore, single-species management generates perverse incentives for sequential depletion. As one stock declines, fishing effort shifts to alternative species, progressively degrading the ecosystem from the top down. This pattern has repeated globally, with fisheries sequentially targeting apex predators, then mid-level consumers, and ultimately low-trophic-level species for reduction to fishmeal. The phenomenon of fishing down marine food webs documents this systematic degradation, with mean trophic level of catches declining steadily as ecosystems are simplified through preferential removal of high-value predators.

3.2 Ecosystem-Based Management Advantages

EBFM addresses these limitations through several mechanisms. First, multispecies models explicitly incorporate trophic interactions, enabling managers to anticipate cascade effects and technical interactions where multiple species are caught simultaneously. These models reveal that optimal fishing strategies for multispecies assemblages often differ markedly from single-species optima, typically requiring lower overall exploitation rates to prevent ecosystem instability. Second, ecosystem indicators provide early warning signals of degradation before individual populations collapse. Metrics including mean trophic level, size structure, functional diversity, and primary production required to sustain fisheries offer integrated measures of ecosystem state. Third, spatial management tools protect critical habitats and maintain ecosystem structure. Marine protected areas (MPAs) preserve reference conditions, serve as source populations for recolonization of fished areas, and protect spawning aggregations and nursery grounds. Evidence demonstrates that well-designed MPA networks enhance both conservation outcomes and fisheries yield through spillover effects, biomass accumulation, and genetic diversity maintenance. Fourth, gear restrictions and seasonal closures minimize bycatch, reduce habitat damage, and protect vulnerable life stages, addressing ecosystem impacts beyond simple biomass extraction.

Table 1. Comparative Framework: Traditional Single-Species vs. Ecosystem-Based Fisheries

Management

Management Dimension	Traditional Single-Species	Ecosystem-Based (EBFM)
Primary Focus	Individual target species biomass and fishing mortality	Ecosystem structure, function, and resilience including all components
Management Objective	Maximum sustainable yield (MSY) for target species	Sustainable resource use while maintaining ecosystem integrity and services
Spatial Consideration	Stock boundaries, minimal spatial protection	Comprehensive spatial planning, habitat protection, MPA networks
Species Interactions	Ignored or treated as external factors	Explicitly modeled through trophic interactions, competition, mutualism
Bycatch Management	Minimal consideration; discards often unaccounted	Central concern; gear restrictions, bycatch reduction devices, full accounting
Habitat Impacts	Not directly addressed in stock assessments	Gear regulations, spatial closures, essential fish habitat designation
Climate & Environment	Environmental effects treated as random variation	Integrated climate projections, regime shifts, environmental drivers
Stakeholder Engagement	Limited; primarily fishing industry consultation	Broad participation: fishers, conservation groups, coastal communities, indigenous peoples
Time Horizon	Short to medium term (annual to decadal)	Intergenerational perspective (decades to centuries)

4. Implementation Strategies and Management Tools

Translating ecosystem-based principles into operational management requires a diverse toolkit combining regulatory measures, spatial protections, technological innovations, and institutional reforms. Successful EBFM implementation draws from multiple disciplines and demands coordination across jurisdictions and sectors.

4.1 Marine Spatial Planning and Protected Areas

Marine spatial planning provides a systematic framework for allocating ocean space among competing uses while safeguarding ecological values. This process maps biological resources, identifies ecologically significant areas, assesses human impacts, and develops zoning schemes that separate incompatible activities. Effective spatial planning requires comprehensive baseline data on species distributions, habitat types, oceanographic features, and human use patterns. Geographic information systems enable integration of multiple data layers, revealing spatial patterns and conflicts invisible when examining individual factors in isolation. Marine protected areas constitute the cornerstone of spatial management, preserving ecosystem structure and function through fishing prohibitions or restrictions. Evidence demonstrates that well-designed MPAs increase biomass, restore size structure, enhance biodiversity, and generate spillover benefits to adjacent fished areas. Optimal MPA design incorporates several principles: adequate size to encompass home ranges and larval dispersal distances, connectivity among sites to facilitate population exchange, representation of diverse habitat types, protection of critical life history stages, and strategic placement to maximize conservation and fisheries benefits. Networks of MPAs prove more effective than isolated reserves, providing redundancy against localized disturbances and maintaining metapopulation dynamics.

4.2 Ecosystem Indicators and Reference Points

Operationalizing EBFM requires metrics that capture ecosystem state and trends beyond single-species biomass. Ecosystem indicators serve multiple functions: tracking changes in community structure, detecting regime shifts, evaluating management effectiveness, and communicating ecosystem status to stakeholders and policymakers. Effective indicators exhibit sensitivity to fishing pressure and environmental change, clear interpretation, cost-effective monitoring, and relevance to management objectives. Size-based indicators provide powerful insights into ecosystem structure and fishing impacts. Mean body size, size spectra, and proportion of large fish reflect fishing intensity, with overfishing systematically removing large individuals and reducing mean size. Trophic indicators including mean trophic level of catches and primary production required to sustain fisheries reveal food web alterations and extraction intensity relative to ecosystem productivity. Biodiversity indicators encompassing species richness, evenness, and functional diversity measure ecosystem complexity and resilience. Habitat

indicators assess extent and condition of critical habitats including coral reefs, seagrass beds, and spawning grounds.

4.3 Harvest Control Rules and Precautionary Limits

Harvest control rules translate ecosystem indicators into management actions, specifying how fishing regulations adjust in response to monitored changes. These pre-agreed decision frameworks reduce political interference, ensure timely responses to declining indicators, and provide industry with predictable management. Ecosystem-based harvest control rules incorporate multiple species interactions, environmental conditions, and fishing impacts on habitat and bycatch species. For instance, forage fish rules may prohibit fishing when predator populations decline below thresholds, recognizing that forage species support ecosystem productivity beyond their direct harvest value. Precautionary reference points establish bounds beyond which fishing should be curtailed to avoid ecosystem damage. Limit reference points define unacceptable states requiring immediate management intervention, while target reference points identify desirable conditions. EBFM expands traditional biomass-based reference points to include ecosystem thresholds for trophic structure, habitat extent, and bycatch mortality. Uncertainty buffers ensure that natural variability and assessment errors do not push systems beyond safe operating space. Dynamic reference points that adjust based on environmental conditions and ecosystem productivity provide greater resilience than static benchmarks.

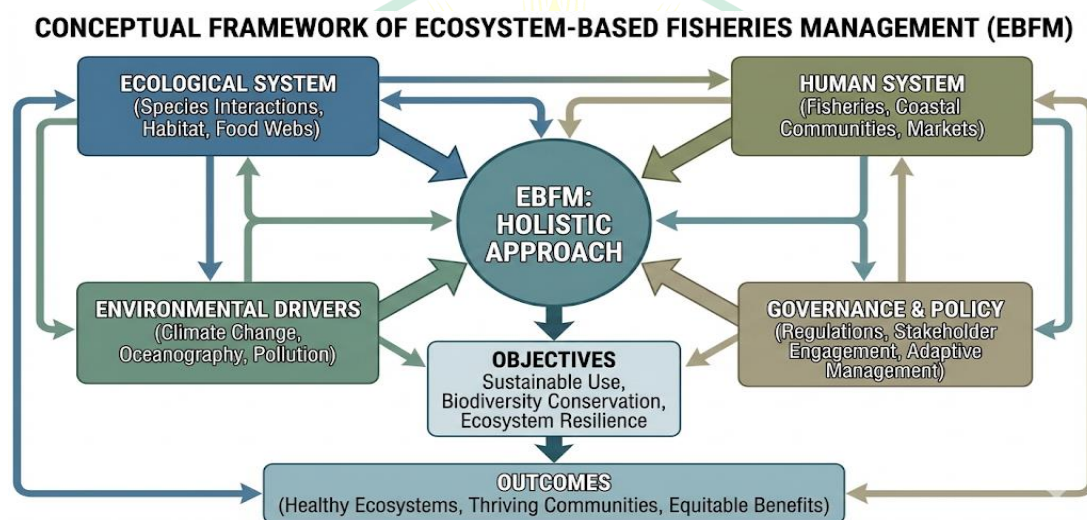


Figure 1. Conceptual Framework of Ecosystem-Based Fisheries Management

5. Case Studies:

Ecosystem-Based Management in Practice Examining real-world applications of EBFM illuminates both the potential and challenges of implementing ecosystem approaches across diverse contexts. These case studies demonstrate that while perfect implementation remains elusive, substantial progress toward ecosystem-based management yields measurable conservation and fisheries benefits.

5.1 Alaska Ecosystem-Based Management

The North Pacific Fishery Management Council has pioneered ecosystem-based approaches in Alaska waters, widely regarded as the gold standard for sustainable fisheries governance. Key elements include comprehensive bycatch monitoring with strict limits enforced through fishery closures when thresholds are exceeded, habitat protection through extensive bottom trawl closures covering millions of square kilometres, ecosystem considerations in harvest specifications where forage fish abundance influences predator quotas, and precautionary management with conservative harvest rates and large uncertainty buffers. The pollock fishery exemplifies ecosystem-based management success. Despite being one of the world's largest single-species fisheries, pollock management incorporates Steller sea lion protection measures including spatial and temporal fishing restrictions, limits on localized depletion to ensure prey availability for predators, ecosystem modelling to understand pollock's role in the broader food web, and adaptive management that adjusts harvest strategies

based on predator population trends. These measures have maintained robust pollock stocks while contributing to sea lion population recovery, demonstrating that economically valuable fisheries and ecosystem conservation can coexist.

5.2 Coral Triangle Initiative

The Coral Triangle, spanning six Southeast Asian nations, contains the world's highest marine biodiversity but faces severe overfishing, destructive fishing practices, and habitat degradation. The Coral Triangle Initiative represents a multilateral commitment to ecosystem-based management in a developing-nation context where food security and poverty alleviation intersect with conservation imperatives. Management strategies emphasize community-based approaches recognizing that top-down regulation proves ineffective where state capacity is limited and coastal populations depend directly on marine resources for subsistence. Key initiatives include locally managed marine areas where communities establish their own rules for resource access and harvest, ecosystem approach to fisheries management (EAFM) training programs building capacity for holistic assessment and planning, mangrove and coral reef restoration recognizing habitat as foundational to fisheries productivity, alternative livelihood development reducing fishing pressure through economic diversification, and transboundary cooperation addressing migratory species and shared stocks. While implementation remains uneven, communities adopting EBFM principles demonstrate improved resource conditions, enhanced catches, and greater resilience to environmental stressors.

5.3 Baltic Sea Integrated Management

The Baltic Sea exemplifies ecosystem-based management challenges in semi-enclosed seas with multiple jurisdictions and cumulative stressors. Beyond fishing, the Baltic faces eutrophication from agricultural runoff, hypoxic dead zones, invasive species, and climate-driven environmental changes. The Helsinki Commission (HELCOM) coordinates regional ecosystem-based management through the Baltic Sea Action Plan, integrating fisheries management with pollution control, habitat protection, and climate adaptation. Multispecies management proves critical given strong trophic interactions among cod, herring, and sprat. Overfishing cod released sprat from predation, enabling sprat population explosions that compete with herring for zooplankton and consume cod eggs, creating a feedback loop maintaining cod at depressed levels. Ecosystem modelling revealed that cod recovery requires not only reduced cod fishing mortality but also sprat harvest to relieve predation pressure on cod recruitment. Integrated management now balances catches across trophic levels, aiming to restore historical ecosystem structure while acknowledging irreversible changes from eutrophication and warming.

Table 2. Key Ecosystem Indicators for Monitoring Fisheries Sustainability

Indicator Category	Specific Metrics	Ecological Significance	Management Response
Trophic Structure	Mean trophic level of catch, trophic spectrum, predator-prey ratios	Indicates fishing down food webs and ecosystem simplification	Reduce pressure on top predators, protect forage species
Size Structure	Mean body size, large fish indicator (LFI), size spectra slope	Reflects fishing intensity and ecosystem productivity; large fish drive reproduction	Implement size limits, reduce overall fishing pressure
Biodiversity	Species richness, Shannon diversity, functional diversity, evenness	Measures ecosystem complexity and resilience to disturbance	Gear selectivity improvements, bycatch reduction, habitat protection
Primary Production	Primary production required (PPR), catch per unit primary production	Assesses extraction intensity relative to ecosystem energy base	Set ecosystem-level catch limits based on productivity
Habitat Condition	Benthic integrity, coral cover, seagrass extent, structural complexity	Habitat provides nursery areas, refugia, and productivity foundation	Gear restrictions, spatial closures, restoration initiatives
Bycatch Mortality	Non-target species catch rates, protected species interactions, discard ratios	Threatens endangered species and disrupts food webs	Bycatch limits, area closures, gear modifications, observer coverage

6. Challenges and Barriers to Implementation

Despite conceptual clarity and demonstrated benefits, ecosystem-based fisheries management faces substantial obstacles to widespread adoption. These barriers span scientific, institutional, economic, and political domains, requiring coordinated efforts to overcome.

6.1 Data and Scientific Capacity Limitations

Comprehensive ecosystem assessment demands vastly more data than single-species management, including multispecies abundance, food web structure, habitat extent and condition, environmental parameters, and fishing impacts across all sectors and gears. Many regions, particularly in developing nations, lack even basic stock assessment capacity, let alone ecosystem-level monitoring infrastructure. The high costs of comprehensive sampling programs—employing research vessels, acoustic surveys, electronic monitoring, and observer programs—exceed budgets of most fisheries management agencies. Ecosystem modelling presents additional challenges. Multispecies and ecosystem models require extensive parameterization of biological interactions, consumption rates, and environmental responses, parameters often poorly known. Model uncertainty compounds across trophic levels and species interactions, potentially yielding predictions too imprecise for management application. Validating ecosystem models against independent data proves difficult given limited time series and confounding factors. These challenges necessitate pragmatic approaches that balance scientific rigor with practical feasibility, employing simplified models, risk-based frameworks, and adaptive learning as knowledge accumulates.

6.2 Institutional and Governance Obstacles

Existing governance structures often impede ecosystem-based management through fragmented jurisdiction, where different agencies regulate fishing, pollution, coastal development, and shipping with minimal coordination. Species-specific management councils and quotas create institutional inertia resisting holistic approaches. Short political cycles prioritize immediate economic returns over long-term sustainability, while diffuse ecosystem benefits prove difficult to defend against concentrated industry opposition. Legal frameworks pose additional barriers. Fisheries legislation often mandates maximum sustainable yield optimization for individual stocks, conflicting with ecosystem-level objectives that may require lower catches to preserve ecological function. Property rights systems based on historical catch allocate harvest privileges to existing participants, creating vested interests opposing changes that reduce overall exploitation rates. Reforming these institutional structures requires political will, stakeholder buy-in, and often legislative amendments—processes measured in years or decades rather than management cycles.

6.3 Socioeconomic Transitions

Implementing ecosystem-based management generates short-term economic costs through reduced catches, displaced fishing effort, and compliance expenses. Small-scale fishers and fishing-dependent communities often bear disproportionate burdens, lacking diversification options and safety nets available to larger operations. Resistance from affected stakeholders can derail reform efforts, particularly where livelihoods depend directly on fishing access. Successful transitions require compensation mechanisms, alternative livelihood development, and transparent processes ensuring equitable distribution of costs and benefits. Market failures compound implementation challenges. Ecosystem services preserved through EBFM—biodiversity, resilience, existence values—generate public goods not captured in market prices. Consumers often lack information on or willingness to pay premiums for sustainably caught fish, undermining incentives for voluntary adoption of ecosystem-based practices. Subsidy reform proves politically difficult despite economic inefficiency and environmental harm, as subsidies create powerful constituencies defending their continuation. Addressing these economic barriers requires innovative financing mechanisms, market-based instruments, and integration of ecosystem service values into decision-making frameworks.

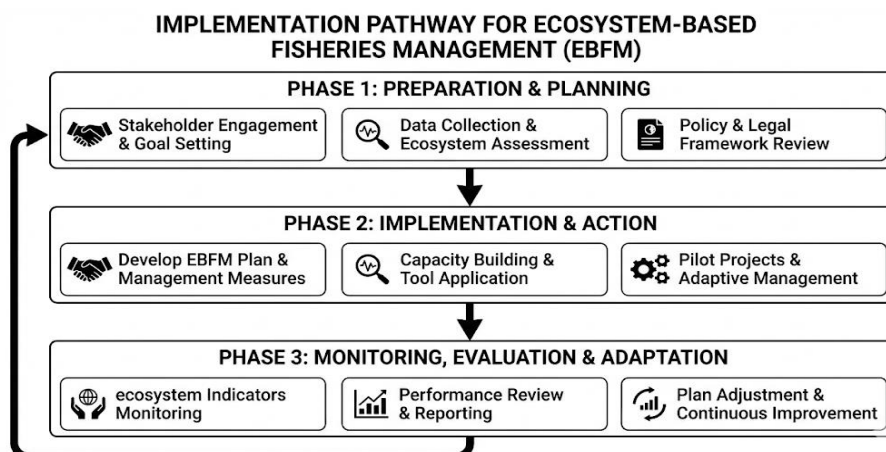


Figure 2. Implementation Pathway for Ecosystem-Based Fisheries Management

7. Climate Change and Adaptive Ecosystem Management

Climate change fundamentally alters the context for fisheries management, driving species redistributions, phenological shifts, productivity changes, and increased variability. Ecosystem-based management provides frameworks for building climate resilience into fisheries governance, though substantial adaptation remains necessary. Ocean warming drives poleward species migrations and depth shifts, redistributing fishing opportunities and creating jurisdictional conflicts as stocks move across management boundaries. Ecosystem-based approaches facilitate adaptation through flexible spatial management that adjusts protected areas and fishing zones as distributions shift, dynamic reference points incorporating environmental covariates rather than assuming stationary productivity, portfolio effects maintaining diverse fleets and target species providing insurance against variable abundance, and precautionary buffers accounting for increased uncertainty in non-stationary systems. Ocean acidification and deoxygenation present additional challenges, particularly for calcifying species and those with high oxygen demands. Ecosystem-based management addresses these stressors through habitat protection preserving refugia and sources of climate-resilient populations, reduced exploitation maintaining age structure and genetic diversity enabling adaptation, integrated coastal management controlling local stressors that compound climate impacts, and long-term monitoring detecting regime shifts and threshold responses. Climate-ready EBFM embraces uncertainty, builds adaptive capacity, and prioritizes ecosystem resilience over short-term yield maximization.

8. Future Directions and Emerging Approaches

Advancing ecosystem-based fisheries management requires continued innovation in science, technology, governance, and stakeholder engagement. Emerging tools and approaches offer promise for overcoming current limitations and deepening ecosystem integration. Environmental DNA (eDNA) technology enables cost-effective biodiversity monitoring through water sampling, detecting species presence without physical capture. This approach facilitates comprehensive ecosystem assessment, revealing cryptic or rare species, tracking community composition changes, and validating ecosystem models. Autonomous vehicles including underwater gliders and surface drones extend spatial and temporal coverage of oceanographic monitoring at reduced cost compared to ship-based surveys. Artificial intelligence and machine learning offer powerful analytical tools for ecosystem assessment. These methods can identify complex patterns in multivariate datasets, predict species distributions under changing conditions, optimize spatial management configurations, and detect regime shifts from indicator time series. However, machine learning models require careful validation and interpretation, as correlative patterns do not necessarily reflect causal relationships and extrapolation beyond training data proves unreliable. Participatory modelling and co-management approaches integrate stakeholder knowledge and values directly into assessment and decision-making processes. These frameworks recognize that fishers possess detailed ecological knowledge and understand trade-offs between management options. Involving stakeholders in model development, scenario evaluation, and harvest control rule design improves both scientific quality and social

legitimacy of management. Future EBFM implementation will increasingly rely on collaborative governance balancing scientific expertise with local knowledge and community priorities.

9. Conclusion

Ecosystem-Based Fisheries Management represents not merely an incremental improvement over traditional approaches but a fundamental reconceptualization of humanity's relationship with aquatic living resources. By embracing ecological complexity, acknowledging uncertainty, and prioritizing long-term sustainability over short-term yield maximization, EBFM offers a pathway toward reversing historical overexploitation and rebuilding degraded marine ecosystems. The scientific foundations of EBFM rest on decades of ecological research demonstrating the inadequacy of single-species models, the pervasiveness of trophic interactions and habitat dependencies, and the critical importance of maintaining ecosystem structure and function. Practical implementation tools—marine spatial planning, ecosystem indicators, multispecies harvest control rules, and adaptive management frameworks—provide operational mechanisms for translating principles into action. Case studies from Alaska, the Coral Triangle, the Baltic Sea, and elsewhere demonstrate that ecosystem-based approaches yield measurable conservation benefits while supporting productive fisheries. Yet substantial challenges persist. Data limitations, institutional inertia, political resistance, and socioeconomic disruptions impede widespread EBFM adoption, particularly in developing regions where capacity and resources prove scarce. Climate change compounds these challenges, driving non-stationary dynamics that undermine historical reference points and require adaptive management capacity. Overcoming these barriers demands sustained commitment from scientific communities, management agencies, political leadership, and civil society. The imperative for ecosystem-based management grows ever more urgent as cumulative human impacts push marine systems toward critical thresholds. Overfishing, pollution, habitat destruction, and climate change interact synergistically, eroding resilience and threatening both ecosystem integrity and food security for billions. The transition to EBFM offers hope that through holistic, precautionary, and adaptive governance, future generations might inherit oceans as productive and biodiverse as those our ancestors enjoyed. Realizing this vision requires not only scientific and technological innovation but political will, social transformation, and genuine commitment to intergenerational equity and ecological stewardship.

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Genetic Enhancement and Breeding Strategies for Improved Aquaculture Species



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1. Introduction

In the contemporary era of global food security challenges, aquaculture stands as the fastest-growing food production sector, contributing over 50 percent of fish consumed worldwide. The exponential growth in human population, coupled with declining wild fish stocks and increasing demand for protein-rich foods, necessitates a paradigm shift in aquaculture productivity. Genetic enhancement and selective breeding have emerged as pivotal tools to address these challenges, offering sustainable pathways to improve growth rates, disease resistance, feed conversion efficiency, and environmental adaptability of cultured species. Unlike terrestrial agriculture, where genetic improvement programs have been systematically implemented for millennia, aquaculture breeding initiatives are relatively nascent. The majority of aquaculture production still relies on phenotypically unimproved or minimally selected stocks. However, recent advances in molecular genetics, genomics, and reproductive technologies have catalyzed a revolution in aquatic breeding programs. The integration of traditional selective breeding with modern genomic tools has created unprecedented opportunities to accelerate genetic gains and develop superior aquaculture strains tailored to specific production environments and market demands. This article provides a comprehensive examination of genetic enhancement strategies employed in aquaculture, encompassing both conventional breeding approaches and cutting-edge biotechnological interventions. We explore the fundamental principles of quantitative genetics as applied to aquatic species, discuss practical breeding program designs, and evaluate the comparative efficacy of various genetic improvement methodologies. Furthermore, we address the socio-economic implications, regulatory frameworks, and sustainability considerations that must be integrated into responsible genetic enhancement programs for aquaculture species.

2. Fundamental Principles of Aquaculture Genetics

The foundation of genetic improvement in aquaculture rests upon understanding the hereditary basis of economically important traits. Quantitative genetics provides the theoretical framework for predicting breeding outcomes and optimizing selection strategies.

2.1 Heritability and Genetic Variance

Heritability represents the proportion of phenotypic variance attributable to genetic factors and serves as the primary determinant of selection response. In aquaculture species, heritability estimates for growth traits typically range from 0.2 to 0.5, indicating moderate to high genetic control. Disease resistance traits often exhibit lower heritability (0.1-0.3), necessitating more intensive selection efforts. Feed conversion efficiency, a trait of paramount economic importance, generally demonstrates heritability values between 0.25 and 0.40 across various species. Understanding these genetic parameters enables breeders to establish realistic improvement targets and optimize breeding program structures. The partitioning of genetic variance into additive, dominance, and epistatic components is critical for breeding strategy formulation. Additive genetic variance, the heritable component transferred from parents to offspring, determines the potential for cumulative genetic improvement across generations. Aquaculture breeding programs primarily exploit additive genetic effects through systematic selection, though dominance variance can be capitalized through strategic crossbreeding and hybrid production systems.

2.2 Selection Response and Genetic Gain

The breeder's equation ($R = h^2S$) quantifies expected genetic progress, where R represents selection response, h^2 denotes heritability, and S signifies selection differential. This fundamental relationship demonstrates that genetic gain is maximized through three avenues: identifying high-heritability traits, applying intense selection pressure,

and minimizing generation intervals. In aquaculture, the unique reproductive characteristics of many species—including high fecundity, external fertilization, and relatively short generation times—provide exceptional opportunities for rapid genetic improvement compared to terrestrial livestock. Realized genetic gains in well-managed aquaculture breeding programs have been remarkable. Norwegian Atlantic salmon programs have achieved 10-12 percent improvement per generation in growth rate, while Nile tilapia breeding initiatives report similar gains. These improvements translate directly to enhanced production efficiency, reduced environmental footprint per unit of product, and improved economic returns for producers. However, maintaining genetic diversity while pursuing rapid improvement requires careful population management to avoid inbreeding depression and preserve adaptive potential.

3. Traditional Selective Breeding Strategies

Traditional breeding methodologies, refined over decades of terrestrial animal improvement programs, form the cornerstone of aquaculture genetic enhancement. These approaches leverage phenotypic evaluation and pedigree information to systematically improve target traits across successive generations.

3.1 Mass Selection and Individual Selection

Mass selection, the simplest form of genetic improvement, involves selecting superior individuals based solely on their phenotypic performance without pedigree tracking. This approach is most effective for highly heritable traits with straightforward measurement protocols, such as body weight at harvest. While mass selection offers operational simplicity and low cost, its efficiency is constrained by inability to distinguish genetic merit from environmental effects and limited control over inbreeding accumulation. Individual selection with pedigree control represents a substantial advancement, enabling precise estimation of breeding values through family relationships. This methodology requires rigorous record-keeping and individual identification systems but yields significantly higher genetic gains, particularly for traits with low to moderate heritability. Contemporary aquaculture programs increasingly implement individual selection using physical tagging (PIT tags, visible implant elastomers) or, more recently, genomic identification technologies that simultaneously enable parentage assignment and marker-assisted selection.

3.2 Family-Based Selection Methods

Family selection exploits genetic relationships to improve selection accuracy, particularly valuable for traits that cannot be measured on selection candidates themselves. Within-family selection evaluates individuals relative to family means, effectively controlling environmental variation and enabling selection for sex-limited traits or characteristics measurable only post-mortem. Combined selection integrates both individual and family information, optimally weighting each component based on trait heritability and family structure. Full-sibling and half-sibling family designs offer complementary advantages. Full-sibling families enable testing in common environments and simplify logistics but confound additive and non-additive genetic effects. Half-sibling designs, typically structured as sire families with multiple dams, provide cleaner estimates of additive genetic variance and facilitate population-wide connectedness. Modern aquaculture breeding programs often implement nested or factorial mating designs that balance statistical power, genetic diversity maintenance, and operational feasibility.

3.3 Crossbreeding and Hybrid Vigour

Crossbreeding between genetically divergent populations or strains capitalizes on heterosis (hybrid vigour) to produce offspring exhibiting superior performance compared to parental averages. In aquaculture, heterosis effects are particularly pronounced for fitness-related traits including survival, disease resistance, and reproductive capacity. Commercial tilapia production extensively utilizes interspecific hybrids between *Oreochromis niloticus* and *O. aureus* or *O. mossambicus*, achieving improved cold tolerance, salinity adaptation, and all-male production through genetic mechanisms. Systematic crossbreeding programs require maintenance of purebred nucleus populations alongside commercial hybrid production, ensuring consistent heterosis levels and genetic improvement in base populations. This multi-tier breeding structure, successfully implemented in poultry and swine industries, is increasingly adopted in aquaculture for species including shrimp, catfish, and carp. The economic benefits of crossbreeding must be balanced against increased breeding program complexity and the need for continued genetic improvement in parental lines.

4. Molecular Breeding Technologies and Genomic Selection

The genomics revolution has fundamentally transformed animal breeding, enabling identification and exploitation of genetic variation at the molecular level. These technologies dramatically accelerate genetic improvement rates and expand the range of traits amenable to selection.

4.1 Marker-Assisted Selection (MAS)

Marker-assisted selection utilizes DNA markers linked to quantitative trait loci (QTL) or genes controlling target traits, enabling selection based on genotype rather than phenotype alone. This approach offers particular advantages for traits with low heritability, sex-limited expression, or late manifestation. Disease resistance represents a prime application domain, where MAS enables identification of resistant genotypes without pathogen challenge, thereby reducing mortality and accelerating genetic gain. Successful MAS implementation requires identification of robust marker-trait associations through linkage mapping or association studies, validation across diverse genetic backgrounds, and integration with conventional selection protocols. In Atlantic salmon, markers for infectious pancreatic necrosis (IPN) resistance have been incorporated into commercial breeding programs, achieving substantial reductions in disease-related mortality. Similar marker systems have been developed for bacterial cold water disease resistance in rainbow trout and white spot syndrome virus resistance in Pacific white shrimp.

4.2 Genomic Selection (GS)

Genomic selection represents a paradigm shift from conventional breeding by simultaneously utilizing thousands of genome-wide markers to predict breeding values, capturing the cumulative effects of all QTL affecting a trait. Rather than identifying specific causal variants, GS exploits linkage disequilibrium between markers and QTL across the entire genome, generating genomic estimated breeding values (GEBVs) with superior accuracy compared to pedigree-based predictions, particularly for young candidates without phenotypic records. The implementation of genomic selection requires establishment of a reference population with both genotypes and phenotypes, development of prediction equations relating marker genotypes to trait values, and routine genotyping of selection candidates for GEBV estimation. In aquaculture, GS adoption has been most rapid in species with established breeding programs and available genomic resources, including Atlantic salmon, rainbow trout, and Pacific white shrimp. Simulation studies and empirical results demonstrate that GS can double genetic gain rates compared to traditional BLUP selection, primarily through increased selection accuracy and reduced generation intervals.

The declining costs of high-throughput genotyping technologies, particularly single nucleotide polymorphism (SNP) arrays and genotyping-by-sequencing approaches, have rendered genomic selection increasingly economically viable for aquaculture applications. Current genotyping costs for medium-density SNP arrays range from \$20-50 per sample, a modest investment relative to the substantial genetic gains achievable. Furthermore, genomic selection enables accurate evaluation of traits that are expensive or difficult to measure, such as carcass quality, disease resistance under field conditions, and feed efficiency in individual animals.

5. Advanced Biotechnological Approaches

Beyond selective breeding and genomic approaches, emerging biotechnologies offer transformative potential for aquaculture genetic enhancement, though many remain in research phases or face regulatory and social acceptance challenges.

5.1 Chromosome Manipulation and Ploidy Modification

Chromosome manipulation techniques alter ploidy levels to produce sterile, faster-growing, or sex-reversed individuals. Triploid production, inducing three chromosome sets through physical or chemical shock of fertilized eggs, creates sterile fish that redirect energy from gonad development to somatic growth. Triploid rainbow trout and Atlantic salmon are commercially produced, exhibiting improved growth rates and reduced environmental risks associated with farmed fish escapement. However, triploidy may compromise welfare under certain conditions, including reduced temperature tolerance and increased susceptibility to cardiac abnormalities.

Gynogenesis and androgenesis, forms of uniparental reproduction induced through gamete irradiation and ploidy restoration, enable rapid inbreeding for developing homozygous lines, sex reversal for monosex production, and

gene mapping through haploid embryo analysis. These techniques have been successfully applied in various species including tilapia, catfish, and sturgeon, facilitating both breeding program acceleration and fundamental genetic research.

5.2 Transgenesis and Gene Editing

Genetic engineering through transgenesis enables introduction of specific genes to confer novel traits unattainable through conventional breeding. The most notable aquaculture application is the AquAdvantage salmon, incorporating growth hormone gene constructs from Chinook salmon under an ocean pout antifreeze promoter, resulting in year-round growth and 50 percent reduced time to market size. Despite rigorous safety evaluations and regulatory approval in several jurisdictions, market acceptance remains limited due to consumer concerns and labeling controversies. CRISPR-Cas9 and related gene editing technologies offer unprecedented precision for targeted genetic modifications, including gene knockouts, insertions, and base editing. Unlike transgenesis, gene editing can produce modifications indistinguishable from natural mutations, potentially addressing some regulatory and public acceptance challenges. Recent research demonstrates successful application of CRISPR for developing disease-resistant fish, eliminating undesirable traits such as early sexual maturation, and enhancing flesh quality characteristics. However, regulatory frameworks for gene-edited aquaculture organisms remain uncertain in most jurisdictions, limiting commercial development despite promising research outcomes.

Table 1. Comparative Analysis of Genetic Improvement Methods in Aquaculture

Method	Genetic Potential	Gain	Implementation Cost	Technical Complexity	Regulatory Status
Mass Selection	Low to Moderate (2–5% per generation)		Very Low	Low	No restrictions
Family-Based Selection	Moderate to High (8–12% per generation)		Low to Moderate	Moderate	No restrictions
Marker-Assisted Selection (MAS)	Moderate to High (trait-specific)		Moderate	Moderate to High	Generally accepted
Genomic Selection (GS)	High to Very High (15–20% per generation)	High	High initially, moderate ongoing	High	Generally accepted
Chromosome Manipulation	Moderate (single generation effect)	(single generation effect)	Low	Moderate	Generally accepted
Transgenesis	High (novel trait introduction)		Very High	Very High	Highly restricted, limited approval
Gene Editing (CRISPR)	High (targeted modifications)		Very High	Very High	Uncertain, jurisdiction-dependent

6. Practical Breeding Program Design and Implementation

Successful genetic improvement programs require careful integration of genetic principles, practical constraints, and commercial objectives. The design phase determines program efficacy, sustainability, and economic viability over multi-generational time horizons.

6.1 Breeding Objective Definition and Trait Selection

Defining breeding objectives represents the foundational strategic decision, establishing which traits warrant selection emphasis and their relative economic weights. Production traits (growth rate, feed conversion, age at maturity) typically dominate breeding goals due to direct economic impacts. However, functional traits including disease resistance, stress tolerance, and behavioural characteristics increasingly receive attention as production intensifies and sustainability concerns mount. Product quality traits (flesh colour, texture, fat content, fillet yield) gain importance in premium market segments where price differentials justify selection investment. Economic selection indices aggregate multiple traits, weighting each according to its economic value and genetic parameters. Index construction requires estimation of genetic and phenotypic correlations among traits, economic values per unit change, and selection intensity feasible for each trait. Unfavourable genetic correlations, such as between

growth rate and disease susceptibility in some species, necessitate balanced selection approaches that prevent degradation of non-selected traits while advancing primary objectives.

6.2 Mating Designs and Population Structure

Mating system design balances genetic gain maximization against maintenance of genetic diversity and minimization of inbreeding. Random mating among selected individuals represents the simplest approach but provides no control over relatedness accumulation. Factorial mating designs, where each sire is mated with multiple dams and each dam with multiple sires, maximize information content for genetic parameter estimation while distributing genetic contribution across the population. Optimal contribution selection algorithms represent sophisticated approaches that simultaneously maximize genetic gain while constraining average relatedness increase per generation. These methods explicitly balance short-term gain against long-term genetic diversity maintenance, particularly valuable for species with limited effective population sizes. Contemporary aquaculture breeding programs increasingly implement such algorithms, facilitated by pedigree tracking and genomic relationship estimation technologies.

6.3 Testing Environments and Genotype-by-Environment Interactions

Aquaculture production occurs across diverse environmental conditions including temperature regimes, salinity levels, production systems (ponds, raceways, sea cages), and management intensities. Genotype-by-environment ($G \times E$) interactions, where genetic rankings differ across environments, complicate breeding program design and may necessitate environment-specific breeding lines. Evaluation of $G \times E$ effects requires testing candidate families across representative production environments, adding logistical complexity and cost but ensuring genetic solutions match commercial realities. The nucleus breeding scheme, borrowed from terrestrial livestock industries, involves genetic improvement in specialized breeding facilities followed by dissemination to commercial producers through a multiplier tier. This structure enables optimal testing conditions, biosecurity control, and genetic gain maximization in the nucleus while providing broad access to improved genetics. Atlantic salmon and shrimp breeding programs extensively utilize nucleus systems, though smaller-scale operations may employ simpler structures where breeding and commercial production are less differentiated.

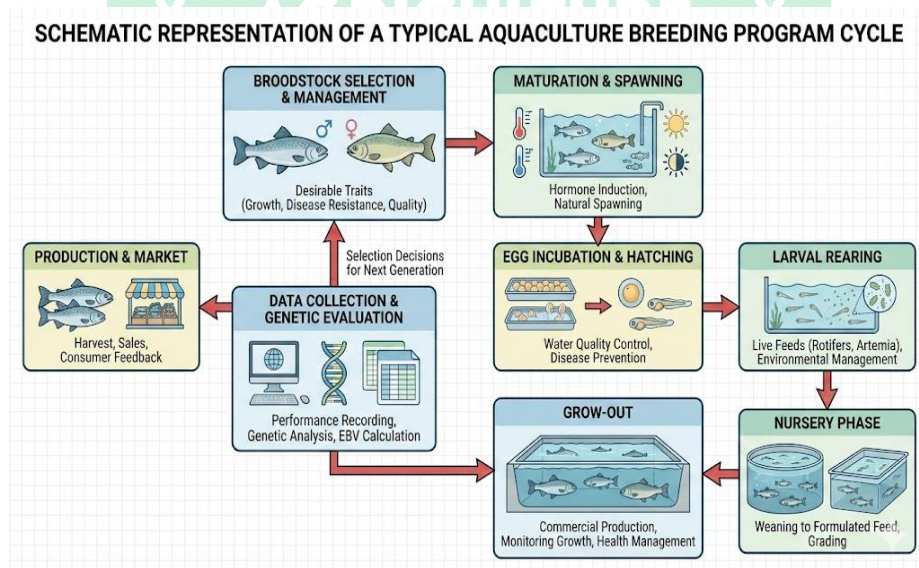


Figure 1. Schematic Representation of a Typical Aquaculture Breeding Program Cycle

7. Sustainability Considerations and Ethical Dimensions

Genetic improvement programs operate within broader sustainability frameworks encompassing ecological, social, and economic dimensions. Responsible genetic enhancement must address potential unintended consequences, ensure equitable access to improved genetics, and maintain public trust in aquaculture products and practices.

7.1 Genetic Diversity and Adaptive Capacity

Intensive selection necessarily reduces genetic diversity within breeding populations, potentially compromising long-term adaptive capacity and resilience to changing environmental conditions or emerging disease threats. Effective population size (N_e), the number of individuals that would produce the observed rate of inbreeding if mating were random, serves as the key metric for genetic diversity assessment. Consensus recommendations suggest maintaining N_e above 50-100 to prevent severe inbreeding depression, with higher values (>200) preferred for sustained long-term selection. Conservation of genetic resources through cryopreservation of gametes provides insurance against diversity loss and enables recovery of valuable genetic material if needed. Sperm cryopreservation protocols are well-established for many aquaculture species, while oocyte and embryo cryopreservation remain technically challenging. Maintenance of multiple breeding lines with different selection histories and genetic backgrounds offers additional security, though requiring substantial resource investment.

7.2 Environmental Interactions and Escapement Concerns

The potential for genetically improved farmed fish to escape into wild populations and interbreed with native stocks raises significant ecological concerns. Genetic introgression from domesticated to wild populations may reduce fitness of wild fish through maladaptation to natural environments, disruption of locally adapted gene complexes, or transmission of deleterious alleles accumulated under relaxed selection in captivity. These risks are particularly acute for species like Atlantic salmon where large-scale farming occurs within the natural range of wild populations. Risk mitigation strategies include physical containment improvements, use of sterile triploids in sensitive regions, development of reproductively isolated strains, and geographic separation of farming from wild populations. Recent research on genetic containment through introduction of recessive lethal alleles or conditional fertility systems offers promising future approaches, though requiring careful risk-benefit evaluation and robust regulatory oversight.

7.3 Animal Welfare Implications

Genetic selection affects animal welfare through multiple pathways. Positive welfare outcomes arise from improved disease resistance, stress tolerance, and better adaptation to production environments. However, intense selection for production traits without consideration of welfare indicators may produce unintended negative consequences, as observed in some terrestrial livestock where rapid growth or extreme body conformations compromise mobility, cardiovascular function, or reproductive capacity. Incorporating welfare-related traits into breeding objectives represents an ethical imperative and practical necessity. Such traits include behavioral indicators (feeding behavior, social interactions, stress responses), physiological markers (heart rate variability, cortisol dynamics), and production-environment fitness measures. Genomic selection facilitates welfare trait improvement by enabling selection on difficult-to-measure characteristics without requiring individual-level phenotyping under stressful conditions.

Table 2. Key Traits for Genetic Improvement in Major Aquaculture Species

Species	Primary Production Traits	Disease Resistance Priorities	Quality Traits
Atlantic Salmon	Growth rate, feed conversion, age at maturity, fillet yield	IPN, sea lice resistance, bacterial kidney disease, PRV	Flesh color, fat content, texture, late sexual maturation
Rainbow Trout	Growth rate, feed efficiency, thermal tolerance	BCWD, IHN, whirling disease, Ceratomyxosis	Flesh color, fillet yield, fat distribution
Nile Tilapia	Growth rate, cold tolerance, salinity tolerance, male bias	Streptococcosis, columnaris, tilapia lake virus (TiLV)	Fillet yield, red color (some markets), delayed maturation
Pacific White Shrimp	Growth rate, survival, feed efficiency, stocking density tolerance	WSSV, EMS/AHPND, TSV, IHHNV	Body shape, tail muscle ratio, shell hardness uniformity
Channel Catfish	Growth rate, feed conversion, low-oxygen tolerance	ESC, columnaris, Ich resistance	Fillet yield, meat color uniformity, processability
Asian Seabass	Growth rate, feed efficiency, temperature adaptation	Viral nervous necrosis (VNN), scale drop syndrome	Fillet yield, flesh texture, low intramuscular fat

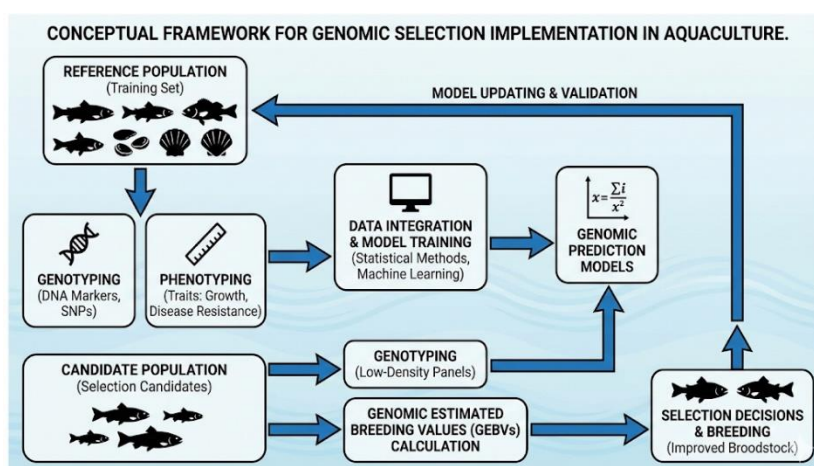


Figure 2. Conceptual Framework for Genomic Selection Implementation in Aquaculture

8. Economic Aspects and Industry Adoption

The economic justification for genetic improvement programs depends on the balance between program costs and the discounted value of cumulative genetic gains across multiple generations. Initial investment requirements include infrastructure establishment, founder stock acquisition, technical expertise development, and implementation of performance recording systems. Ongoing costs encompass labour, facility maintenance, genetic evaluation, and dissemination infrastructure. Benefit realization occurs through increased productivity, reduced production costs, improved product quality premiums, and enhanced market access. For major commercial species, well-documented economic analyses demonstrate benefit-cost ratios exceeding 10:1 over 10–15-year time horizons, with genetic gains compounding across generations to generate substantial competitive advantages. However, smaller-scale operations face challenges achieving economic viability due to fixed cost dilution across limited production volumes. Intellectual property considerations increasingly influence genetic improvement strategies. Private sector breeding companies typically protect improved genetics through trade secrets, biological patents, or contractual restrictions on reproduction and distribution. This model has driven substantial private investment but raises concerns regarding smallholder access, genetic diversity concentration, and dependencies on multinational corporations. Alternative models including cooperative breeding programs, public-private partnerships, and open-source breeding initiatives aim to balance innovation incentives with broader accessibility objectives.

9. Future Directions and Emerging Technologies

The convergence of artificial intelligence, advanced genomics, and reproductive technologies promises to further accelerate aquaculture genetic improvement. Machine learning algorithms applied to phenotype prediction from high-dimensional genotype, transcriptome, and phenome data enable identification of subtle genetic patterns and interactions invisible to conventional analysis. Computer vision and automated phenotyping systems reduce labour costs while capturing detailed growth, behavioural, and morphological data previously impractical to collect systematically. Epigenetic modification and transgenerational inheritance represent frontier areas with potential implications for breeding strategy. Evidence suggests that environmental exposures can induce heritable epigenetic changes affecting offspring phenotypes, potentially enabling rapid adaptation to novel production conditions. However, epigenetic effects' stability, predictability, and interaction with conventional genetic selection require substantial additional research before practical application. Precision breeding through gene editing, particularly base editing and prime editing technologies offering single-nucleotide precision without double-strand breaks, may eventually achieve broader acceptance if products prove indistinguishable from conventionally bred organisms. Regulatory evolution toward trait-based rather than process-based oversight could accelerate adoption, though public perception remains a critical uncertainty. Regardless of technological capability, social license and transparent stakeholder engagement will ultimately determine which genetic technologies achieve commercial viability.

10. Conclusion

Genetic enhancement stands as a cornerstone of sustainable aquaculture intensification, offering pathways to substantially increase production efficiency while reducing environmental footprints and improving animal welfare. The integration of conventional selective breeding with genomic technologies has created unprecedented opportunities for rapid, precise genetic improvement across diverse species and production systems. Demonstrated successes in major commercial species validate the biological and economic feasibility of systematic breeding programs; while emerging molecular technologies promise further acceleration of genetic gains. However, responsible genetic improvement must operate within comprehensive sustainability frameworks that maintain genetic diversity, protect wild populations from genetic introgression, ensure animal welfare, and promote equitable access to genetic resources. The technical capacity to modify organisms rapidly carries commensurate responsibility to anticipate and mitigate unintended consequences, engage stakeholders transparently, and align breeding objectives with broader societal values. Looking forward, the successful integration of genetic improvement into global aquaculture development will depend not only on continued technological innovation but also on development of supportive policy frameworks, investment in technical capacity building, and cultivation of public understanding and trust. As aquaculture assumes an increasingly vital role in global food security, genetic enhancement will remain an indispensable tool for meeting production demands sustainably, provided its application is guided by rigorous science, ethical consideration, and genuine commitment to long-term ecological and social well-being.

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Health Management Practices and Disease Mitigation in Intensive Aquaculture



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Abstract

The rapid intensification of global aquaculture has become indispensable for ensuring food and nutritional security; however, this transformation has simultaneously introduced profound biological and ecological vulnerabilities. High-density production systems, characterized by elevated biomass loading and organic enrichment, create optimal conditions for the amplification, persistence, and rapid transmission of infectious agents. Traditional disease control strategies, heavily reliant on chemotherapeutics and antibiotics, have proven increasingly unsustainable due to antimicrobial resistance, environmental contamination, and regulatory restrictions.

This review critically evaluates the evolving landscape of aquatic animal health management, emphasizing the paradigm shift from reactive chemotherapy toward an Integrated Health Management (IHM) framework. Core components examined include structural and operational biosecurity, the deployment of advanced “Omics” technologies for early pathogen detection and risk prediction, functional nutrition strategies aimed at strengthening mucosal immunity, and ecological approaches to managing microbial communities within production systems. The synthesis highlights that disease emergence in intensive aquaculture is not pathogen-driven alone but results from a dynamic imbalance between host physiology, microbial ecology, and environmental stressors. The review concludes that adopting a “One Health” approach—harmonizing animal health, environmental sustainability, and public health—is the only viable pathway for the long-term resilience and productivity of intensive aquaculture systems.

1. Introduction: The Challenges of Intensification

Global aquaculture production has surpassed 80 million tonnes annually, with intensive farming systems accounting for the majority of high-value finfish and crustacean species. Stocking densities in these systems frequently range from 30 to 100 kg m⁻³, pushing cultured organisms close to their physiological limits. While intensification improves land and water-use efficiency, it simultaneously reduces the biological buffering capacity of the system.

In such environments, disease outbreaks are rarely caused by a single etiological agent acting in isolation. Instead, they emerge from a convergence of stressors—including hypoxia, hypercapnia, elevated ammonia, temperature instability, and handling stress—that compromise innate immune defenses. Once host resistance is weakened, opportunistic pathogens can rapidly exploit these conditions, leading to acute morbidity and high mortality. Consequently, disease management in modern aquaculture must move beyond pathogen eradication toward system-level risk mitigation. This review provides a comprehensive framework for understanding and managing these risks under intensive production conditions.

2. Structural and Operational Biosecurity

Biosecurity represents the first and most critical line of defense in intensive aquaculture systems. Rather than a single intervention, effective biosecurity functions as a multilayered barrier designed to prevent pathogen entry, establishment, and dissemination.

2.1 Physical Barriers and Water Treatment

In Recirculating Aquaculture Systems (RAS), where water reuse exceeds 90%, pathogen accumulation poses a significant risk. Consequently, continuous water treatment is mandatory.

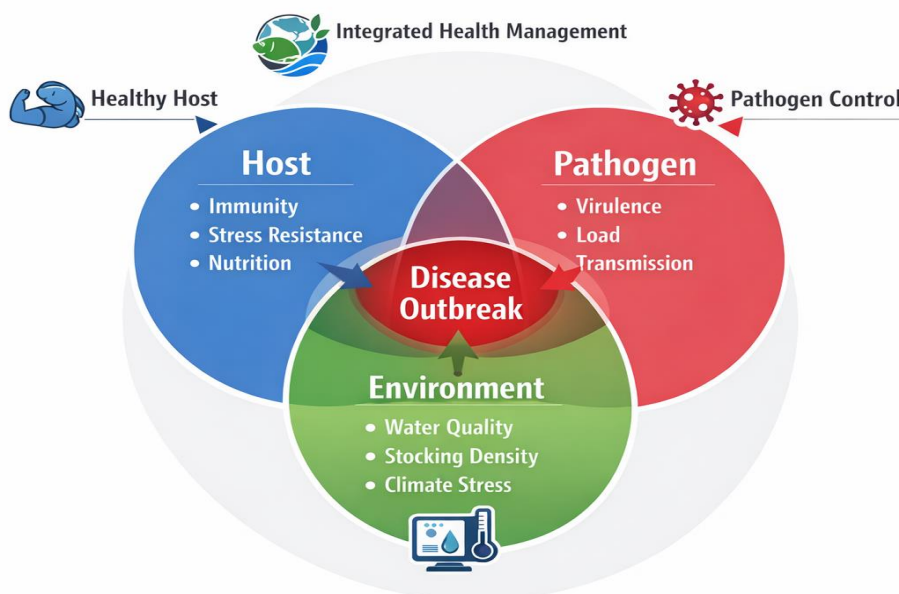
- **Ozonation:** Ozone (O₃) acts as a potent oxidizing agent, effectively reducing dissolved organic matter and inactivating bacteria, viruses, and parasites. Its application improves water clarity and biofilter

efficiency; however, residual ozone and by-products must be removed through degassing or activated carbon filtration to prevent oxidative damage to gill tissues.

- **Ultraviolet (UV) Sterilization:** UV irradiation at 254 nm disrupts nucleic acids, rendering microorganisms incapable of replication. Its efficacy is highly dependent on water transparency, flow rate, and exposure time, making pre-filtration essential for optimal performance.

Together, these technologies form a complementary barrier system that minimizes microbial pressure in intensive units.

The Disease Triangle in Intensive Aquaculture Systems



2.2 Seed Quality and SPF Stocks

The use of high-quality seed is non-negotiable in intensive aquaculture. Specific Pathogen Free (SPF) and Specific Pathogen Resistant (SPR) stocks significantly reduce the risk of catastrophic disease introduction, particularly in shrimp and salmonid farming. In contrast, wild-caught seed often functions as a biological “Trojan Horse,” introducing latent viral pathogens such as White Spot Syndrome Virus (WSSV) or Infectious Myonecrosis Virus (IMNV). Rigorous quarantine, molecular screening, and certification protocols are therefore essential components of operational biosecurity.

3. Disease Mitigation Through Advanced Nutrition

The gastrointestinal tract is the primary interface between the host and its microbial environment and serves as a critical gateway for pathogen entry. Nutritional strategies that enhance gut integrity and immune competence have therefore become central to modern health management.

3.1 Functional Feeds and Immunostimulants

Contemporary aquafeeds extend far beyond basic protein and lipid provision. Functional ingredients are increasingly incorporated to modulate immune responses:

- **Peptidoglycans and Lipopolysaccharides:** These microbial-associated molecular patterns (MAMPs) stimulate pattern recognition receptors, priming innate immunity without inducing disease.
- **Organic Acids:** By reducing gut pH, organic acids inhibit opportunistic pathogens such as *Vibrio* and *Aeromonas* while favoring beneficial lactic acid bacteria, thereby improving microbial balance and nutrient utilization.

3.2 Probiotics and Biofloc Technology

Biofloc Technology (BFT) represents a paradigm shift in shrimp health management. By maintaining a high carbon-to-nitrogen ratio, heterotrophic bacteria assimilate nitrogenous waste into microbial biomass. These

bioflocs serve dual functions: improving water quality and acting as a continuous source of probiotic nutrition. Through competitive exclusion, beneficial microbes suppress pathogen proliferation, enhancing disease resistance at the system level.

4. Analytical Framework for Health Risk Management

Environmental stressors exert direct physiological impacts that predispose cultured animals to disease. Elevated CO₂ levels impair oxygen transport, ammonia damages gill epithelia, and temperature fluctuations disrupt metabolic homeostasis. Mapping these stressors to associated pathogens enables predictive risk assessment and targeted prevention strategies.

Similarly, emerging mitigation technologies—such as vaccines, bacteriophages, RNA interference, and quorum sensing inhibitors—offer promising alternatives to antibiotics. While each approach has limitations, their strategic integration within an IHM framework maximizes overall system resilience.

Table 1: Environmental Stressors and Associated Disease Risk

Stress Factor	Physiological Impact	Associated Pathogen	Prevention Strategy
Hypercapnia (CO₂)	Blood acidosis, reduced O ₂ affinity	<i>Streptococcus agalactiae</i>	Proper degassing and pH buffering
High Ammonia (NH₃)	Gill hyperplasia, mucus stripping	<i>Flavobacterium columnare</i>	Biofilter optimization; C:N ratio adjustment
Temperature Fluctuations	Metabolic shock; immune suppression	<i>Saprolegnia</i> (Fungi); Viral outbreaks	Climate control in RAS; deep-water cages
Low Salinity (Marine)	Osmotic stress	<i>Vibrio parahaemolyticus</i>	Salinity stabilization; slow acclimation

Table 2: Comparison of Mitigation Technologies

Technology	Mode of Action	Best Used For	Limitation
Injection Vaccines	Acquired Immunity	Salmon, Tilapia, Trout	High labor cost; size restriction
Bacteriophages	Viral predation of bacteria	<i>Vibrio</i> in hatcheries	Narrow host specificity
RNA Interference	Gene silencing	Viral inhibition (Shrimp)	Regulatory hurdles; delivery methods
Quorum Sensing Inhibition	Disrupts bacterial communication	Preventing biofilm formation	Experimental stage in field

5. Visual Conceptualization of Disease Dynamics

The disease triangle model illustrates that disease manifests only when susceptible hosts, virulent pathogens, and permissive environmental conditions overlap. This conceptual tool reinforces the principle that disease prevention is achievable by intervening at any one of these three vertices.

Long-term survival trend analyses further demonstrate that antibiotic-dependent systems exhibit declining efficacy due to resistance, whereas probiotic- and ecology-based approaches sustain survival rates above 80%, underscoring the benefits of preventive health management.

6. Emerging Diagnostics and Digital Health

Early disease detection remains the most cost-effective intervention strategy. Advances in multiplex PCR now allow simultaneous screening of multiple pathogens from a single sample, enabling rapid decision-making.

Artificial intelligence and computer vision technologies further enhance surveillance capacity. Behavioral anomalies—such as reduced feeding, lethargy, or erratic swimming—can be detected algorithmically before overt clinical signs emerge, allowing preemptive management actions.

7. Case Study: Integrated Control of *Streptococcus* in Tilapia

In Southeast Asian cage culture systems, *Streptococcus agalactiae* outbreaks are strongly associated with elevated summer temperatures. Integrated control strategies combining pre-season vaccination and adaptive feeding regimes have proven highly effective. Temporarily reducing feeding during thermal stress lowers metabolic

demand and oxygen consumption, significantly reducing mortality. This case exemplifies the power of anticipatory, physiology-based health management.

8. Conclusion

Aquatic animal health management has transitioned from a reactive, treatment-focused paradigm to a proactive, systems-based discipline. The integration of structural biosecurity, functional nutrition, microbial ecology, and genomic diagnostics creates a multidimensional protective framework around intensive farms. As aquaculture advances toward 2030, sustainable success will depend less on pathogen elimination and more on managing microbial ecosystems and host resilience within the broader “One Health” context, as emphasized by FAO and allied scientific bodies.

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Heat Stress in Crops and Livestock: Emerging Challenges for Indian Farmers



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1. Introduction

The prevalence of anthropogenic climate change ceases to be a hypothetical idea but a tangible phenomenon that is transforming the agrarian landscapes of the Indian subcontinent. Although changes in precipitation regimes often dominate the climate talk, a growing menace has appeared as thermal stress that has become extremely insidious and widespread. Being heavily dependent on rainfed agro-ecosystems and having a sizeable domestic livestock industry maintained on a large scale, India is uniquely susceptible to the pernicious impacts of elevated ambient temperature. Heat stress refers to a physiological state where the body reaches high temperatures that are beyond its normal temperature levels, and as such, the body cannot regulate its body temperature; hence, it becomes overheated. To the Indian agricultural sector (that forms a substantial part of the national gross domestic product and provides more than half of the labour force) extreme temperature events present both a twin threat: not only are they likely to impair crop physiology (and this means that yields can stop or start to decrease), but they also pose a serious threat to livestock health, productivity, and reproductive performance. The article at hand identifies the multi-dimensional effects of heat stress on Indian agriculture through examining the physiological basis of thermal stress in plants and animals, assessing the socioeconomic impacts, and describing the necessary adaptation measures. The balance between rising average temperatures and more frequent incidences of extreme heat is so great that a scientifically aware change in farm operations and policy is urgently needed.

2. The Climatological Imperative

The country of India is located at geographic positions within the tropical and subtropical climatic zone, of which a large part of the landmass is prone to high temperatures. However, recent climatological data show that there is a significant deviation from the historical baselines. The data provided by the India Meteorological Department (IMD) and supported by other international organisations, including the Intergovernmental Panel on Climate Change (IPCC), indicate that the frequency, duration and intensity of heatwaves all over the Indian subcontinent have increased significantly during the last few decades. It is estimated that mean surface temperatures throughout the country could rise by about 4.0 °C by the end of the twenty-first century, in high-emission situations. What is more damaging to the agricultural practice, the number of days at or above critical physiological temperature levels, such as 35 °C or 40 °C, depending on species and area of practice, is increasing. This problem is not just irritation by summer heat but also includes terminal heat stress, which takes place during critical transition periods, including the Rabi (winter) crop maturity period in March/April, and extreme heat in the middle of the season, which thus negatively impacts crop development and livestock performance.

3. Physiological Impacts on Crop Production

Sessile organisms like plants are not able to avoid extremes in the environment. They react to heat stress in various ways, and they include morphological, physiological and biochemical changes. Heat stress could be acute, where it is associated with episodes of extreme temperature exposure in a short duration, or it could be chronic, where the exposure to moderately higher temperatures is sustained over time. Both of them are pathological, but with different impacts depending on the growth stage.

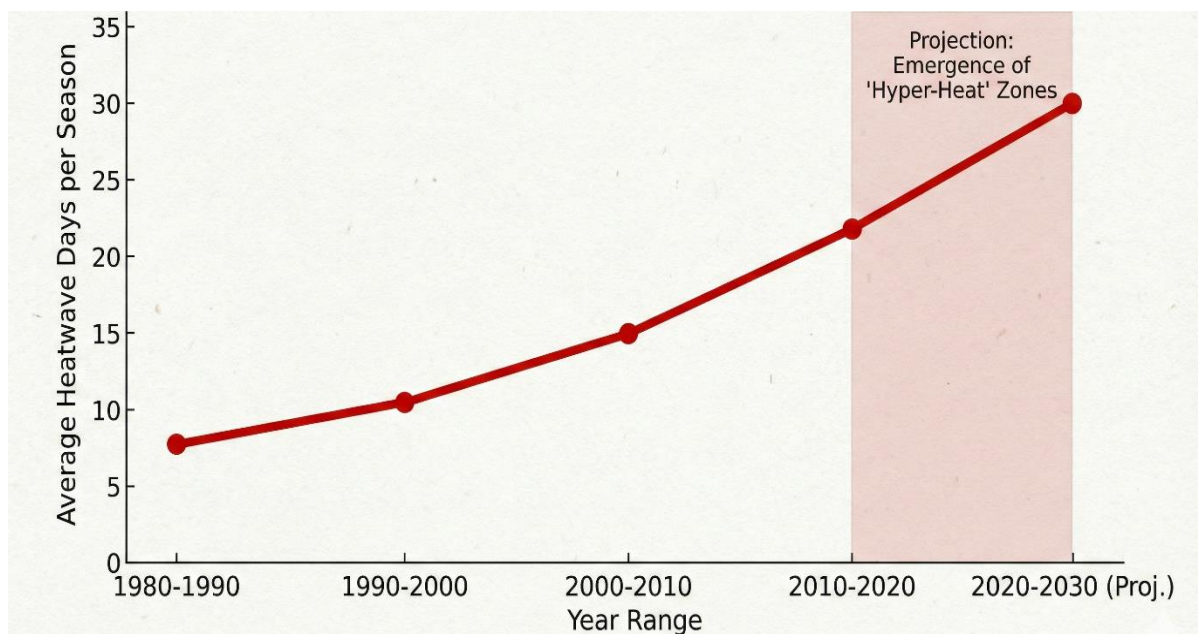


Figure 1. Trend of Heatwave Frequency in Indian Agricultural Zones

3.1 Photosynthetic Decline and Respiratory Losses

The main mechanism through which heat stress reduces biomass increase is by preventing photosynthesis. High temperatures hamper the thylakoid membrane of chloroplasts and inhibit the work of the major enzyme of carbon fixation, Rubisco. At the same time, the intensity of photorespiration and dark respiration rates increases with temperature increases. The adverse carbon balance that ensues with the plant using up more energy to sustain metabolic processes than it absorbs through photosynthesis causes retarded growth.

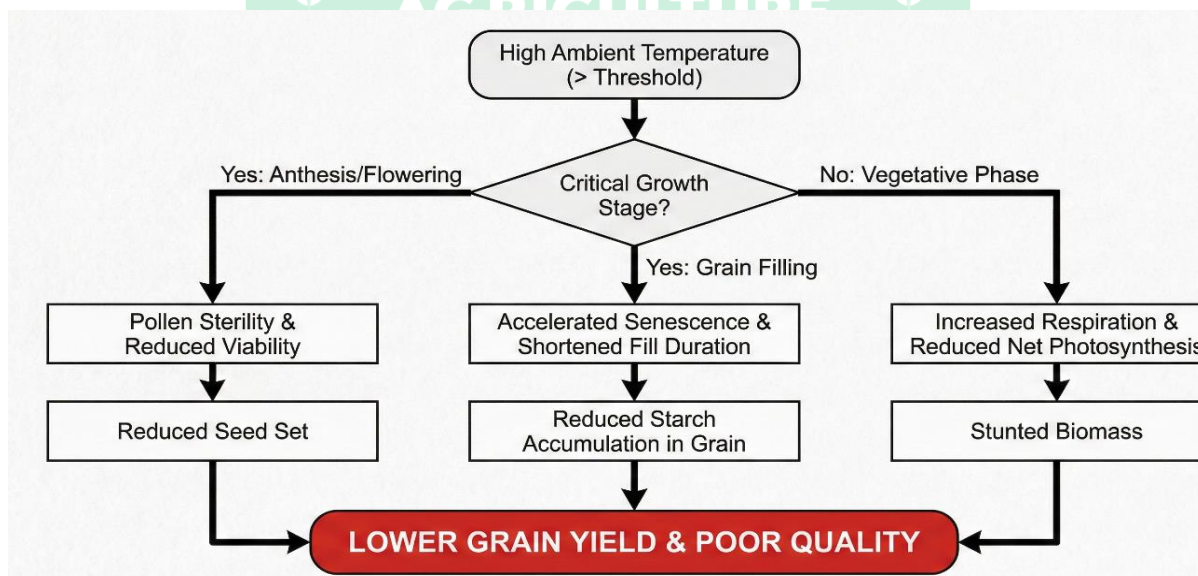


Figure 2. Diagrammatic Representation of Heat Stress Impact on Cereal Grain Yield

3.2 Reproductive Failure and Terminal Heat Stress

The costliest effect of heat stress is experienced in the reproductive phases, that is, flowering (anthesis) and grain-filling. This is especially important to the staple cereal products in India, wheat and rice. Terminal heat stress in February and March has also become common in the Indo-Gangetic plains in wheat, a Rabi crop. The high temperatures of over 30-32 °C during anthesis may cause sterility of pollen, thus leading to low seed set.

Moreover, when high temperatures occur during the period of grain-filling, it weakens the process of the senescence of the plants; the lack of time to have proper translocation of photosynthates in the leaves to the grains results in the appearance of shrivelled grains and substantially lower yields. Empirical research indicates that with each 1 °C rise in average temperature beyond the optimal temperatures of the grain-filling period, the yield of wheat can decrease by 4-6 °C. The same can be said of rice, where the high spikelet sterility can be brought about by high temperatures exceeding 35 °C during flowering. Anther dehiscence and pollen viability are interfered with by heat stress, which reduces the number of filled grains per panicle directly.

3.3 Water Relation & Oxidative Stress

Hot weather always increases the vapour pressure gap (VPD) among the surfaces of leaves and the atmosphere, prompting increased rates of transpiration. Although transpiration helps to cool down the leaf, too much water loss causes dehydration. Stomata of plants are closed under combined heat-and-drought stress to save water, but this further suppresses photosynthesis and increases leaf temperature, promoting thermal damage. Additionally, heat stress brings about excessive production of reactive oxygen species (ROS) in plant cells, which leads to oxidative degradation of lipids, proteins and DNA, ending up in the death of plant cells.

4. Physiological and Productive Impacts on Livestock

India has one of the largest livestock populations in the world, which is an important aspect of nutritional security and livelihoods in rural areas. Animals, especially the high-yielding dairy cattle and poultry, are more sensitive to the thermal environment. They act in a thermoneutral range of temperatures - a range of temperatures around which the core body temperature can be set without incurring additional metabolic cost. Heat stress occurs in animals whenever environmental temperature and humidity are out of this range.

4.1 Thermoregulatory Failure and Energy Diversion

Animal core body temperatures rise (hyperthermia) when the heat load of the animal is beyond the animal's ability to lose the excess heat. The animal starts behavioural and physiological adaptation to reach cooling. Such measures in cattle and buffalo are an elevated respiration rate (panting), sweating and finding a shade. These cooling systems are energetically expensive; energy that could have been used to produce milk, help meat accretion, or reproductive activities is instead used in thermoregulation, thus decreasing productivity.

4.2 Impact on Dairy Production

Heat stress is one of the major limitations in the dairy industry. The main behavioural reaction of heat stress is dry matter intake (DMI) reduction. Fewer feeds are consumed by animals in a bid to reduce metabolic heat produced by the digestive system, and this reduced intake of nutrients is directly proportional to reduced milk yield. Further, heat stress alters the physiology of the mammary glands by reducing the population of the mammary epithelial cells, which impairs the quality of milk, often leading to low fat and protein content. And crossbred cattle, which constitute a significant share of the dairy intensification policy in India and which have the highest yield potential, are characterised by significantly higher heat stress susceptibility compared to native *Bos indicus* strains. The latter have greater thermotolerance characteristics due to the increased sweating ability and reduced metabolic rates.

4.3 Reproductive and Health Consequences

Stress caused by heat has a severe negative effect on the fertility of both male and female cattle. In dairy cows, it is expressed through the decreased oestrous behaviour (silent heat), low rates of conception, and high rates of embryo death. High temperatures in bulls deteriorate the quality and viability of sperm. In addition, heat stress impairs the immune system, which leaves livestock more susceptible to illnesses like mastitis and teck bites.

4.4 The Poultry Sector Vulnerability

Chicken is arguably the most heat-sensitive type of livestock, which is explained by the fact that they do not have sweat glands, their metabolic rate is high, and they have insulating feather coverage. Broilers experience heat stress, and the results of this include high ratios of feed to weight and high deaths caused by heat prostration. It suppresses egg production, egg size and thins the eggshells in layers through respiratory alkalosis caused by excessive panting.

Table 11. Thermoneutral Zones and Critical Heat Stress Thresholds for Selected Indian Livestock

Livestock Category	Thermoneutral Zone (°C)	Critical Threshold (THI*)	Primary Physiological/Productive Impacts
Dairy Cattle (Crossbred)	5°C – 20°C	> 72	Reduced feed intake, significant milk yield drop (10-30%), reduced fertility, and increased respiration.
Dairy Cattle (Indigenous)	10°C – 27°C	> 78	Moderate yield drop, better thermoregulation, maintain intake longer than crossbreds.
Buffaloes	13°C – 24°C	> 75	Seek water/wallowing due to poor sweating mechanism. Severe impact on reproduction during summer.
Poultry (Layers)	18°C – 24°C	> 27°C (Ambient)	Thin eggshells, reduced egg laying rate, and increased mortality.
Poultry (Broilers)	18°C – 22°C	> 26°C (Ambient)	Reduced weight gain, poor feed conversion, and high mortality risk near market age.

5. Socio-Economic Consequences for the Indian Farmer

The physiological effects outlined above trickle down to socio-economic difficulties amongst agrarian societies. **Economic Losses and Debt Traps:** The smallholder farmers, with already a razor-thin profit margin, experience a 10-20 % loss in wheat crop, or a 50 % decline in the daily milk output at the hottest time of the year, which can ruin the seasonal income. Other inputs like more irrigation water to crops or electricity to fans and sprinklers in the sheds where livestock are kept continue to drive down profitability, such that farmers are found in the cycles of debt. **Nutritional Insecurity:** Household nutritional security is compromised directly by the low availability and access to staple grains, milk and eggs, primarily by vulnerable rural populations. **Agricultural Geography Shift:** Chronic heat stress can make specific regions unfavourable to traditionally grown crops, and this will force a change in patterns of cropping that might fail to match the local market organisation or experience of farmers.

6. Mitigation and Adaptation Strategies

The problem of heat stress needs to be approached in a two-pronged strategy, including immediate approaches (mitigation) and long-term, strategic changes (adaptation).

6.1 Crop Sector Strategies

- Genetic Improvement:** Heat tolerance breeding is the most sustainable long-term solution. Researchers like the Indian Council of Agricultural Research (ICAR) are already producing varieties of wheat and rice that are resistant to climatic conditions with special properties, like early flowering (to avoid terminal heat), high pollen viability at high temperatures, and deeper roots to reach soil water.
- Agronomic Management:**
 - Time of Sowing:** Adaptation of sowing dates would mean that the sensitive reproductive phase was not during the hottest times. A known strategy in Northwest India is the early planting of wheat.
 - Irrigation Scheduling:** Heatwaves During heatwaves, light, frequent irrigation can reduce the temperature of the crop canopy, as a result of evaporative cooling; sprinkler irrigation is very useful.
 - Residue Management:** Crop residue mulching lowers the temperature of the soil and also conserves moisture, alleviating the heat and drought effects together.

6.2 Livestock Sector Strategies

- Physical Change of Environment:** The first thing that should be done is to decrease the thermal load. This includes appropriate shade, having sufficient ventilation in sheds and active cooling mechanisms like fans, foggers and sprinklers, especially for crossbred cattle and poultry of high value.
- Nutritional Management:** The decrease in feed consumption is compensated by changing the ration to raise the energy content (e.g. adding fats). Feeding is supposed to be done on cooler days (at the beginning of the day or at the end of the day). Oxidative stress is alleviated with the help of supplementation with electrolytes and vitamins C and E.

- c. **Genetic Strategies:** A new necessity to heroise native breeds. Development of breeding programs ought to aim at introjecting the trait of thermotolerance in the indigenous breeds of *Bos indicus* into crossbreds of high yields.

Table 2: Matrix of Adaptive Strategies for Heat Stress in Indian Agriculture

Sector	Short-Term / Management Solutions	Long-Term / Strategic Solutions
Crops	Adjusting sowing dates (e.g., early wheat sowing). Frequent, light irrigation during critical stages. Mulching to reduce soil temperature. Foliar spray of osmoprotectants (e.g., potassium nitrate).	Breeding heat-tolerant varieties (heat-shock protein expression). Developing short-duration varieties to escape heat. Diversifying towards heat-hardy crops like millets.
Livestock	Providing adequate shade and ventilation. Active cooling (fans, sprinklers, foggers). Feeding during cooler hours; increasing dietary fat. Ad libitum access to cool, clean water.	Selective breeding for thermotolerance traits. Promoting indigenous breeds in hyper-heat zones. Designing climate-smart animal housing infrastructure. Integrated agroforestry-livestock systems for natural shade.

7. Conclusion

The heat stress is no longer an occasional inconvenience, but a structural dilemma that is putting the existence of Indian agriculture at stake. The simultaneous approach of critical physiological limits in both crop and high-producing livestock, in the face of a growing adversarial thermal climate, creates a dangerous situation for national food security and the livelihoods of farmers. Addressing the problem requires a shift from reactive management of disasters to proactive climate-adaptive management. That would demand high levels of research and development on heat-tolerant genetics, extensive extension services to educate farmers on heat mitigation agronomy and animal life and policy frameworks that encourage climate-resilient infrastructure. The adaptability of the Indian farmer will depend on how fast science is converted into application level in the field to fight the rising heat.

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The Mighty Particle: Unveiling the Role of Nano-Fertilizers in Sustainable Agriculture



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ABSTRACT

With the rising need for sustainable agricultural practices, nano-fertilizers have emerged as an innovative alternative to traditional fertilizers. These advanced fertilizers enhance nutrient use efficiency, promote crop growth, and minimize environmental harm by enabling precise nutrient delivery. This review evaluates various nano-fertilizer application techniques and their influence on plant growth, yield, and quality. Additionally, it explores their interactions with soil composition and microbial communities, emphasizing their role in enzymatic activity and nutrient cycling. While nano-fertilizers offer significant benefits, challenges such as proper dosage regulation, potential toxicity, and long-term ecological effects necessitate further research. This study highlights recent advancements in nano-fertilizer technology and underscores the importance of an integrated approach to optimize agricultural productivity while preserving soil health and environmental sustainability

Key word; Nano-fertilizers, conventional fertilizer and sustainable agriculture.

INTRODUCTION

Agriculture, the cornerstone of human civilization, faces unprecedented challenges in the 21st century. Growing global populations, dwindling arable land, and the pressing need for environmental sustainability demand innovative solutions to enhance crop productivity while minimizing ecological impact. Nano-fertilizers have emerged as a promising technology with the potential to revolutionize agricultural practices and pave the way for a more sustainable future. Nano-fertilizers are nutrient formulations encapsulated or coated in nanomaterials, enabling controlled nutrient release and gradual dispersion in the soil. Compared to traditional fertilizer options, nano-fertilizers provide several advantages, including improved nutrient utilization, reduced environmental impact, and enhanced agricultural output and product quality. This improvement is largely attributed to the nanoscale size of these fertilizers, which facilitates better absorption and penetration into plant tissues. In addition, the interaction between nano-fertilizers and soil microorganisms is a critical area of interest because soil microbes are essential organisms for soil nutrient cycling and plant growth. Optimizing the application methods and dosages of nano-fertilizers remains a key area of research. Various techniques, including foliar sprays and root applications, have been investigated with varying levels of success. The timing and frequency of application are also crucial factors that significantly influence crop responses and yield.

The Conventional Fertilizer Dilemma:

Traditional fertilizers, while crucial for boosting crop yields, often suffer from several drawbacks. They are often applied in excess, leading to:

- **Nutrient Runoff:** Excess nutrients leach into water bodies, causing eutrophication, harming aquatic ecosystems, and contaminating drinking water sources.
- **Greenhouse Gas Emissions:** The production and application of some conventional fertilizers contribute to the release of greenhouse gases like nitrous oxide.
- **Low Nutrient Use Efficiency:** Plants often utilize only a fraction of the applied nutrients, with the rest being lost to the environment.
- **Soil Degradation:** Overuse of certain fertilizers can alter soil pH and microbial balance, leading to long-term soil degradation.

Nano-Fertilizers: A Smarter Approach:

Nano-fertilizers are engineered materials at the nanoscale (1-100 nanometers) that are designed to deliver nutrients to plants in a more efficient and targeted manner. These tiny particles possess unique properties that offer significant advantages over conventional fertilizers:

Advantages of Nano-Fertilizers:

- **Enhanced Nutrient Use Efficiency (NUE):** Nano-fertilizers can encapsulate nutrients, protect them from leaching and volatilization, and release them gradually as per the plant's needs. This leads to significantly higher NUE, reducing fertilizer wastage.
- **Targeted Nutrient Delivery:** Nano-fertilizers can be designed to specifically target different parts of the plant, such as roots or leaves, ensuring efficient nutrient uptake.
- **Controlled Release:** The controlled release mechanism of nano-fertilizers ensures a sustained supply of nutrients throughout the plant's growth cycle, eliminating the need for frequent applications.
- **Improved Crop Yield and Quality:** By optimizing nutrient availability, nano-fertilizers can lead to increased crop yields and enhance the nutritional value of the produce.
- **Reduced Environmental Impact:** The higher NUE and targeted delivery of nano-fertilizers minimize nutrient runoff and leaching, thereby reducing the environmental footprint of agriculture. This contributes to cleaner water bodies and reduced greenhouse gas emissions.
- **Reduced Application Rates:** Due to their enhanced efficiency, nano-fertilizers often require lower application rates compared to conventional fertilizers, leading to cost savings for farmers.
- **Improved Soil Health:** Some nano-fertilizers can interact with the soil microbiome, promoting beneficial microbial activity and improving soil health.
- **Potential for Foliar Application:** Nano-fertilizers can be effectively applied through foliar sprays, allowing for rapid nutrient uptake and addressing specific nutrient deficiencies quickly.

Types of Nano-Fertilizers and Their Applications:

Various types of nano-fertilizers are being developed based on the nutrient they deliver and their formulation:

- **Nano-Nitrogen Fertilizers:** Designed to improve nitrogen use efficiency and reduce nitrogen losses.
- **Nano-Phosphorus Fertilizers:** Enhance phosphorus availability in the soil, which is often limited.
- **Nano-Potassium Fertilizers:** Improve potassium uptake and utilization by plants.
- **Nano-Micronutrient Fertilizers:** Deliver essential micronutrients like zinc, iron, and manganese in a readily available form.
- **Nano-Encapsulated Fertilizers:** Nutrients are encapsulated within nanoparticles to control their release and protect them from degradation.
- **Nano-Composites:** Combinations of nanoparticles with other materials to enhance nutrient delivery and soil health.
- These nano-fertilizers are being explored for a wide range of crops, including cereals, pulses, oilseeds, fruits, and vegetables, offering tailored solutions for different agricultural needs.

Challenges and Future Directions:

While the potential of nano-fertilizers is immense, there are also challenges that need to be addressed:

- **Long-Term Environmental Impact:** More research is needed to fully understand the long-term effects of nanoparticles on soil ecosystems and human health.
- **Standardization and Regulation:** Establishing standardized protocols for the production, application, and regulation of nano-fertilizers is crucial.
- **Cost-Effectiveness:** The cost of production and application of some nano-fertilizers needs to be optimized to make them accessible to smallholder farmers.
- **Scalability:** Scaling up the production of nano-fertilizers to meet the demands of global agriculture is a significant challenge.

Table-1: Effects of various nano-fertilizers on several crops, along with the range of doses for each crop

Nano-Fertilizers	Range of Doses	Plant/Crop	Effect
Zn NPs	5–20 mg/L	<i>Allium cepa</i> L.	Reduced root growth
Nano SiO ₂ + Nano TiO ₂	100–500 ppm	<i>Capsicum annuum</i> L.	Significant increase in seed germination
ZnO NPs	100 mg/kg	<i>Cucumis sativus</i> L.	Inhibited growth
ZnO NPs	20 mg/L	<i>Triticum aestivum</i> L.	Enhanced biological yield and grain production
	10 mg/L	<i>Cyamopsis tetragonoloba</i> L.	Increased growth biological yield and nutrient contents
	10 mg/L	<i>Zea mays</i> L.	Enhanced shoot and root growth, plant height, leaf size, chlorophyll levels, and grain quality
	5–20 mg/L	<i>Solanum melongena</i> L.	Decreased germination, root length, and leaf area in culture media, but an increase in these parameters in soil conditions
Cu NPs	20–80 mg/L	<i>Coriandrum sativum</i> L.	Reduced germination and shoot development
	50–500 mg/L	<i>Solanum lycopersicum</i> L.	Enhanced antioxidant and improved fruit firmness
	10–20 mg/L	<i>Lactuca sativa</i> L.	Reduced seed growth and dry weight and impacted water balance and nutrient content
	130–660 mg/kg	<i>Lactuca sativa</i> L.	Enhanced root and shoot length
Nano-Fe ₂ O ₃	500–1000 mg/L	<i>Cuminum cyminum</i> L.	Enhanced stem length and iron concentration
Nano-N	25–100%	<i>Oryza sativa</i> L.	Boosted the number of tillers per plant, height and dry weight
Nano-potash	1500–2500 mg/L	<i>Arachis hypogea</i> L.	Enhanced shoot length, stem biomass, biological yield, and number of flowers per plant

Conclusion

Nano-fertilizers represent a significant step towards achieving sustainable agriculture. By enhancing nutrient use efficiency, reducing environmental pollution, and improving crop productivity, they offer a promising solution to address the challenges facing modern agriculture. As research and development in this field continue to advance, nano-fertilizers have the potential to play a pivotal role in ensuring food security, protecting our environment, and building a more resilient and sustainable agricultural system for generations to come. Embracing this innovative technology can empower farmers, conserve precious resources, and contribute to a healthier planet.

Natural Farming Practices for Sustainable Soil Health and Crop Productivity



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Abstract

Soil degradation, declining efficiency of agricultural inputs, and increasing climate variability pose serious challenges to global food security and the long-term sustainability of farming systems. Although chemical-intensive agriculture has contributed to short-term yield gains, its prolonged use has led to the deterioration of soil physical, chemical, and biological properties, resulting in reduced soil resilience and rising production costs. In response to these challenges, natural farming has gained attention as a sustainable approach that works in harmony with ecological processes and promotes biological soil regeneration using on-farm resources. Natural farming practices aim to restore soil health by enhancing soil organic matter, microbial diversity, and nutrient cycling, while completely avoiding synthetic fertilizers and pesticides. The system integrates low-cost natural inputs, diversified cropping patterns, mulching, minimal tillage, and ecologically based pest management to achieve stable crop productivity across varied agro-climatic conditions. Improvements in soil structure, water-holding capacity, and biological activity under natural farming systems strengthen crop tolerance to environmental stresses and contribute to yield stability over time. This article provides an overview of the principles and practices of natural farming, emphasizing their role in improving soil health and sustaining crop productivity. It also examines the socio-economic and environmental implications of adoption, along with existing challenges and future prospects, highlighting natural farming as a viable pathway toward resilient and climate-smart agricultural systems.

Keywords: Natural farming; soil health; sustainable agriculture; crop productivity; ecological farming

1. Introduction

Agriculture across the world is facing an unprecedented crisis. Decades of intensive farming, excessive dependence on synthetic fertilizers and pesticides, declining organic matter, and improper water management have resulted in widespread soil degradation. According to global estimates, nearly one-third of the world's agricultural soils are moderately to highly degraded, threatening long-term food security. Climate change has further intensified these challenges by increasing the frequency of droughts, floods, and temperature extremes, making crop production more uncertain and costly for farmers.

Chemical-intensive agriculture, though successful in boosting yields during the Green Revolution, has revealed serious limitations over time. Continuous application of chemical fertilizers has disturbed soil nutrient balance, reduced microbial diversity, and increased soil compaction. Similarly, repeated pesticide use has led to pest resistance, resurgence, and contamination of food and ecosystems. Rising input costs have placed small and marginal farmers under economic stress, often trapping them in cycles of debt.

Against this backdrop, natural farming has emerged as a promising and sustainable alternative. Rooted in ecological principles, natural farming emphasizes working with nature rather than attempting to dominate it. The

approach seeks to regenerate soil health, reduce dependency on external inputs, and promote resilient cropping systems capable of withstanding environmental stress.

Natural farming is particularly relevant for food security, as it prioritizes long-term productivity over short-term yield maximization. By restoring soil fertility and biological activity, it supports stable yields while conserving natural resources. For smallholder farmers, especially in developing countries, natural farming offers a low-cost, locally adaptable system that strengthens livelihoods while protecting the environment.

The objective of this article is to present a comprehensive yet accessible overview of natural farming practices, highlighting their role in improving soil health and sustaining crop productivity. The article discusses key principles, soil processes, on-farm inputs, pest management strategies, and socio-economic implications, offering insights into how natural farming can contribute to sustainable agriculture.

2. Concept and Principles of Natural Farming

2.1 Definition and Philosophy

Natural farming is an agricultural approach that relies on natural ecological processes to maintain soil fertility and crop health. Unlike conventional farming, which depends heavily on synthetic fertilizers and chemical pesticides, natural farming minimizes external inputs and avoids synthetic chemicals altogether. While it shares similarities with organic farming, natural farming goes a step further by emphasizing on-farm resource use, microbial enhancement, and minimal soil disturbance.

At its core, natural farming views soil not as an inert medium for plant growth but as a living, dynamic ecosystem. Billions of microorganisms, insects, fungi, and earthworms interact within the soil to cycle nutrients, improve structure, and support plant health. Natural farming aims to nurture these interactions rather than disrupt them.

2.2 Core Principles

The foundation of natural farming rests on a few key principles. First, it avoids the use of synthetic fertilizers and pesticides, recognizing their long-term harmful effects on soil life and environmental health. Second, it promotes self-reliance by encouraging farmers to prepare inputs using locally available materials such as cow dung, cow urine, plant residues, and soil from undisturbed areas. This reduces production costs and dependence on external markets.

Another important principle is biodiversity enhancement. Natural farming systems encourage crop diversity, intercropping, and the integration of trees and livestock. Biodiversity above and below the soil surface improves nutrient cycling, pest regulation, and ecosystem resilience. Together, these principles create a regenerative system capable of sustaining productivity while restoring environmental balance.

3. Soil Health as the Foundation of Natural Farming

Healthy soil is the cornerstone of natural farming. Soil health is determined by the interaction of physical, chemical, and biological properties, all of which are addressed through natural farming practices.

3.1 Physical Properties of Healthy Soil

Physically healthy soil has a well-aggregated structure that allows adequate air and water movement. Good soil aggregation improves root penetration and reduces surface runoff and erosion. Organic matter plays a crucial role in binding soil particles into stable aggregates, enhancing porosity and water infiltration.

In natural farming systems, regular addition of organic residues, mulching, and minimal tillage help maintain soil structure. Improved water-holding capacity is particularly important under rainfed conditions, where soils with higher organic matter can retain moisture for longer periods, reducing crop stress during dry spells.

3.2 Chemical Properties

From a chemical perspective, natural farming emphasizes nutrient cycling rather than nutrient addition. Instead of supplying nutrients in readily soluble forms, natural inputs stimulate microbial activity that gradually releases nutrients from organic matter and soil minerals. This leads to balanced nutrient availability and reduces the risk of leaching and nutrient losses. Natural farming also helps stabilize soil pH and improve cation exchange capacity, enabling soils to retain and supply essential nutrients more effectively. Over time, this results in improved soil fertility without the negative side effects associated with excessive chemical fertilizer use.

3.3 Biological Properties

The biological component of soil health is central to natural farming. Soil microorganisms, including bacteria, fungi, actinomycetes, and algae, drive nutrient transformations and support plant growth. Earthworms improve soil structure and enhance organic matter decomposition, while mycorrhizal fungi extend the effective root system of plants, improving nutrient and water uptake.

The rhizosphere—the zone surrounding plant roots—is particularly active in natural farming systems. Root exudates feed beneficial microbes, creating a mutually supportive relationship that enhances plant nutrition and disease resistance.

Table 1. Indicators of Soil Health Under Natural Farming Systems

Soil Parameter	Conventional Farming Status	Natural Farming Status	Functional Significance
Soil organic carbon	Low to declining	Moderate to increasing	Improves structure and nutrient retention
Microbial diversity	Reduced	High	Enhances nutrient cycling
Soil aggregation	Poor	Stable	Reduces erosion and compaction
Water-holding capacity	Low	High	Improves drought resilience

4. Natural Inputs and On-Farm Preparations

Natural farming relies on simple, low-cost inputs prepared on the farm to stimulate soil biology and plant health.

4.1 Microbial Formulations

Jeevamrit and Beejamrit are widely used microbial formulations in natural farming. Prepared using cow dung, cow urine, jaggery, pulse flour, and a small quantity of soil, these inputs act as microbial inoculants. They do not directly supply nutrients in large quantities but enhance microbial activity, accelerating the decomposition of organic matter and nutrient release.

Beejamrit is primarily used as a seed treatment to protect young seedlings from soil-borne diseases and promote early root development. Jeevamrit is applied to soil or irrigation water to boost microbial populations throughout the crop growth period.

4.2 Botanical and Biological Inputs

Panchagavya, a fermented mixture of cow-based products, functions as a natural growth promoter. Plant-based extracts prepared from neem, chili, garlic, and other botanicals are used for pest and disease management. These inputs are biodegradable, environmentally safe, and compatible with beneficial organisms.

4.3 Economic and Ecological Benefits

One of the major advantages of natural inputs is cost reduction. Farmers can prepare most inputs using locally available materials, significantly lowering expenditure on agrochemicals. Ecologically, these inputs improve soil resilience, reduce pollution, and enhance on-farm biodiversity.

5. Cropping System Diversification and Soil Regeneration

5.1 Crop Rotation and Intercropping

Diversified cropping systems are central to natural farming. Crop rotation prevents nutrient depletion and disrupts pest and disease cycles. Intercropping systems, such as cereals with legumes, improve resource use efficiency and reduce weed pressure.

5.2 Role of Legumes and Green Manure Crops

Legumes play a critical role by fixing atmospheric nitrogen through symbiotic bacteria. Green manure crops such as sunhemp and dhaincha add organic matter and improve soil structure when incorporated into the soil.

5.3 Agroforestry Integration

Integrating trees with crops enhances nutrient recycling, improves microclimate, and provides additional income sources. Trees contribute leaf litter and root biomass, enriching soil organic matter.

6. Mulching and Minimal Tillage Practices

Mulching is a key practice in natural farming that protects soil from erosion and moisture loss. Live mulches include cover crops, while dry mulches consist of crop residues and straw. Soil mulch is achieved through shallow

cultivation that breaks capillary action. Mulching moderates soil temperature, suppresses weeds, and enhances microbial activity. Combined with minimal tillage, it preserves soil structure and reduces carbon loss, contributing to long-term soil health.

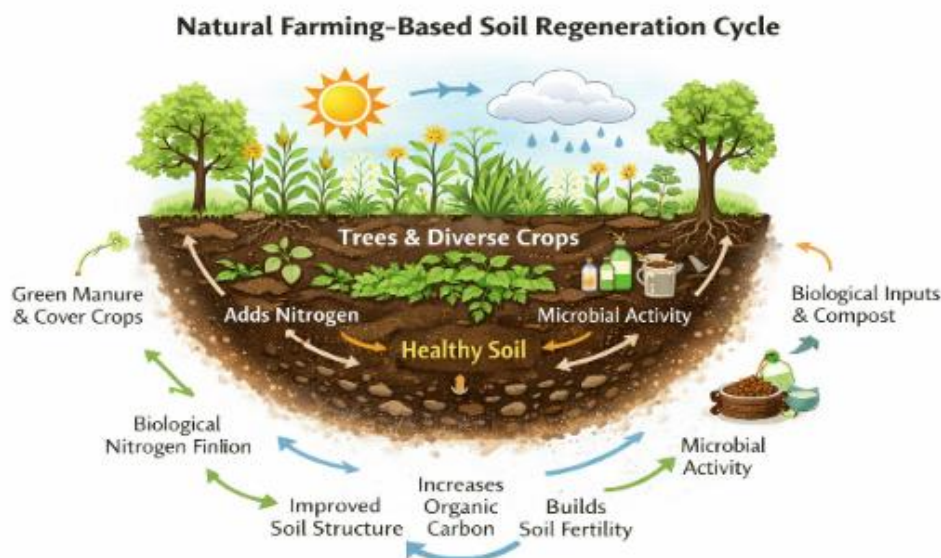


Figure 1. Schematic representation of natural farming-based soil regeneration cycle

7. Natural Pest and Disease Management

7.1 Ecological Pest Regulation

Natural farming emphasizes prevention over control. Healthy soils produce robust plants that are less susceptible to pests. Beneficial insects and predators are conserved through habitat management and avoidance of toxic chemicals.

7.2 Botanical Pesticides

Neem-based formulations and fermented plant extracts are commonly used to manage pests and diseases. These substances act as repellents, antifeedants, or growth inhibitors rather than instant killers.

7.3 Preventive Plant Health Approach

Strengthening plant immunity through balanced nutrition and microbial activity reduces the need for curative interventions.

Table 2. Common Natural Pest Management Inputs and Their Functional Effects

Input	Source Material	Target Pests/Diseases	Mode of Action
Neem extract	Neem leaves/seeds	Sucking pests	Antifeedant, growth inhibition
Chili-garlic extract	Chili, garlic	Chewing insects	Repellent
Fermented buttermilk	Milk products	Fungal diseases	Microbial antagonism

8. Impact of Natural Farming on Crop Productivity and Yield Stability

During the initial transition phase, yields under natural farming may be comparable or slightly lower than conventional systems. However, as soil health improves, yield stability increases. Crops grown in biologically active soils show greater tolerance to drought, pests, and nutrient stress.

Long-term studies indicate that natural farming systems can sustain comparable yields while reducing input costs and environmental risks.

9. Socio-Economic and Environmental Implications

Natural farming reduces farmers' dependence on costly external inputs, improving income stability. Environmentally, it contributes to climate change mitigation by enhancing carbon sequestration and reducing greenhouse gas emissions. At the community level, it promotes sustainable rural development and resilience.

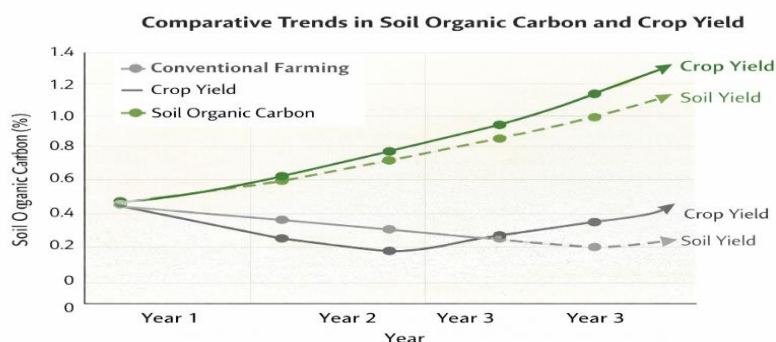


Figure 2. Comparative trends in soil organic carbon and crop yield under conventional and natural farming systems

10. Challenges, Limitations, and Adoption Barriers

Despite its benefits, natural farming faces challenges such as initial yield fluctuations, the need for knowledge-intensive management, and limited institutional support. Policy incentives, extension services, and market recognition are crucial for wider adoption.

11. Conclusion and Future Perspectives

Natural farming offers a viable pathway toward sustainable agriculture by restoring soil health and ensuring long-term crop productivity. By embracing ecological processes and farmer self-reliance, it addresses both environmental and economic concerns. Future efforts should focus on research, capacity building, and supportive policies to scale up natural farming for global food security.

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Precision and Digital Technologies in Modern Aquaculture Practices



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1. Introduction

The global protein needs of aquatic species are growing fast due to population growth and changing lifestyles that incline towards healthier proteins. With capture fisheries having now matured to a level of plateau following excessive exploitation, aquaculture has risen to become the major source of meeting this increased need, now contributing more than half of all fish being consumed worldwide. However, the acceleration of aquaculture production faces high hurdles such as the increased scrutiny on environmental consequences, outbreaks of diseases, fluctuating operational expenses, especially those in relation to feed and a decreasing workforce. To deal with these complex challenges and to maintain sustainability and profitability, the sector is experiencing a paradigm shift similar to the terrestrial agriculture Green Revolution that is typified by the introduction of Precision Aquaculture.

Precision aquaculture, commonly placed within the umbrella term of Aquaculture 4.0, is the use of information and communication technologies (ICT), the Internet of Things (IoT), robotics, as well as artificial intelligence (AI) in farming. Contrary to the past approaches, which were mainly manual, intuitive, and reactive in management, precision aquaculture uses a data-driven approach to handle spatial and temporal variation in the production systems. With real-time monitoring of environmental parameters and the health of stock, the farm operators can move towards proactive management.

2. The Foundation of Precision

The ability to gather continuous and trustworthy data about the water body is the foundation of accurate aquaculture. The quality of water is the main factor that determines the health of fish, their growth rates and survival. Conventional monitoring meant that sampling had to be done manually at set times, i.e. once or twice a day or a week, which often failed to capture quick changes in parameters like dissolved oxygen (DO) or pH, thus triggering stress episodes or death.

Internet of Things (IoT) has transformed this process by creating interconnected networks of autonomous sensors installed directly in ponds, tanks or sea cages. These sensors watch over such critical parameters as DO, temperature, pH, salinity, turbidity, ammonia, and nitrate continuously. The information received is through wireless protocols (e.g., LoRaWAN, cellular network, satellite) to cloud-based infrastructure, allowing farm managers to see real-time dashboards on a smartphone or computer remotely. Importantly, the systems can be programmed to send immediate alerts through SMS or email, once the parameters are out of the fixed optimal limits, so that timely intervention can be carried out. As an example, when DO suddenly drops at 3:00 AM, an automated alarm is sent, which enables the manager to turn on the backup aeration systems remotely and thus avoid a possible fish kill.

The development of sensor technology has gone beyond simple physicochemical parameters; biosensors are now being developed so that they can be able to detect a certain pathogen or stress biomarkers in the water, which presents the prospect of early warning systems of disease outbreaks before it is too late to give clinical signs in the stock.

Table 12. Comparison of Traditional versus IoT-Enabled Environmental Monitoring in Aquaculture

Feature	Traditional Monitoring	IoT-Enabled Precision Monitoring
Sampling Frequency	Periodic (daily/weekly); Snapshots in time.	Continuous (seconds/minutes); Real-time dynamic streams.
Data Accuracy & Integrity	Prone to human error in sampling and recording.	High precision sensors; automated logging reduces error.
Response Time	Reactive; actions taken after an event is discovered.	Proactive; real-time alerts enable preventative action.
Labor Requirement	High; requires manual presence for sampling.	Low; autonomous operation requires minimal intervention.
Data Utilization	Limited to immediate operational decisions.	Form historical datasets for long-term trend analysis and AI modelling.
Spatial Coverage	Limited to easily accessible sampling points.	Distributed sensor networks cover diverse depths and locations within a cage/pond.

3. Operational Efficiency through Automation and Robotics

Sensors supply the nervous system of the farm, but automation and robotics are the muscle, as they can perform their work much more accurately and predictably than a person.

3.1 Intelligent Feeding Systems

The feed in aquaculture takes up about 50-70% of the total operation costs. Excessive feeding leads to loss of money and degradation of the environment by increased nutrient enrichment (eutrophication) of the waters surrounding the feeding area, and underfeeding leads to low growth rates and development of aggressive behaviour. The common feeding programs are usually predetermined without consideration of the daily variation in fish feeding as a result of temperature variations or stress.

Precision feeding systems combine both environmental sensor information and behavioural monitoring to feed on-time optimally. The sensors are advanced acoustic sensors (hydrophones) that can detect the specific sounds of a feeding fish, and this enables the system to know when the feeding intensity has decreased and thus when the fish has been fed; at this point, the feed cannons will automatically be turned off. More advanced systems use computer vision and underwater cameras to monitor feeding behaviour and pellet consumption so that feed is given out only when the fish are actively seeking it. This style of demand feeding has a significant positive effect on the Feed Conversion Ratio (FCR).

3.2 Underwater Robotics (ROVs and AUVs)

It is dangerous, labour-intensive and expensive to maintain infrastructure in the aquatic environment, especially in the offshore sea cages. Divers are normally used in net inspection, mortality collection, and cleaning.

These risky behaviours are gradually being replaced by Remotely Operated Vehicles (ROVs) or Autonomous Underwater Vehicles (AUVs) to replace human divers. High-definition cameras and sonar-fitted ROVs perform rigorous checks of cage nets to detect tears or biofouling debris to reduce the potential of fish escape. Other ROVs have manipulator arms for some small checks or suction arms to collect mortalities in deep cage bottoms- a necessary activity to avoid the spread of the disease. Also, there are autonomous net-cleaning robots, which move around the cage mesh, cleaning with high-pressure cavitation jets. Clean nets are crucial in providing sufficient water exchange and oxygen in the cage, hence keeping the stocks healthy.

4. The Brain of the Operation

The large amount of data that is produced by Internet of Things (IoT) sensors, cameras, and automated equipment has little inherent value when using basic methods of analysis. Artificial Intelligence (AI) and Machine Learning (ML), therefore, take a central position whereby they convert raw data into actionable information.

4.1 Computer Vision for Biomass Estimation and Health Monitoring

The total biomass in a cage or pond is very important in estimating correct feeding rates, harvesting, and determining the stocking density. Traditional techniques include the physical capture of a sample of fish and weighing them; traditional techniques have the disadvantage of placing stress on the animals involved, are labour-intensive, and generally produce statistically invalid results due to sampling bias.

Stereoscopic underwater cameras are used in computer vision to acquire images of the stock. The algorithms implemented using AI can recognise single fish, determine their length and width, and predict their weight with great precision (usually more than 95%). This allows the continuous, non-invasive estimation of biomass.

In addition to biomass analysis, computer vision is used in health analysis. The AIs are based on video feed analysis to identify apparent signs of disease, including cutaneous lesions, fin rot, or abnormal swimming behaviour. Specialised algorithms have also been created to find and measure sea lice infestation in swimming fish in the field of salmon farming, which will solve a significant parasitism issue in the industry.

4.2 Predictive Analytics

Machine-learning solutions are capable of processing complex data-sets including the history of water-quality, weather predictions, stock feeds, and stock performance, to predict what may happen in the future.

- **Growth Forecasting:** AI will be able to estimate harvest dates more closely by evaluating existing size parameters and environmental factors, and operate more efficiently by matching production schedules and demand in the market.
- **Environmental Forecasting:** Artificial Intelligence can forecast harmful algal blooms or low oxygen conditions by examining patterns in temperature, sunlight, and nutrient levels, thus allowing farmers a chance to mitigate the situation in time.

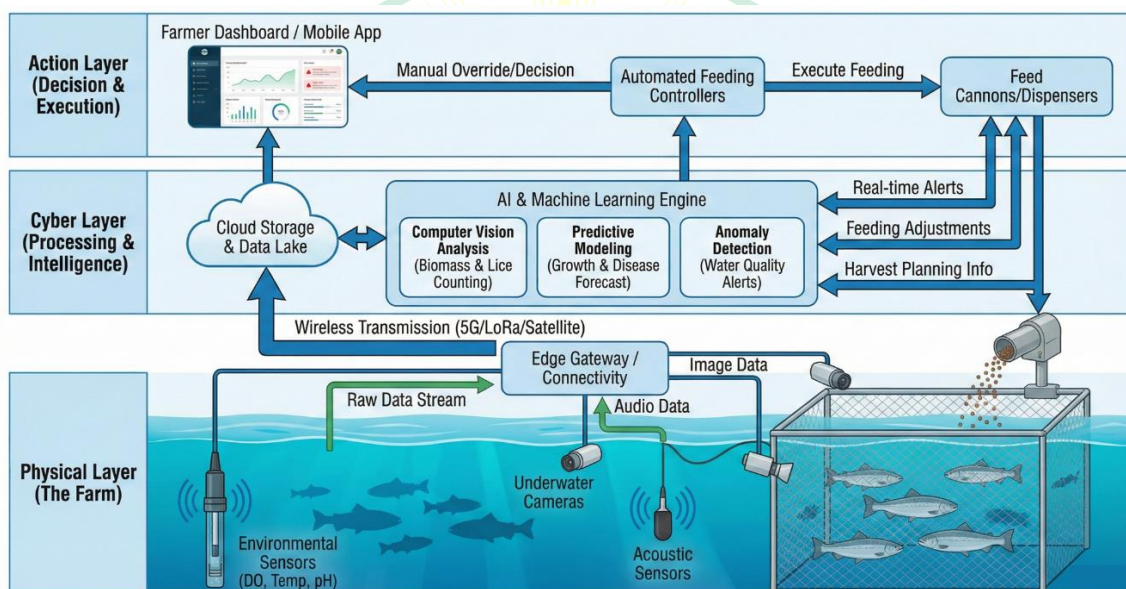


Figure 5. Data flow in a modern precision aquaculture system

5. Traceability and Supply Chain Transparency

Digital technologies are not within the farm gate. Increasingly, consumers and retailers in the contemporary world seek verifiable information regarding seafood products on sustainability, origin and welfare criteria.

The blockchain technology is becoming a potent instrument for guaranteeing traceability. Being a decentralised system and an immutable ledger, blockchain can document all the transactions and data points within the supply chain, including the source of hatchery and the feed ingredients used, water-quality records during grow-out and process information on the fish, a digital passport of the fish that can never be altered.

Consumers can get this information by scanning a QR code on the final packaging and can ensure that the product is not falsely labelled and meets stated sustainability rates. Such transparency creates awareness of consumer confidence and helps high-end producers to stand out in the ever-saturated market.

6. Challenges and Future Outlook

Although the advantages of precision aquaculture can be proven, the process of its implementation is not devoid of significant issues.

6.1 Economic and Infrastructure Barriers

The sensors, remote operated vehicles (ROVs) and software platforms are initially expensive to install, and may be unaffordable to small-scale farmers, particularly in developing countries where most aquaculture is practised. Additionally, high-speed internet connectivity, e.g. 5G, which is required to deliver high-definition video to cloud servers located in offshore areas, is often inaccessible in coastal rural areas.

6.2 Data Security and Interoperability

When farms are digitised, they are prone to cybercrimes. Secrecy of proprietary information on feed compositions or stock health is of the highest priority. Also, the lack of standardisation is an issue in the industry now; sensors of one manufacturer might fail to interoperate with the software platform of another, creating silos of data that cannot be analysed holistically.

6.3 The Skills Gap

Effective adoption of these technologies demands novel categories of aquaculture scholars; these are individuals with combined knowledge in aquatic biology and data science/IT. In the current situation, there is a large skills gap in the labour pool required to handle and perceive these complicated systems.

6.4 Future Outlook

In the future, the trend will lead to more autonomous agriculture. The industry is changing from connected farms (IoT monitoring) to smart farms (AI analysis) and eventually into autonomous farms, where the system is able to create and implement complex decisions without much human intervention. The next-generation developments will probably include swarm robots to perform maintenance of large cages and more sophisticated genetic algorithms to use in combination with AI to select broodstock on the basis of performance data gathered throughout generations.

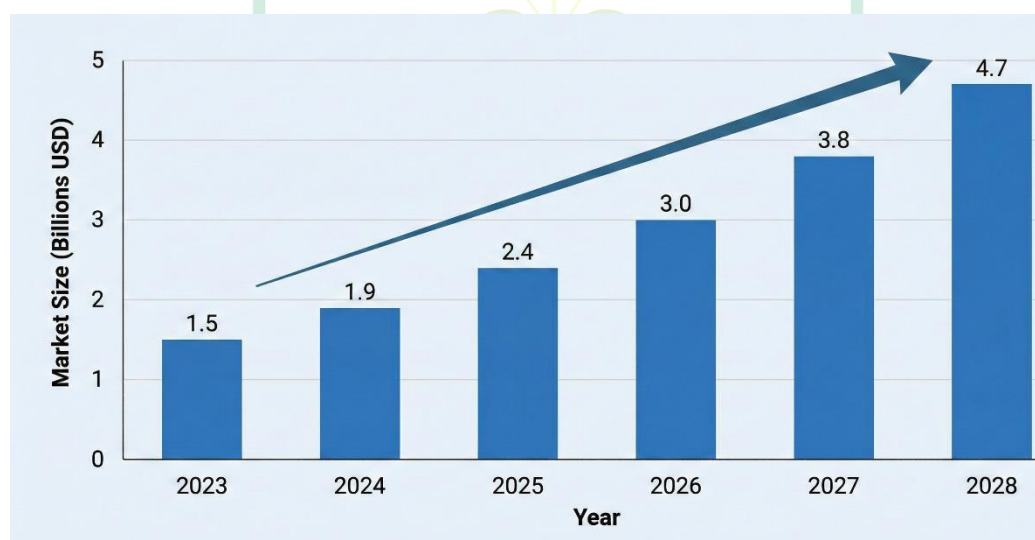


Figure 6. Projected Global Precision Aquaculture Market Growth

7. Conclusion

Precision and digital technologies are no longer considered a futuristic idea in aquaculture; they are quickly becoming key tools for survival and competitiveness in a competitive global market. Through a shift of management, which relies on intuition, to the precision made with data, aquaculture businesses will be able to reach a higher yield status in addition to better animal welfare, a significant decrease in environmental footprint due to the optimised feed and energy consumption, and supply-chain transparency. Despite issues of economic and technical challenges, the ever-growing maturation of these technologies and the increasing demand for sustainable food systems surely will lead the so-called Blue Revolution into the digital era. Such a future of fish farming is explicitly data-centric.

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Recent Innovations in Aquafeed Formulation and Nutritional Management



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1. Introduction

Aquaculture has become one of the most rapidly expanding sectors of global food production, playing an increasingly vital role in ensuring food and nutritional security. With global aquaculture production exceeding 125 million metric tons annually, the sector now contributes nearly 52% of the aquatic food consumed by humans. This remarkable growth has been driven by stagnation in capture fisheries, rising population pressure, and increasing demand for high-quality animal protein. However, the long-term sustainability of aquaculture depends fundamentally on innovations in aquafeed formulation and nutritional management, as feed represents both the primary production input and the main interface between farming practices and the aquatic environment. Feed costs account for approximately 40–60% of total operational expenditure in most aquaculture systems, making aquafeed the single largest determinant of economic viability. Beyond cost considerations, feed composition and feeding strategies strongly influence growth performance, feed conversion efficiency, health status, immune competence, product quality, and environmental outcomes. Inefficient feeds result in excess nutrient discharge, deterioration of water quality, increased disease incidence, and reduced farm profitability. Consequently, improving feed efficiency while minimizing environmental impact has become a central objective of modern aquaculture.

Historically, aquafeeds have relied heavily on fishmeal and fish oil derived from wild-caught pelagic fish species such as anchovies, sardines, and menhaden. These ingredients have been valued for their high protein quality, balanced amino acid profiles, and rich content of long-chain polyunsaturated fatty acids (LC-PUFA). However, global fishmeal production has plateaued at approximately 4.5–5 million metric tons per year, while demand from aquaculture and livestock sectors continues to rise. This imbalance has led to escalating prices, supply instability, and growing concerns over the ecological sustainability of forage fisheries. Climate change, overfishing, and ecosystem variability further exacerbate these constraints. In response, aquaculture nutrition has undergone a fundamental transformation over the past two decades. The focus has shifted from maximizing short-term growth through high inclusion of marine ingredients toward developing nutritionally efficient, environmentally responsible, and economically viable feed solutions. Advances in ingredient innovation, feed processing technologies, and precision nutritional management now form the foundation of sustainable aquaculture development.

2. Evolution of Aquafeed Formulation

The evolution of aquafeed formulation reflects broader changes in scientific understanding and production philosophy within aquaculture. Early commercial feeds, particularly during the 1980s and 1990s, were designed primarily to maximize growth rate and survival. These formulations emphasized crude protein and energy content, often with little consideration of nutrient digestibility, bioavailability, or environmental consequences. As a result, large proportions of dietary nitrogen and phosphorus were excreted into the surrounding environment, contributing to eutrophication and sediment enrichment.

The early 2000s marked a turning point with the recognition that nutrient utilization efficiency is as important as nutrient quantity. This shift toward quality-driven nutrition emphasized digestible protein, balanced amino acid profiles, lipid utilization efficiency, and mineral bioavailability. Species-specific nutritional requirements were increasingly recognized, along with the role of anti-nutritional factors present in many plant-based ingredients. Improvements in analytical techniques and feeding trials enabled more precise estimation of digestible nutrients and metabolic demands. Contemporary aquafeed formulation integrates multiple objectives,

including growth performance, health promotion, environmental protection, and product quality enhancement. Modern feeds are designed to support immune function, improve stress resilience, and reduce metabolic waste while maintaining economic feasibility. This transition reflects the maturation of aquaculture into a science-based and sustainability-oriented industry.

3. Innovations in Aquafeed Ingredients

3.1 Alternative Protein Sources

Reducing dependence on fishmeal remains one of the most critical challenges in aquafeed development. Rather than direct replacement, current research supports diversified protein strategies that combine multiple alternative ingredients to achieve nutritional balance.

Plant-based proteins continue to dominate fishmeal replacement strategies due to their availability and cost-effectiveness. Soybean meal remains the most widely used alternative, supported by decades of nutritional research. However, anti-nutritional factors such as trypsin inhibitors, lectins, and phytic acid can reduce nutrient digestibility and mineral availability. Advanced processing technologies, including microbial fermentation and enzymatic treatment, have significantly improved the nutritional value of plant proteins. Fermentation using *Aspergillus* and *Bacillus* species reduces phytic acid content and enhances amino acid availability, while enzyme supplementation improves fiber degradation and nutrient release. Sequential processing approaches now achieve protein digestibility coefficients approaching those of fishmeal. Pea protein concentrate and processed rapeseed meal have gained attention as complementary protein sources. Pea protein contains fewer anti-nutritional factors and has been associated with improved intestinal morphology and mucosal health. Rapeseed meal, once limited by glucosinolate content, can now be effectively utilized following thermal and enzymatic processing.

Insect meals represent a major conceptual shift in aquafeed formulation by aligning sustainability with circular bioeconomy principles. Black soldier fly (*Hermetia illucens*) larvae are particularly promising due to their ability to convert organic waste into high-quality protein. BSF meal typically contains 45–50% crude protein and exhibits amino acid profiles comparable to fishmeal. The presence of chitin provides additional functional benefits by supporting gut microbiota and enhancing intestinal barrier function. Feeding trials across multiple fish species consistently demonstrate comparable growth performance and improved immune indicators when BSF meal replaces up to 50% of fishmeal.

Single-cell proteins derived from bacteria, yeast, fungi, and microalgae represent an emerging frontier in aquafeed innovation. These ingredients offer rapid production rates, minimal land use, and consistent nutritional quality. Yeast-based products provide immunostimulatory compounds such as β -glucans, while microalgae contribute both protein and essential fatty acids. Despite current limitations related to cost and infrastructure, ongoing advances in fermentation technology are expected to improve scalability and economic viability.

3.2 Innovations in Lipid Sources

Sustainable replacement of fish oil is essential due to its role as the primary source of dietary EPA and DHA. Carnivorous fish species exhibit high LC-PUFA requirements, while omnivorous species display greater metabolic flexibility. Algal oils have emerged as the most promising alternative source of EPA and DHA. Modern algal oil products provide fatty acid concentrations approaching those of fish oil, enabling partial or complete replacement in high-value feeds. However, high production costs currently limit widespread adoption. Plant-based oils such as canola, soybean, and linseed oil are widely used as energy sources but lack LC-PUFA. Blended lipid strategies combining small amounts of algal oil with plant oils have demonstrated economic and nutritional advantages, maintaining growth performance and flesh quality while improving sustainability.

4. Advances in Feed Processing Technologies

Modern feed processing technologies play a critical role in maximizing nutrient utilization and feed stability. Extrusion technology improves pellet uniformity, water stability, and digestibility through high-temperature short-time processing. This approach reduces anti-nutritional factors while enhancing amino acid availability. Microencapsulation protects heat- and oxygen-sensitive nutrients such as probiotics, enzymes, vitamins, and essential oils. Encapsulation ensures targeted delivery and consistent bioactivity, enabling the development of functional feeds with reliable performance. Enzyme supplementation and fermentation further enhance nutrient availability and generate beneficial bioactive metabolites.

Comparison of Processing Techniques for Alternative Aquafeed Proteins			
Protein Source	Processing Method	Key Improvement	Nutritional Benefit
 Plant-Based (Soy/Pea)	 Fermentation & Enzyme Treatment	 Reduced Anti-Nutritional Factors (ANFs)	 Increased Amino Acid Bioavailability
 Insect Meal (Black Soldier Fly)	 Mechanical Drying & Defatting	 Circular Bioeconomy	 High-Quality Protein & Lipid Profile
 Single-Cell Protein (Yeast/Bacteria)	 Controlled Bioreactor Cultivation	 Immunostimulatory Effects & Consistent Profile	 Immunostimulatory Effects & Consistent Profile

5. Innovations in Nutritional Management

5.1 Species- and Stage-Specific Nutrition

Aquaculture encompasses hundreds of farmed species, each with distinct physiological and nutritional requirements. Ontogenic feeding strategies align diet composition with developmental stage, optimizing metabolic programming, immune development, and long-term productivity. Early-life nutrition has been shown to exert lasting effects on growth potential and disease resistance.

5.2 Precision and Automated Feeding

Precision feeding systems integrate behavioural monitoring, environmental sensors, and machine learning algorithms to dynamically adjust feeding strategies. These systems reduce feed waste, improve feed conversion efficiency, and lower nutrient discharge. Economic analyses consistently demonstrate rapid return on investment through reduced feed costs and improved performance.

6. Functional Feeds and Health-Oriented Nutrition

Functional feeds have gained increasing importance in modern aquaculture as producers seek sustainable alternatives to chemotherapeutic agents and prophylactic antibiotics. Intensification of aquaculture systems often elevates stress levels and disease pressure, making nutritional intervention a key strategy for maintaining animal health. Functional feeds are formulated not only to meet basic nutritional requirements but also to actively enhance physiological functions related to immunity, gut health, and stress tolerance.

Probiotics such as *Bacillus subtilis*, *Bacillus licheniformis*, and *Lactobacillus plantarum* are widely incorporated into aquafeeds due to their stability during processing and ability to colonize the gastrointestinal tract. These beneficial microorganisms improve digestive enzyme activity, competitively exclude pathogenic bacteria, and produce antimicrobial compounds such as bacteriocins. Prebiotics, including fructooligosaccharides (FOS) and mannanoligosaccharides (MOS), selectively stimulate beneficial gut microbiota, leading to improved nutrient absorption and intestinal integrity.

Phytogenic feed additives derived from herbs, spices, and essential oils have also received considerable attention. Bioactive compounds such as carvacrol, thymol, eugenol, and cinnamaldehyde exhibit antimicrobial, antioxidant, and anti-inflammatory properties. At appropriate inclusion levels, these compounds enhance disease resistance without negatively affecting feed palatability or flesh quality. Immunostimulants, particularly β -1,3-glucans derived from yeast cell walls, activate innate immune responses by stimulating phagocytic activity, lysozyme production, and oxidative burst mechanisms. The cumulative use of functional feed additives has been shown to improve survival rates, reduce disease outbreaks, and lower dependence on antibiotic treatments in commercial aquaculture operations.

Table 1. Innovative Aquafeed Ingredients and Their Functional Roles

Category	Examples	Functional Role
Plant proteins	Soybean meal, pea protein	Sustainable protein source
Insect proteins	Black soldier fly larvae	High digestibility, eco-friendly
Single-cell proteins	Yeast, bacterial biomass	Consistent quality, immune support
Lipid alternatives	Algal oil, vegetable oil	Fish oil replacement

Table 2. Functional Feed Additives in Modern Aquafeeds

Additive	Examples	Key Benefits
Probiotics	<i>Bacillus</i> , <i>Lactobacillus</i>	Gut health
Prebiotics	MOS, FOS	Microbiome balance
Phytogenics	Essential oils	Antimicrobial activity
Immunostimulants	β -glucans	Enhanced immunity

7. Environmental and Economic Implications

Innovations in aquafeed formulation and nutritional management offer significant environmental benefits by improving nutrient-use efficiency and reducing waste outputs. Enhanced digestibility of proteins and minerals directly decreases nitrogen and phosphorus excretion, which are major contributors to eutrophication and sediment degradation in aquaculture environments. The use of phytase and highly digestible protein sources has been shown to reduce phosphorus discharge by up to 30%, while optimized amino acid balance lowers ammonia and nitrous oxide emissions.

From an economic perspective, improved feed efficiency translates into substantial cost savings, particularly in intensive and semi-intensive production systems. Even modest improvements in feed conversion ratio can significantly reduce total feed consumption over a production cycle, improving profit margins. Functional feeds further contribute to economic resilience by reducing disease-related mortality, minimizing treatment costs, and improving uniformity of harvested stock. In addition, adoption of sustainable feed formulations supports compliance with increasingly stringent environmental regulations and enables access to premium markets that value eco-certified and responsibly produced seafood.

Improved feed digestibility and precision feeding significantly reduce nitrogen and phosphorus excretion, mitigating eutrophication risks. Economically, enhanced feed efficiency directly improves profitability, particularly in intensive systems. Sustainable feed formulations also facilitate regulatory compliance and access to premium markets.

8. Current Challenges and Research Priorities

Despite substantial progress, several challenges continue to limit the widespread adoption of innovative aquafeed technologies. One of the most significant constraints is the high cost of novel ingredients such as single-cell proteins, algal oils, and insect meals, which currently remain more expensive than conventional marine ingredients. Improving production efficiency, scaling fermentation technologies, and utilizing low-cost substrates are key research priorities for reducing costs.

Regulatory approval processes for novel feed ingredients also pose challenges, as safety and efficacy assessments can be time-consuming and region-specific. Differences in regulatory frameworks across countries further complicate global adoption. In addition, aquafeed formulations must be adapted to regional conditions, species diversity, and locally available raw materials, particularly in tropical and developing regions where production systems differ markedly from temperate aquaculture. Knowledge transfer remains a critical bottleneck, as many research advances are not effectively translated into on-farm practices. Strengthening extension services, industry-academia partnerships, and capacity-building initiatives will be essential to ensure that small- and medium-scale producers benefit from scientific innovation.

9. Future Prospects and Research Directions

The future of aquafeed formulation lies in the integration of biological insights with digital and systems-based technologies. Nutrigenomics and transcriptomics are expected to enable more precise understanding of nutrient-

gene interactions, supporting the development of diets tailored to specific species, strains, and production stages. Such precision nutrition approaches have the potential to enhance growth efficiency, disease resistance, and stress tolerance.

Advances in artificial intelligence and machine learning will further refine precision feeding systems by integrating real-time data on fish behavior, growth, environmental conditions, and market dynamics. These tools will enable predictive feeding strategies that optimize productivity while minimizing environmental impact. Sustainable ingredient development, including improved microbial fermentation and circular bioeconomy approaches, will play a central role in reducing the environmental footprint of aquafeeds. Future aquafeed development will be driven by advances in nutrigenomics, metabolomics, artificial intelligence, and sustainable ingredient production. Precision nutrition tailored to genetic and physiological profiles will enable proactive health management and improved feed efficiency. Integration of digital technologies with farm management systems will further optimize production outcomes.

10. Conclusion

Innovations in aquafeed formulation and nutritional management have fundamentally reshaped modern aquaculture by aligning productivity with sustainability and animal health. Diversification of protein and lipid sources has reduced dependence on finite marine resources while maintaining nutritional adequacy and growth performance. Advances in feed processing technologies and functional nutrition have improved nutrient utilization, immune competence, and stress resilience in cultured species. Precision feeding and health-oriented nutritional strategies deliver measurable environmental benefits through reduced nutrient discharge and improved water quality, while simultaneously enhancing economic efficiency. As global demand for aquatic protein continues to rise, sustained investment in research, regulatory harmonization, and knowledge dissemination will be critical. The continued evolution of aquafeed science will remain central to achieving resilient, environmentally responsible, and economically viable aquaculture systems.

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Reproductive Health Management and Biotechnologies in Livestock



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1. Introduction

It is estimated that the global increase in demand of animal-source foods will be immense by 2050 driven by population growth and increased economic set standards in the third world countries. In order to meet this demand in a sustainable way, livestock sector needs to increase production efficiency. At the focus of this aim is reproductive performance, which is one of the major limiting factors in dairy as well as meat production systems across the globe.

In earlier times, reproductive management had been based solely on the phenotypic observation, e.g. heat detection, combined with rudimentary veterinary care. However, the modernization of agriculture has prompted the need to change the paradigm to a proactive Reproductive Health Management (RHM). RHM is an integrated model of nutrition, biosecurity, environmental management, and veterinary intervention to achieve the best fertility.

In addition, animal breeding has been transformed with the introduction of reproductive biotechnologies. The technologies allow producers to decouple genetic possibilities and the geographic limitations, are able to replicate superior genotypes and are able to control reproductive physiology to lead to strategic management goals. The paper is a synthesis of the fundamental aspects of RHM, and an analysis of the present-day situation in biotechnological research that is revolutionizing the way livestock is bred.

2. Holistic Reproductive Health Management

Another requirement before biotechnological interventions is successfully implemented is that underlying health and husbandry practices must be strong. Biotechnology is not a replacement of a lacking management; it enhances the results of a good management practice.

2.1 Nutritional Influences on Fertility

Nutrition is arguably the most important environmental factor of reproductive status. Energy balance is paramount. Negative energy balance (NEB) in high-yielding dairy cows within the initial lactation period is known to trigger anestrus and also lowers conception rates. GnRH pulse frequency is suppressed by mobilizing body stores to sustain lactation requirements which in turn retards ovarian follicular growth. On the other hand, the overconditioning of beef heifers may result in the development of dystocia and metabolic disorders which negatively impact the future fertility. Sufficient macronutrient and micro-mineral supplementation, which involves phosphorus, selenium, and copper, is also required to have normal reproductive physiology.

2.2 Biosecurity and Disease Control

Reproductive performance may be seriously inhibited by infectious diseases by early embryonic mortality, abortion, stillbirth, or permanent sterility. As a result, a complete biosecurity plan and an inoculation agenda would become the inalienable parts of RHM.

Table 13. Common Reproductive Pathogens in Bovine Production and Management Strategies

Pathogen/Condition	Causative Agent	Clinical Reproductive Manifestation	Management/Prevention Strategy
Brucellosis	<i>Brucella abortus</i> (Bacteria)	Abortion (usually late gestation), retained placenta, orchitis in bulls.	Vaccination (strain RB51/S19), test-and-slaughter policies, strict biosecurity.
IBR	Bovine Herpesvirus-1 (Virus)	Abortion (mid-to-late gestation), infectious pustular vulvovaginitis.	Modified-live or killed virus vaccination protocols prior to breeding.
BVD	Bovine Viral Diarrhea (Virus)	Early embryonic death, abortion, congenital defects, persistent infection (PI) in calves.	Identification and removal of PI animals, vaccination, biosecurity screening of purchased stock.
Leptospirosis	<i>Leptospira</i> spp. (Bacteria)	Abortion, stillbirths, weak calves, infertility.	Annual or bi-annual vaccination with serovar-specific bacterins; water source management.
Trichomoniasis	<i>Tritrichomonas foetus</i> (Protozoa)	Early embryonic death (often mistaken as infertility), post-coital pyometra.	Using virgin bulls, testing bulls pre-breeding season, utilizing Artificial Insemination.

2.3 Environmental Stressors

Heat stress is one of the leading causes of reduced fertility especially in the tropical and subtropical environment. The high core temperatures impair the quality of the oocytes, reduce the period of estrus expression and increase the rate of early embryonic death. The management interventions are shading, fan ventilation, misting and breeds that are adapted to local climatic conditions.

3. The Triumvirate of Modern Breeding

There are three technologies that are interrelated, namely artificial insemination, estrus synchronization and cryopreservation that form the basis of modern livestock reproduction.

3.1 Artificial Insemination (AI)

The most spread reproductive biotechnology is artificial insemination in the world. Its main influence has not only reproductive management but also genetic propagation. AI also helps in serving thousands of females by one, genetically superior sire in large geographical areas, which significantly compounds selection. In addition, AI can act as a critical tool of biosecurity, eradicating the venereal diseases that are spread through natural service, such as trichomoniasis (see Table 1).

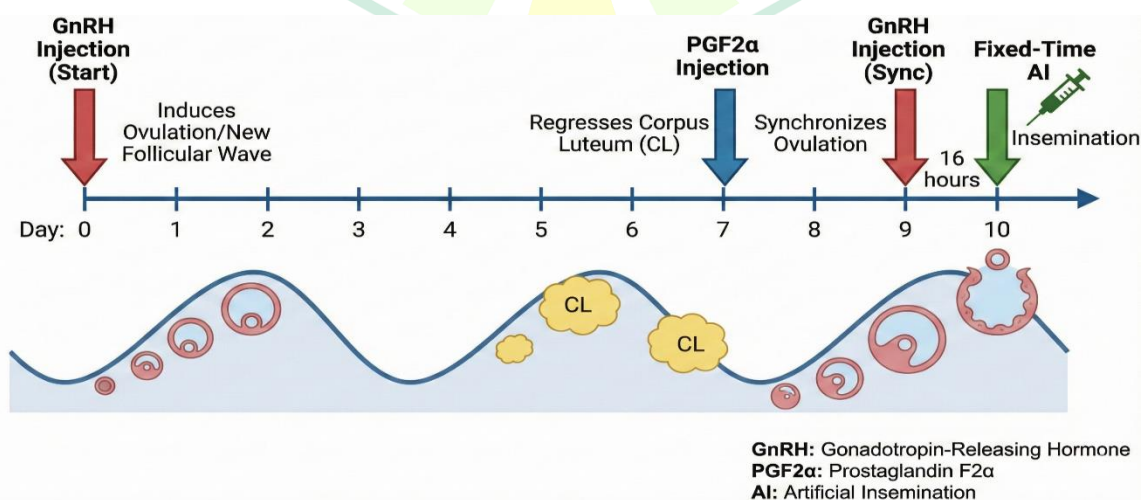


Figure 1. Conceptual Flow of a Standard Ovsynch FTAI Protocol in Dairy Cattle

3.2 Estrus Synchronization Programs

The effectiveness of AI will depend on proper heat detection that is intensive and likely to have mistaken. The estrous cycle of a group of females is synchronized to produce heat simultaneously with exogenous hormones, most commonly GnRH, prostaglandin (F) 2, and progesterone through the use of CIDR devices to control the estrous cycle. This enables artificial insemination (FTAI) which is fixed at a certain time and regardless of visual heat detection insemination takes place. FTAI, therefore, saves labour and makes sure that anestuous cows are treated properly.

3.3 Cryopreservation

Cryopreservation of semen and embryos over an indefinite duration has transformed cross-border animal genetic trade. It offers an insurance system against the loss of valuable breeding stock and allows to retain genetic diversity on a long-term basis. More recent methods of vitrification, such as the use of ultra-rapid freezing, have significantly increased the viability of the cryopreserved embryos making embryo transfer a more commercially viable procedure.

4. Advanced Reproductive Biotechnologies

In addition to AI, more advanced methods are also used to breed high-quality females by maximising their potential reproductive purpose and manipulate particular characteristics.

4.1 Multiple Ovulation and Embryo Transfer (MOET)

Multiplication ovulation and embryo transfer (MOET) solves the female part of the process of genetic reproduction. The superior donor cows are treated with follicle-stimulant hormones (FSH) so as to cause super ovulation leading to release of more than one ov in a single cycle. These oocytes are fertilised and the resultant embryo is flushed non-surgically usually on day 7 and implanted to lower-genetic-value recipient surrogate dams. Therefore, a superior cow will give birth to dozens of cows a year as opposed to just a single one.

4.2 In Vitro Embryo Production (IVEP): IVF and OPU

IVEP has gained significant traction, particularly in the dairy and elite beef sectors. It involves two main steps:

- 1. Ovum Pick-Up (OPU):** Ultrasound-guided transvaginal aspiration of immature oocytes directly from the ovaries of living donors. This can be done more frequently than MOET flushing, even on pregnant animals or those with certain reproductive tract pathologies.
- 2. In Vitro Fertilization (IVF):** The harvested oocytes are matured and fertilized in a laboratory setting.

IVEP allows for greater flexibility in sire usage (one straw of semen can fertilize many oocytes in a dish) and faster generation turnover.

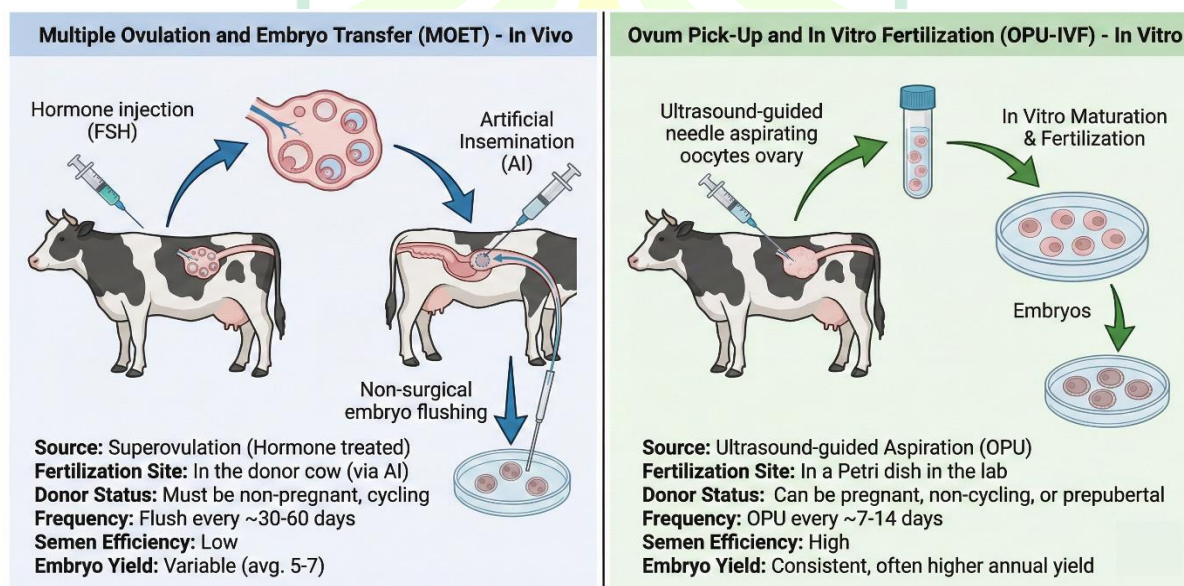


Figure 2. Comparative Workflows of MOET vs. OPU-IVF

4.3 Sexed Semen Technology

Sexed semen technology uses flow cytometry to separate X-chromosome-bearing spermatozoa (female) and Y-chromosome-bearing spermatozoa (male) by sorting them using a marginal difference in DNA content. This allows producers to pre-select the sex of offspring with a success rate of about 90 per cent.

- a) **Dairy Application:** The large-scale use of sexed semen creates replacement heifers using the most productive dams, and uses the semen that is conventional to beef on the lower-end dairy cows in order to raise higher-value crossbred calves, which are sold in the meat market.
- b) **Beef Application:** This is used to produce maternal lines or on the other hand to produce male calves to be sold in the terminal markets. Despite the fact that sexed semen does not possess equivalent conception rates (average) compared with conventional semen, advancements in sorting technology and fertility protocols are increasingly bringing the performance gap between the two close together.

5. The Genomic Revolution in Reproductive Management

Molecular genetics in combination with reproductive technology has ushered in starting with what is known as Genomic Selection. In the past, fertility traits were hampered by their low heritability (usually less than 10 per cent). It needed improvement by observing and reproducing individual animals through several cycles after maturation to get enough data on progeny making the process slow and expensive.

Genomic selection assumes the examination of single nucleotide polymorphisms (SNP) that are distributed in the genome of an animal, acquired by a sample of DNA, like hair, blood, or tissue. These SNP markers have been linked with economically important traits, such as complex fertility measures (e.g. Daughter Pregnancy rate or Heifer Conception rate). Genotype breeders can now determine genetic merit, in terms of Genomic Estimated Breeding Value (GEBV), with some degree of accuracy on young animals, including embryos produced through in vitro fertilization (IVF), before they have yet reached reproductive maturity. This method is remarkable in reduction of the generation interval and increases genetic gain.

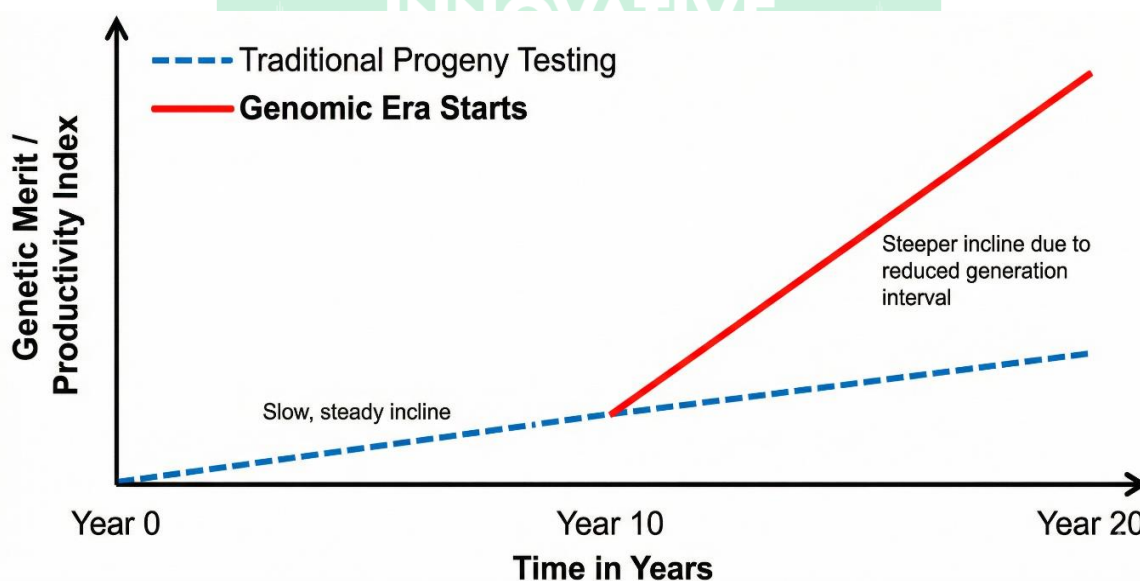


Figure 3. Conceptual Impact of Genomic Selection on Genetic Gain Rate

6. Challenges and Future Outlook

Although biotechnologies promise a lot in their implementation, there are several challenges that it faces:

1. **Economic Barriers:** The initial investment in technologies like IVF, genomic testing and sexed semen is usually restrictive to small-scale producers.
2. **Technical Expertise:** Achievement of protocols such as Ovsynch or embryo transfer requires effective veterinarians and technicians, which might be unavailable in some areas.

3. **Animal Welfare and Ethics:** Reproductive management should at all times take care of the welfare of the animals. Ethical issues that the industry has to face include the long-term consequences of repeated ovum pick-up (OPU) and extra male calves in the dairy systems.

The Future: Gene Editing: In contrast to traditional breeding, where both the genetic material exchanges the entire genomes, gene editing allows manipulation of specific DNA sequences. Possible uses include introducing heat tolerance alleles into high-production breeds or removing genes that cause certain diseases. Even though currently this technology is highly regulated and is mostly limited to laboratory research in livestock, this technology does have the potential to transformative impact in the context of reproductive or holistic health management.

7. Conclusion

The management of reproductive health in livestock has developed past primitive observation to an integrative field combining science in veterinary, physiology, as well as high-throughput genomics. The integration of the basic health management, including nutrition and biosecurity, with the innovative biotechnologies, including artificial insemination, IVF, genomics, is a mandatory component of the modern and efficient livestock production. With the world agricultural sector facing the twin challenges of growing food demand and environmental limits, the prudent and considered use of these reproductive technologies will be of critical significance in guaranteeing a sustainable future of food.

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ROLE OF ARTIFICIAL INTELLIGENCE AND AUTOMATION IN MODERN HORTICULTURE



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Abstract

Modern horticulture is experiencing a transformative shift due to the integration of Artificial Intelligence (AI) and automation technologies. Historically, horticultural practices have relied heavily on manual labor, traditional knowledge, and experience-based decision-making. With the increasing demands for food security, labor efficiency, and sustainability, AI and automation are emerging as critical tools for optimizing horticultural systems. AI enables data-driven decision-making through machine learning, predictive analytics, and deep learning models, while automation facilitates precise implementation of interventions such as irrigation, fertilization, pruning, and harvesting. This review explores the multifaceted applications of AI and automation in horticulture, including precision agriculture, sensor networks, autonomous robotics, digital twins, and decision support systems, and also examines the challenges and future prospects of these technologies. By integrating research findings and practical applications, this article highlights how AI and automation are reshaping horticultural practices to achieve higher productivity, environmental sustainability, and economic viability.

Keywords: Artificial Intelligence, Automation, Horticulture, Precision Agriculture, Machine Learning, Robotics, IoT, Smart Farming, Digital Twins, Sustainable Agriculture

Introduction

Horticulture, which encompasses the cultivation of fruits, vegetables, ornamentals, and landscape plants, forms an essential component of global food systems and contributes significantly to economic development. Traditional horticultural methods have largely depended on manual labor, observational knowledge, and experience-based decision-making. The growing challenges of labor shortages, climate variability, and the need for sustainable production practices have accelerated the adoption of technological solutions. Among these, Artificial Intelligence and automation have emerged as transformative forces in modern horticulture. Artificial Intelligence refers to computational systems that simulate human cognitive processes such as learning, reasoning, and decision-making. Machine learning, deep learning, and neural networks allow these systems to analyze large datasets, identify patterns, and predict outcomes. Automation involves systems capable of performing repetitive or complex tasks with minimal human intervention, often through robotics, mechanized systems, and digital controls. The integration of AI and automation allows horticultural operations to evolve from labor-intensive, reactive systems to proactive, data-driven, and efficient practices.

Precision Horticulture and Smart Farming

Precision horticulture represents a paradigm shift in horticultural management, focusing on the application of inputs such as water, fertilizers, and pesticides in a highly targeted manner based on spatial and temporal variability in crop conditions. Unlike traditional uniform crop management, precision horticulture seeks to optimize resources and improve productivity by using detailed data. AI plays a crucial role in this domain by processing complex datasets obtained from drones, satellite imagery, and ground-based sensors. Machine learning

models can detect subtle variations in plant health, nutrient status, and pest infestations, often before visual symptoms appear. For instance, convolutional neural networks are widely used for image-based disease detection, enabling early identification of fungal infections, nutrient deficiencies, or pest damage in crops such as tomatoes, strawberries, and citrus. Automation complements AI by translating data-driven insights into precise interventions. Variable Rate Technology allows fertilizers, irrigation, and pesticides to be applied exactly where and when needed, reducing waste, minimizing environmental impacts, and increasing productivity. In controlled environments such as greenhouses, sensor networks integrated with automated systems regulate temperature, humidity, and lighting, providing optimal conditions for crop growth. This combination of AI and automation in precision horticulture establishes a foundation for sustainable, efficient, and high-quality crop production.

Table 1: Examples of AI and Automation Applications in Precision Horticulture

Application Area	AI Techniques Used	Automation Tools	Benefits
Disease Detection	CNNs, Deep Learning	Automated sprayers	Early disease control, reduced chemical use
Precision Irrigation	Predictive models, Regression	Smart irrigation systems	Optimized water use, improved yield
Nutrient Management	Machine learning forecasting	Fertilizer VRT	Targeted fertilization, reduced nutrient loss
Pest Monitoring	Image classification, Object detection	Sensor traps, robotic sprayers	Early pest detection, reduced pesticide application
Greenhouse Climate Control	Reinforcement learning	HVAC automation, shading systems	Optimal growth conditions, energy efficiency

The integration of AI and automation in precision horticulture enables growers to monitor crops continuously, apply interventions accurately, and maximize both economic and environmental outcomes. Continuous data collection and analysis ensure that growers can respond to changes in crop conditions in real-time, leading to improved yields and resource efficiency.

Decision Support Systems in Horticulture

AI-powered decision support systems are revolutionizing the management of horticultural operations by transforming the way decisions are made. Traditional approaches rely on subjective observation and historical experience, which are often limited in scale and precision. AI-based decision support systems integrate diverse datasets including soil characteristics, weather patterns, crop phenology, and market trends to provide actionable insights. Machine learning models are capable of predicting crop growth stages, yield potential, and the risk of pest or disease outbreaks. Predictive modeling allows growers to evaluate different management strategies and their economic consequences, enabling them to implement practices that optimize both productivity and profitability. These systems are often accessible through mobile applications or cloud-based platforms, providing users with recommendations that include confidence levels and scenario analyses. The result is a transition from intuition-based decision-making to evidence-based, data-driven management that enhances efficiency and sustainability across horticultural operations.

Robotics and Automation in Horticulture

Automation and robotics are transforming horticulture by addressing labor-intensive tasks that have historically limited productivity. Labor shortages, particularly during planting, weeding, pruning, and harvesting, have driven the development of AI-enabled robotic systems. Robotic harvesters are equipped with machine vision and AI algorithms that allow them to identify ripe produce based on color, size, and texture. Deep learning models improve the accuracy of these systems, while soft robotic grippers enable gentle handling of delicate crops such as strawberries, tomatoes, and leafy vegetables. This not only addresses labor constraints but also reduces post-harvest losses and ensures consistent quality. Robotic systems are also increasingly applied to weeding and crop maintenance. Autonomous weeding robots use AI to distinguish crops from weeds and can either mechanically remove weeds or apply targeted herbicides, reducing chemical use and improving sustainability. Similarly, pruning robots in orchards or vineyards employ AI to determine optimal cuts, enhancing canopy structure and

fruit quality. Automation extends to transplanting, sorting, and packaging, where robotic arms and conveyors integrated with AI inspection systems ensure precise handling and quality control.

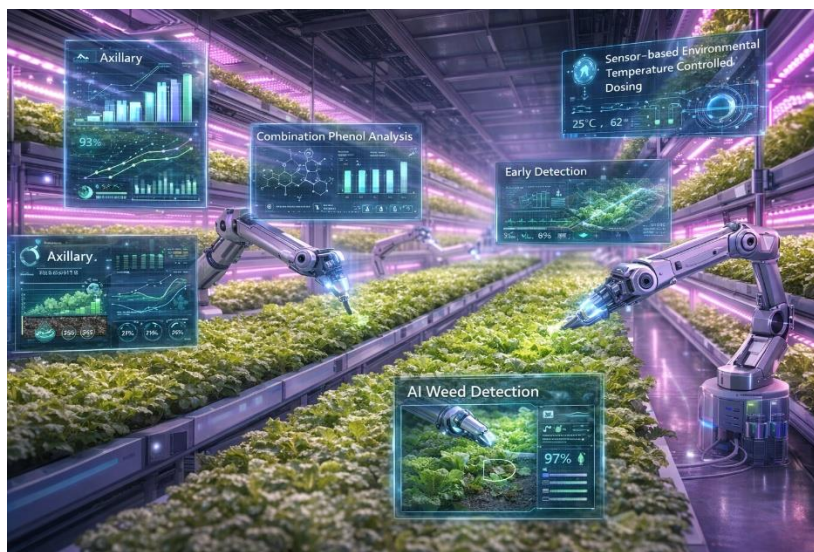


Table 2: Examples of Robotics and Automation in Horticulture

Task	Robotic Technology	AI Integration	Advantages
Harvesting	Robotic arms, soft grippers	CNN-based ripeness detection	Reduced labor, improved quality
Weeding	Autonomous field robots	Object detection, Image classification	Reduced herbicide use, labour savings
Pruning	Robotic pruning arms	Predictive plant modeling	Optimized canopy structure, higher yield
Transplanting	Automated planters	Machine vision	Precision planting, labour efficiency
Sorting & Packaging	Robotic conveyors	AI-based defect detection	Quality assurance, operational efficiency

These technologies have significantly improved operational efficiency while reducing the dependency on human labor, which is especially critical during peak production periods.

Sensor Networks and the Internet of Things

The deployment of sensor networks and IoT devices has created an infrastructure that allows horticultural systems to be continuously monitored and analyzed. Sensors installed across fields or greenhouses collect real-time data on environmental parameters such as soil moisture, temperature, light intensity, and nutrient levels. These datasets are analyzed using AI algorithms to identify trends, detect anomalies, and provide predictive insights. For example, soil moisture sensors integrated with predictive models can determine the optimal timing and amount of irrigation, reducing water consumption and improving crop growth. In controlled environments, climate sensors connected to AI-driven control systems can autonomously adjust heating, cooling, ventilation, and shading to maintain ideal growing conditions. The combination of AI and IoT transforms horticultural operations from periodic manual monitoring to continuous, automated oversight, resulting in increased productivity, improved resource management, and enhanced crop quality.

Machine Learning for Pest and Disease Management

Pests and diseases remain among the most significant challenges in horticulture, often leading to substantial yield losses. Traditional scouting methods, which rely on human observation, are labour-intensive and susceptible to errors. AI introduces sophisticated methods for early detection and precise management of pests and diseases. Image-based deep learning models can identify pest damage or disease symptoms with high accuracy, often before visible signs appear. Spectral imaging using multispectral or hyperspectral sensors, combined with AI analysis,

enables detection of physiological plant stress caused by pathogens or nutrient deficiencies. Automated pest traps with AI-based counting and classification systems provide real-time monitoring of pest populations, allowing growers to implement integrated pest management strategies that are targeted, efficient, and environmentally sustainable. Early detection facilitated by AI reduces crop losses, minimizes chemical inputs, and supports sustainable horticultural practices.

Autonomous Vehicles and Logistics

Automation in horticulture extends beyond crop production to logistics and material handling. Autonomous tractors, drones, and utility vehicles perform field operations such as soil preparation, spraying, and transport of materials with high efficiency. In greenhouse and nursery environments, automated guided vehicles transport plants, harvested produce, and raw materials between workstations, reducing human labor requirements and enhancing operational efficiency. These systems also improve worker safety by minimizing manual handling of heavy loads and ensuring smooth workflow management. By integrating AI with autonomous vehicles, horticultural enterprises can plan, schedule, and execute tasks with minimal human intervention while maintaining high levels of productivity and precision.

Digital Twins and Predictive Modeling

Digital twins, virtual replicas of horticultural systems, allow growers to simulate plant growth, environmental conditions, and management interventions in a digital environment. AI models use real-time data from sensors and other monitoring devices to predict the outcomes of various management strategies, including irrigation adjustments, nutrient supplementation, or pest control measures. By testing scenarios virtually, growers can reduce risk, optimize resource use, and enhance resilience against climatic stresses. Digital twins also allow long-term planning by simulating crop performance under different environmental conditions, facilitating supply chain management and sustainable horticultural practices.

Challenges and Limitations

Despite the transformative potential of AI and automation, there are challenges associated with widespread adoption. High initial costs of AI platforms, robotics, and sensor networks can be prohibitive, especially for small and medium-scale horticultural operations. Data quality, coverage, and connectivity remain critical, as AI models are only as effective as the data they analyse, and poor infrastructure can limit real-time monitoring and control. Technical expertise is required to operate and maintain AI and automated systems, which may necessitate training programs and extension services. Furthermore, automation raises social concerns, including potential labor displacement and ethical issues related to data ownership, decision accountability, and environmental management. Integration of diverse technologies across heterogeneous horticultural systems can also be complex, requiring interoperable solutions and robust management frameworks.

Future Directions

The future of horticulture is increasingly linked to the evolution of AI and automation technologies. Edge AI, which allows data processing on local devices rather than relying entirely on cloud platforms, promises faster response times and reduces dependency on internet connectivity. Collaborative robotics, or cobots, are designed to work alongside human labour, improving productivity without fully replacing human oversight. Advances in AI algorithms, robotics, and sensor technology will continue to make these systems more cost-effective and accessible to smaller growers. Sustainability will remain a central focus, with AI optimizing resource use, reducing waste, and enhancing resilience against climate variability. Integrating AI with genomics and plant breeding may allow predictive modeling of crop growth, yield potential, and disease resistance, opening new avenues for intelligent horticultural management.

Conclusion

Artificial Intelligence and automation are transforming horticulture from a labor-intensive, experience-based practice into an intelligent, efficient, and sustainable industry. Through precision horticulture, sensor networks, autonomous robotics, digital twins, and decision support systems, growers can optimize resource use, enhance productivity, and reduce environmental impacts. While challenges such as high capital investment, technical expertise, and social concerns remain, ongoing technological advances and increasing accessibility are

accelerating adoption. The future of horticulture is poised to become more connected, data-driven, and resilient, with AI and automation serving as central pillars for sustainable and high-quality crop production.

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Role of Remote Sensing and GIS in Modern Agronomic Decision-Making



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1. Introduction

The modern world of agriculture is shifting towards a new paradigm of non-homogeneity in the field management instead of site-specific data-driven interventions. This shift to precision agriculture is based on the high-tech tools to track the spatial and temporal variations in agricultural landscapes. Out of them, Remote Sensing (RS) and Geographic Information Systems (GIS) have become essential resources, the technological base of contemporary agronomic decisions (Huang et al., 2018). Through their provision of extensive, spatially explicit information, these technologies allow farmers, agronomists and policymakers to cease the use of subjective judgments in favour of more evidence-based approaches toward the production of crops and management of resources.

In the past, farmers used to practice agricultural monitoring based on field surveys, which were labour-intensive. RS technologies now offer non-invasive platforms to sample the data in large areas with different temporal and spatial resolutions. Combined with GIS, such disparate data sets are converted to information layers of context; that is, soil characteristics, crop conditions, and crop potential, which can be geographically analysed. With this synergy, it becomes possible to have a holistic perspective of the farming ecosystem and to make tactical decisions at the field level and strategic planning at the regional level (Huang et al., 2018). The paper discusses the major principles of RS and GIS, their combined uses in major agronomic fields, and the economic consequences of using them.

2. Fundamentals of Remote Sensing and GIS in Agriculture

2.1 Principles of Agricultural Remote Sensing

Remote sensing entails getting information on an object or a region at a distance and generally with the support of sensors installed on different platforms. In farming, these platforms include satellites that rotate around the earth, manned aircraft, and recently, Unmanned Aerial Vehicles (UAVs) or drones. Satellite sensors, including MODIS, Landsat, and Sentinel, are extensively used due to their global coverage and frequent data collection, and MODIS is often used to predict the yield in regions because of its high temporal resolution (Joshi et al., 2023). The UAVs with a greater spatial resolution are getting more popular with the use of farm scale and accurate yield prediction models (Joshi et al., 2023).

Agri-RS is fundamentally based on the analysis of electromagnetic radiation reflected or emitted on the canopy of crops and on the soil surfaces. Sensors are divided in general into passive sensors, which receive naturally reflected sunlight, and active sensors, like radar, which send their own pulses of energy and measure the backscatter. The visible and near-infrared (NIR) bands of the spectrum (400-700 nanometers and more) are

especially the most important in determining the condition of vegetation. Healthy and thick vegetation is very reflective of the NIR radiation but absorbs the red radiation, the similarity behind many vegetation indices.

2.2 The Role of Geographic Information Systems (GIS)

Remote sensing is an activity that offers the uncoded spatial information, whereas GIS offers the analytic framework to process and handle it. GIS is an effective tool that aims at capturing, storing, manipulating, analysing and displaying any type of information that has geographic reference. GIS is considered in agronomics as the main hub in which various spatial data layers are combined and superimposed. A georeferenced RS image can serve as a base map, and other important data can be overlaid on this, including field boundaries, soil sampling points, yield maps of past harvests and topographic data. This is necessary to determine spatial relationships and patterns that cannot be seen when datasets are individually viewed. As an example, the superimposition of a crop health map created after the RS imagery with a soil property map in GIS can be used to identify the existence of regions of low crop vigour in relation to certain soil deficiencies.

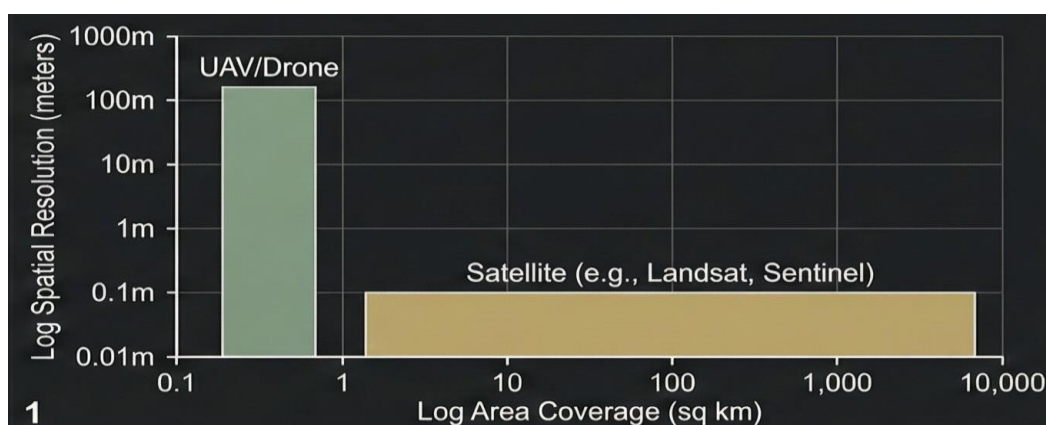


Figure 7. Trade-off: Spatial Resolution vs Area Coverage

3. Key Applications in Agronomic Decision-Making

3.1 Crop Health Monitoring and Yield Prediction

Among the most well-developed applications of RS and GIS, one can identify the monitoring of the state of crops and the prediction of the possible harvest. RS data can be utilised to compute most vegetation indices, which are proxies of plant health and biomass, by measuring surface reflectance.

Normalised Difference Vegetation Index (NDVI) is the most commonly used, which is a measure of vegetation greenness. A high NDVI indicates good, dense canopies of crops, and the reverse of this is also true because low values may be an indicator of stress factors like disease, nutrient deficiency or sparse cover. The NDVI can be monitored over time so that agronomists can monitor the development stages of crops and detect anomalies at the beginning of the growing season. The NIR and shortwave infrared bands are also used in other indices like the Normalised Difference Moisture Index (NDMI), which is used to determine the water content of vegetation in question and therefore provide the much-needed information on water stress before it is reflected in the field.

Contemporary methods have also updated to augment these RS-derived indices with next-generation machine learning classifiers, including random forests and deep-learning convolutional neural networks (CNNs) to formulate powerful crop mapping and yield prediction frameworks (Joshi et al., 2023). These models are able to model and describe complex and non-linear relationships between spectral data and crop yield, providing accurate predictions, which provide farmers with better planning of post-harvest logistics and marketing to plan.

3.2 Soil Mapping and Land Suitability Analysis

Agricultural productivity depends on the physical and chemical characteristics of soil as the basic determinants. RS and GIS offer effective techniques for mapping the spatial variability of the soil, as well as assessing the suitability of land to certain crops. Although in some cases direct spectral mapping of soil properties can be complicated because of other factors like moisture and crop residue, bare-soil images can be used to determine

areas that share common physical properties, which can be used to determine the adaptive cost-effective soil-sampling approaches.

Multi-Criteria Decision Analysis (MCDA) to evaluate land suitability is heavily applied with the help of GIS. This is done through the incorporation of different spatial layers that represent important variables or factors that include the texture of the soil, its depth, pH, availability of nutrients, the topography (slope) and climatic conditions (rainfall, temperature). GIS is able to produce detailed land-suitability maps by allocating weights to each of these criteria with respect to their relative importance to a target crop. These maps group land into groups that are highly suitable and those that are not suitable, which enables land managers to make good decisions with regard to crop selection and land-use planning. This is a very important strategy of maximising the utilisation of their resources and making sure that agricultural growth can be sustainable.

Table 14. Common Vegetation Indices Derived from Remote Sensing Data for Agronomic Assessment

Index Name	Abbreviation	Spectral Bands Used	Primary Agronomic Application
Normalised Difference Vegetation Index	NDVI	Red, Near-Infrared (NIR)	Monitoring crop health, vigour, and biomass; identifying stress areas.
Normalised Difference Moisture Index	NDMI	Near-Infrared (NIR), Shortwave Infrared (SWIR)	Assessing crop water content and detecting early signs of water stress.
Land Surface Temperature	LST	Thermal Infrared	Providing insights into soil moisture storage and indirectly characterising evapotranspiration rates.

Note: Adapted from data in Modern Phytomorphology and Nature Environment and Pollution Technology.

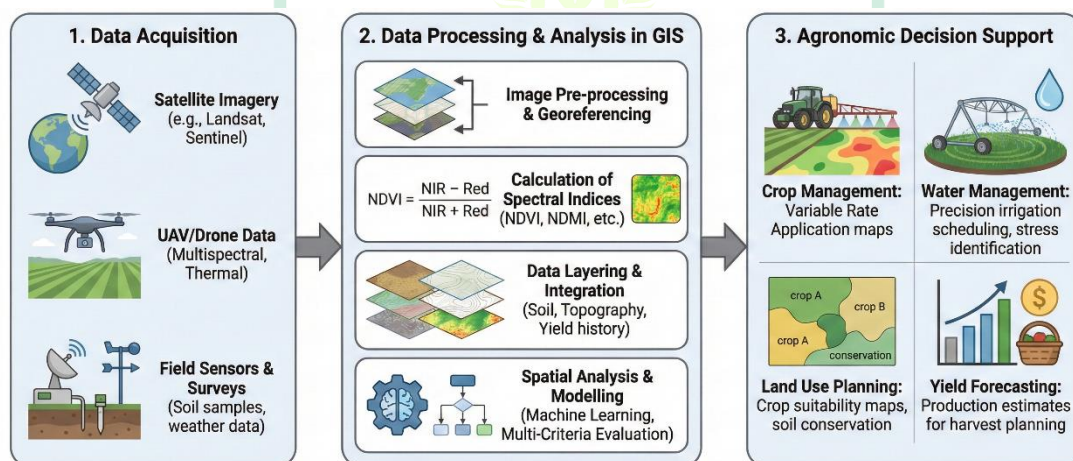


Figure 2. Conceptual Workflow of Integrated RS and GIS for Agronomic Decision-Making.

3.3 Precision Water Management

Sustainable farming needs efficient water management, especially in arid and semi-arid areas. The combination of remote sensing (RS) and geographic information systems (GIS) has completely changed the way that agricultural water resources are monitored and managed. RS data cannot be used without estimating evapotranspiration (ET), a very important parameter in estimating the water needs of crops. The surface energy balance-based models, including SEBAL (Surface Energy Balance Algorithm for Land) and METRIC (Mapping Evapotranspiration at High Resolution using Internalised Calibration), use thermal infrared observations with satellites to estimate ET on large scales (Pradipta et al., 2022).

Furthermore, microwave remote sensing, especially Synthetic Aperture Radar (SAR), is a useful instrument in both the identification of water on the surface and the dynamics of moisture without a cloudy sky or during sunrise and sunset. This is essential in the measurement of the efficiency of irrigation and monitoring of the supply of water in reservoirs and wetlands. GIS systems combine products of RS-derived moisture and ET with soil maps and meteorological data to assist farm irrigation planning. Such a data-based solution allows adopting advanced irrigation technologies, e.g., variable-rate irrigation (VRI), which modulates the rates of water

application based on the unique moisture requirements of particular field areas, thus minimising the waste of water and maximising the output of water (Getahun et al., 2024).

4. Economic Benefits and Adoption Challenges

The integration of RS and GIS technology into the agricultural sector is driven by the fact that economic and environmental benefits could be achieved immensely. These tools can be used to enable site-specific management, which enables farmers to optimise the input applications: fertilisers, pesticides, and water. The preference of using different sub-areas of an area to receive specific treatment instead of treating it with a blanket treatment result in lower wastage of inputs, lower costs, and minimised environmental effects, including nutrient runoff. The ability to monitor crop stress and, in addition, forecast yields also increases profitability because it allows timely corrective measures to be taken, as well as better planning in the market. After all, such developments result in increased production and quality of crops in addition to the efficiency of resources (Getahun et al., 2024).

However, mass adoption is not without a challenge. Start-up costs associated with equipment, including GPS-guided machinery, sensors, and drones, can be costly, particularly to the smallholder farmers (Getahun et al., 2024). Agricultural remote sensing is also associated with the challenges of big data quality; large datasets require significant computing resources and technical skills to be acquired, processed, stored, and analysed (Huang et al., 2018). Lack of adequate staff trained in mathematics, informatics, and decision-making processes is also another setback to the successful interpretation of RS data. Furthermore, in several rural areas, the infrastructural barriers, including the unstable internet connection and the lack of access to electricity, may hinder the use and real-time functioning of these high-tech systems (Getahun et al., 2024).

5. Conclusion

The combination of remote sensing and GIS has essentially transformed the agronomy of the contemporary world and provided an effective framework on which informed decision-making can be based. These technologies allow farmers to control their land with more accuracy than ever before, since they allow a synoptic view of the agricultural systems and analytical tools that allow them to break down spatial variability. They can be used in a wide range of applications, including crop health and yield forecasting, water use optimisation, soil suitability mapping; the list of applications is endless and has been demonstrated as essential in the context of food security in the future. As long as economic and technical obstacles to adoption remain, further developments in sensor technology, data-processing algorithms and machine-learning integration will make these tools more accessible and more efficient. In the future, the synergetic application of RS and GIS will continue to play a leading role in creating sustainable agricultural methods that are capable of supporting increasing demands in the world without depleting the necessary natural resources.

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Soil Degradation, Restoration and Carbon Recovery under Changing Climate



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1. Introduction

Soil is a finite and non-renewable natural resource that underpins agricultural productivity, ecosystem stability and climate regulation. Globally, soils store nearly 2,500 gigatonnes (Gt) of carbon, which is more than three times the carbon present in the atmosphere and about four times that stored in vegetation. Despite this critical role, soil degradation has accelerated at an alarming rate due to intensive agriculture, deforestation, urban expansion and climate change.

According to global assessments, nearly 33–40% of the world's soils are moderately to severely degraded, leading to reduced crop yields, declining nutrient-use efficiency and increased vulnerability to climate extremes. Climate change further exacerbates soil degradation through rising temperatures, altered precipitation patterns and increased frequency of extreme events such as droughts and floods.

In this context, soil restoration and carbon recovery have emerged as key strategies for sustainable land management and climate change mitigation. Restoring degraded soils not only enhances agricultural productivity but also enables soils to function as effective carbon sinks, thereby contributing to global efforts to limit greenhouse gas emissions. This article synthesizes current scientific evidence on soil degradation processes, restoration strategies and carbon recovery potential under changing climatic conditions.

2. Soil Degradation: Extent, Drivers and Climate Interactions

2.1 Global Extent of Soil Degradation

Soil degradation is no longer a localized issue but a systemic global crisis. Scientific assessments from the UNCCD (2025) and the Soil Atlas (2024) confirm that up to 40% of the Earth's land surface is now degraded, directly impacting the livelihoods of 3.2 billion people. This degradation is classified into three interdependent domains:

a) Physical Degradation: The Structural Collapse

- **Accelerated Soil Erosion:** Conventional agriculture accelerates erosion rates to 1.0 mm/year, which is 10 to 100 times faster than natural soil formation rates. Globally, the loss of 75 billion tonnes of topsoil annually equates to an economic drain of approximately \$400 billion USD per year.
- **Compaction and Porosity Loss:** The use of heavy machinery has increased soil bulk density from a healthy 1.2 t/m³ to critical levels of 1.4 - 1.5 t/m³. This physical "suffocation" reduces root penetration and water infiltration, making crops 25% more susceptible to drought stress.

b) Chemical Degradation: Nutrient and Ionic Imbalance

- **Anthropogenic Salinization:** Beyond the 830 million hectares naturally affected, secondary salinization—driven by poor drainage and low-quality irrigation—now threatens one-third of all irrigated land. In arid regions, the annual economic loss from yield failure due to salinity is estimated at \$27.3 billion USD.

- **Nutrient Mining & Acidification:** Intensive monocropping without adequate organic replenishment has led to "nutrient mining," particularly in Sub-Saharan Africa and South Asia. In rainfed systems, this depletion is a primary driver of the 20–40% yield gap observed between potential and actual harvests.
- c) **Biological Degradation: The Carbon Deficit**
- **SOC Depletion:** Soil Organic Carbon (SOC) is the "biological glue" of soil. Cultivated soils have lost 116 to 133 Pg C (petagrams of carbon) historically. Current research indicates that in the first 20 years of converting natural land to cropland, SOC stocks typically plummet by 30–50% due to increased oxidation and microbial mineralization.

2.2 Climate Change as a Degradation Multiplier

The relationship between soil and climate is a positive feedback loop: climate change accelerates soil breakdown, which in turn releases more greenhouse gases (GHGs).

1. **Thermal Acceleration of Decomposition:** Rising global temperatures increase the kinetics of microbial respiration. A temperature rise of 4°C is projected to increase soil CO₂ emissions by up to 55%, primarily through the loss of heterotrophic organic matter.
2. **Hydrological Extremes: Intense Precipitation:** Altered rainfall patterns result in high-velocity runoff. A single extreme storm can strip more topsoil than a decade of moderate rain.
 - **Prolonged Drought:** Drought reduces Net Primary Productivity (NPP), meaning less biomass (roots and residue) is returned to the soil, leading to a net loss in the carbon balance.
3. **Coastal Saline Intrusion:** Sea-level rise (SLR) is forcing saltwater into coastal aquifers and topsoils, a phenomenon known as "coastal squeeze," which renders formerly productive deltaic regions (e.g., the Mekong or Ganges-Brahmaputra) sterile.

Scientific Note: Even a minor perturbation of $\pm 1\%$ in global soil carbon stocks could release enough CO₂ to equal roughly two years of all global anthropogenic emissions, highlighting the extreme sensitivity of the soil-climate nexus.

3. Soil Restoration Strategies under a Changing Climate

Restoring degraded soils is not just about adding inputs; it is about rebuilding the soil's living architecture so it can better withstand climate stresses such as heavy rainfall, droughts and rising temperatures. Effective soil restoration works on three interconnected levels—physical, chemical and biological—each playing a distinct role in strengthening soil resilience.

3.1 Physical and Structural Interventions: Rebuilding Soil Stability

Physical restoration focuses on repairing soil structure so that it can absorb water efficiently and resist damage from wind and flowing water.

Conservation and Zero Tillage:

Conservation tillage and zero tillage protect the soil's natural structure by avoiding repeated ploughing. When soil is left undisturbed, large soil aggregates remain intact and natural channels formed by earthworms and old root systems are preserved. These macropores allow rainwater to infiltrate quickly rather than running off the surface. As a result, water erosion can be reduced by 40–70%. From a scientific perspective, this is crucial because it shields particulate organic matter from rapid breakdown, helping soils retain carbon for longer periods.

Contour Farming and Terracing:

On sloping lands, contour farming and terracing act like speed breakers for water. By shortening the slope length and slowing runoff, these practices reduce the force with which water moves across the soil surface. This prevents the loss of fine clay and silt particles, which are especially important because they carry a large share of soil organic carbon and nutrients.

Mulching and Residue Retention:

Keeping crop residues on the soil surface creates a protective cover that absorbs the impact of raindrops, preventing soil particles from being dislodged. Mulching also helps regulate soil temperature. Research shows that residue-covered soils can remain 5–8°C cooler during heatwaves, protecting sensitive soil microbes and enzymes that drive nutrient cycling and organic matter formation.

3.2 Chemical and Nutrient-Based Approaches: Improving Soil Buffering Capacity

Chemical restoration aims to create a balanced soil environment that supports healthy plant growth while minimizing nutrient losses under extreme weather conditions.

- **Integrated Nutrient Management (INM):**

INM combines chemical fertilizers with organic inputs such as compost or farmyard manure. While fertilizers supply nutrients quickly, organic materials improve soil structure and provide carbon that enhances nutrient-use efficiency. This balanced approach reduces nitrogen losses through leaching and lowers emissions of nitrous oxide, a powerful greenhouse gas associated with excessive fertilizer use.

- **Soil Ameliorants (Lime and Gypsum):**

Lime is widely used in acidic soils, where it neutralizes harmful aluminum and hydrogen ions. This improves root growth and nutrient uptake.

Gypsum plays a key role in reclaiming sodic soils. The calcium it supplies replaces sodium on soil particles, allowing excess sodium to be washed away. This restores soil aggregation and improves water movement through the soil.

- **Biochar Amendments:**

Biochar is a carbon-rich material produced by heating biomass in low-oxygen conditions. Its highly porous structure allows it to hold nutrients and water, making it especially valuable in sandy soils. Because biochar decomposes very slowly, it can store carbon in soils for hundreds of years, effectively turning farmland into a long-term carbon sink.

3.3 Biological and Ecological Restoration: Activating the Living Soil

Biological restoration relies on living plants and microorganisms to move carbon from the atmosphere into the soil and lock it there.

- **Cover Crops and Green Manures:**

Cover crops ensure that soil is never left bare or biologically inactive. Their roots release sugars and organic compounds that feed soil microbes throughout the year. This continuous biological activity encourages the production of glomalin—a sticky substance produced by beneficial fungi that helps bind soil particles together and stabilize soil carbon.

- **Agroforestry Systems:**

Agroforestry combines trees with crops or livestock, creating a layered system that mimics natural ecosystems. Deep tree roots capture nutrients from lower soil layers that would otherwise be lost, while fallen leaves and root biomass add organic matter to the soil. Over time, this significantly increases the stable carbon pool belowground.

- **Microbial Inoculants and Mycorrhizal Associations:**

Arbuscular mycorrhizal fungi form partnerships with most crop plants, extending their root systems many times over. These fungi improve phosphorus uptake, enhance water absorption and help plants cope with drought stress. In return, plants supply carbon to the fungi, strengthening the soil's biological engine and long-term carbon storage capacity.

4. Soil Carbon Recovery: Mechanisms and Sequestration Potential

Soil carbon recovery lies at the heart of both soil restoration and climate change mitigation. Healthy soils function as dynamic carbon reservoirs, continuously exchanging carbon with the atmosphere through plant growth, microbial activity and organic matter turnover. When soils are degraded, this balance is disrupted, leading to carbon loss. Restoration practices reverse this trend by enhancing carbon inputs and improving the mechanisms that stabilize carbon within the soil matrix (Fig.1).

4.1 Soil Carbon Pools and Stabilization Mechanisms

Soil organic carbon is not a single entity but exists in multiple pools, each differing in stability and turnover time.

- **Active (Labile) Carbon:** This pool includes fresh plant residues, root exudates and microbial biomass. It has a rapid turnover, often ranging from days to months and serves as the primary energy source for soil microorganisms. Although short-lived, active carbon is critical because it drives nutrient cycling and fuels the biological processes that build more stable carbon forms.

- **Slow Carbon:** Slow carbon is associated with soil aggregates—clusters of soil particles bound together by organic compounds and microbial by-products. Carbon in this pool is physically protected from rapid decomposition, remaining in the soil for years to decades. Aggregate formation is therefore a key mechanism through which restoration practices enhance carbon retention.
- **Passive (Stable) Carbon:** This is the most durable carbon pool, stabilized through chemical bonding with clay minerals and metal oxides. Passive carbon can persist in soils for centuries to millennia and represents long-term carbon sequestration. Its formation is strongly influenced by soil texture, mineralogy and long-term organic inputs.

Soil restoration practices increase carbon recovery by simultaneously feeding the active pool and strengthening the protective mechanisms—aggregation and mineral association—that transfer carbon into slow and passive pools. In this way, short-term biological activity is converted into long-term climate benefits.

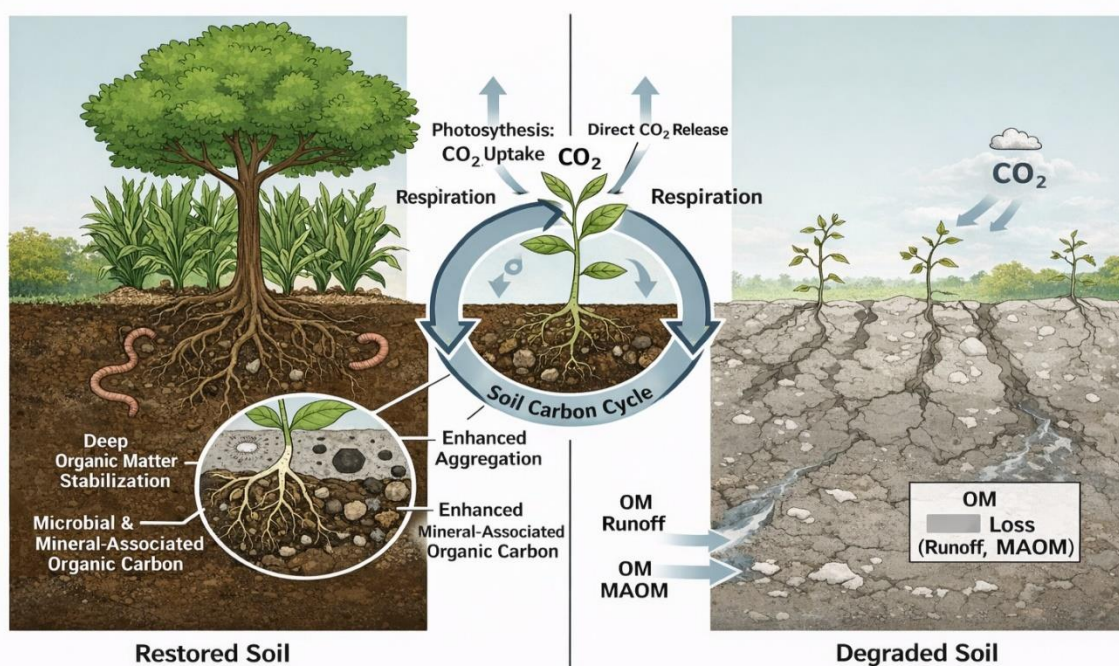


Fig.1. Conceptual comparison of soil carbon sequestration in restored and degraded soils.

4.2 Carbon Sequestration Potential of Restored Soils

A growing body of scientific research demonstrates that restored soils can act as significant carbon sinks, with sequestration rates varying by climate, land use and management intensity.

- **Agricultural Soils:** Restored croplands managed with conservation tillage, organic amendments and diversified cropping systems can sequester approximately $0.3\text{--}1.0 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$. While modest on a per-hectare basis, the vast global area under agriculture makes this contribution highly significant.
- **Grasslands and Agroforestry Systems:** These systems generally exhibit higher sequestration rates, ranging from $1.0\text{--}2.5 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$. Continuous ground cover, extensive root systems and minimal soil disturbance promote greater carbon inputs and improved stabilization in deeper soil layers.
- **Global Mitigation Potential:** At the global scale, improved soil management practices could offset an estimated 5–15% of annual anthropogenic CO_2 emissions. Although soil carbon sequestration alone cannot solve climate change, it represents one of the most immediately available and cost-effective natural climate solutions.

Importantly, soil carbon recovery also enhances climate adaptation by improving water-holding capacity, nutrient availability and crop resilience to drought and heat stress. Thus, carbon-rich soils provide a dual benefit—mitigating climate change while strengthening the resilience of agricultural systems.

5. Research Evidence on Soil Restoration and Carbon Recovery

Extensive scientific research demonstrates that restoring degraded soils leads to significant improvements in soil carbon stocks, soil health and climate resilience. Long-term field experiments across diverse agroecosystems show that conservation practices such as reduced tillage, residue retention and crop diversification can increase soil organic carbon by 10–40% over time, particularly in surface soil layers.

Studies on organic amendments and integrated nutrient management indicate carbon accumulation rates of 0.3–1.0 Mg C ha⁻¹ yr⁻¹ in restored croplands. These practices enhance nutrient-use efficiency, reduce nitrogen losses and support the stabilization of carbon within soil aggregates and mineral-associated organic matter. Agroforestry and grassland restoration systems consistently show higher sequestration potential than conventional cropping systems. Empirical evidence suggests that these systems can sequester 1.0–2.5 Mg C ha⁻¹ yr⁻¹, driven by continuous root inputs, minimal soil disturbance and enhanced microbial activity.

Advanced soil studies confirm that restoration promotes the transfer of labile carbon into stable pools protected by soil minerals and aggregates, increasing long-term carbon retention. At the global scale, improved soil management has the potential to offset 5–15% of annual anthropogenic CO₂ emissions, highlighting soil restoration as a practical and cost-effective climate mitigation strategy.

Table 1. Impact of Soil Restoration Practices on Soil Carbon and Productivity

Restoration Practice	Climate Zone	Increase in SOC (%)	Carbon Sequestration Rate (Mg C ha ⁻¹ yr ⁻¹)	Yield Improvement (%)
Conservation tillage	Temperate	15–25	0.4–0.8	5–15
Cover cropping	Sub-tropical	20–35	0.5–1.2	10–25
Agroforestry	Tropical	30–60	1.0–2.5	15–40
Organic amendments	Semi-arid	10–30	0.3–0.9	8–20
Biochar application	Arid	20–50	0.5–1.5	10–30

6. Economic, Environmental Implications, Challenges and Future Directions

Soil restoration and carbon recovery deliver substantial economic and environmental benefits, making them attractive strategies for sustainable land management under a changing climate. Improved soil structure and biological activity enhance nutrient cycling, reducing the need for synthetic fertilizers by 15–30%. At the same time, restored soils improve yield stability under drought and heat stress, lowering production risks for farmers. In the long term, emerging carbon markets and ecosystem service payments offer additional income opportunities, improving farm-level profitability.

From an environmental perspective, restored soils exhibit better water infiltration and reduced surface runoff, thereby minimizing erosion and nutrient losses. Enhanced soil biodiversity and microbial activity strengthen ecosystem functioning, while increased soil carbon storage contributes directly to long-term climate change mitigation by removing carbon dioxide from the atmosphere.

Despite these benefits, several challenges and knowledge gaps limit large-scale adoption. Carbon sequestration rates vary widely across soil types, climates and management systems, creating uncertainty in outcomes. Long-term field experiments, particularly in tropical and subtropical regions, remain limited.

Additionally, many restoration practices require high initial investment and economic returns are often delayed. A major scientific and policy challenge is the lack of standardized, cost-effective systems for measuring, reporting and verifying soil carbon stocks.

Looking ahead, future soil management must adopt an integrated and forward-looking approach. This includes scaling up climate-smart and regenerative agricultural practices, deploying digital soil monitoring and carbon accounting tools and blending indigenous knowledge with modern soil science. Strong policy incentives, institutional support and effective extension services will be essential to translate scientific evidence into widespread on-ground adoption.

9. Conclusion

Soil degradation poses a serious threat to food security and climate stability, but scientific evidence clearly demonstrates that soil restoration and carbon recovery are achievable and impactful solutions. Restored soils not only enhance agricultural productivity but also function as significant carbon sinks, supporting climate mitigation and adaptation goals. Placing soil at the center of climate-resilient agriculture is essential for sustainable development in the 21st century.

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Sustainable Aquaculture Systems for Balancing Productivity and Environmental Integrity



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1. Introduction

A combination of increasing population and changing dietary habits, such as the rise in high-quality protein, is putting extraordinary pressure on aquatic resources globally in the imperative to ensure food security. As capture fisheries are levelling off, aquaculture, the rearing of aquatic species, has become the most rapidly expanding food production industry globally. In many references, this growth has been described as the Blue Revolution, and this has played a significant role in satisfying the requirement of seafood, which today, makes more than half of all fish eaten by man. Nevertheless, the history of development of traditional aquaculture has often put its focus on yield maximisation at the expense of the environment, thus creating considerable negative externalities. Traditional intensive systems, especially open net pen systems in coastal areas and flow-through pond systems, have been linked to nutrient enrichment of the immediate waters (eutrophication), destruction of benthic habitats, chemical and antibiotic contamination, and pathogen transmission to wild populations. The main issue that is confronting the sector in the modern world is the non-linkage between the increase in production and the degradation of the environment. To ensure sustainable aquaculture, there is a need to change the paradigm of the linear models of production towards the circular, integrated systems that will internalise externalities. This paper is an analysis of the enhanced production systems, namely Recirculating Aquaculture Systems (RAS), Integrated Multi-Trophic Aquaculture (IMTA), and Biofloc Technology (BFT), and how these systems address the demands of high-productivity and strict environmental integrity.

2. The Environmental Nexus of Intensive Aquaculture

In order to comprehend the need to have sustainable systems, there is a need to first place the constraints of traditional methods into context. Intensive aquaculture usually has an open basis in which the untreated effluent that is full of uneaten feed, feces and metaccretion (mainly ammonia) is released into the environment. The footprint on the environment is mostly due to the inefficiencies of feed conversion and poor management of the waste materials. The loading of nitrogen and phosphorus may cause algae blooms, which kill the local biodiversity through the creation of hypoxic areas. Moreover, dependence on marine-derived products of aquafeeds (fishmeal and fish oil) causes a problem to the net protein production of the industry, though considerable progress has been made on the terrestrial replacements.

3. Recirculating Aquaculture Systems (RAS): Precision Engineering for Biosecurity

The technologies of Recirculating Aquaculture Systems (RAS) have become the highest level of technological management in fish culture. RAS reuses 90-99 per cent of culture water by transferring production out of open-water systems and into closed land-based facilities. This change radically changes the aquaculture paradigm of integrating ecosystem services to dilute wastes into the ecosystem to one that is driven by engineering and energy.

3.1 Mechanisms of Operation

RAS is based on the main principle of continuous treatment of culture water to eliminate metabolic waste products, thus to keep the conditions at the optimum level of high stocking densities. An average RAS loop will include mechanical filtration (removal of suspended solids like faeces and uneaten feed), biological filtration (the most important step wherein toxic ammonia is converted to less toxic nitrate through the action of nitrifying bacteria), biochemical oxygen demand control, and disinfection (UV or ozone) before being pumped back into the culture tank. Biofilter is the core of the RAS, which presents a medium of high surface area on which Nitrosomonas and Nitrobacter bacteria thrive. The efficiency of this community of microbes determines the carrying capacity of the system.

Table 15. Comparative Environmental Metrics: Conventional vs. Sustainable Aquaculture Models

Metric	Conventional Open Systems (e.g., Net Pens, Flow-through Ponds)	Sustainable Targets (RAS, IMTA, Biofloc)	Environmental Implication
Water Use	High (flow-through required to maintain water quality)	Low to Ultra-Low (high recirculation rates)	Reduced pressure on freshwater aquifers; lower effluent volume.
Nutrient Discharge (N & P)	High point-source discharge to receiving waters	Minimal; captured as sludge or utilised by co-cultured species	Prevention of eutrophication and coastal hypoxia.
Biosecurity & Disease Risk	High exposure to wild pathogens; high risk of transmission to wild stocks	Controlled environments with strict quarantine protocols	Reduced reliance on antibiotics and therapeutics.
Escapement Risk	Moderate to High due to infrastructure failure or storms	Near Zero (in land-based systems)	Prevention of genetic dilution and competition with native wild populations.
Land/Space Efficiency	Moderate (requires specific coastal or riparian zones)	High (intensive stocking densities possible in controlled footprints)	Decoupling site selection from sensitive ecological zones.

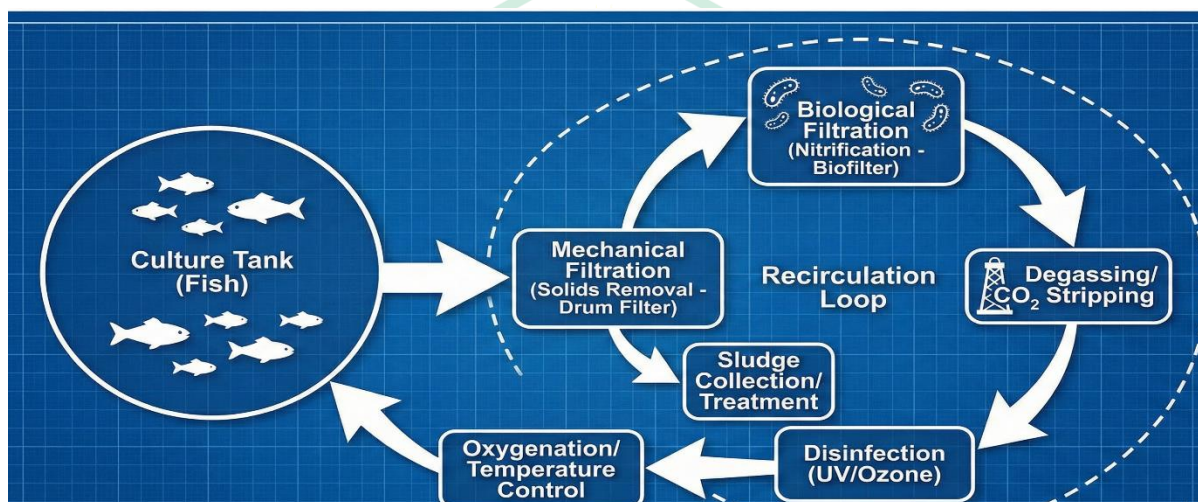


Figure 1. Simplified Schematic Diagram of a Recirculating Aquaculture System (RAS) Water Flow

3.2 Productivity versus Environmental Trade-offs

RAS has a high level of environmental integrity with respect to localised effects. The volume of effluent is low, and solid waste (sludge) can be captured and converted into agricultural nutrients (fertiliser) and biogas feedstock. Biosecurity is also greatly improved and lowers the incidence of disease outbreaks, as well as eradicating instances of escapees. The ecological impact of RAS, however, is buying a greater global energy footprint. Pumping, aeration, temperature regulation and water treatment require a lot of energy; therefore, the sustainability of RAS depends partially on the decarbonisation of the energy grid powering the facility. Also, RAS infrastructure is a high-capital expenditure (CAPEX), which requires value-powered species (e.g., salmon smolt, kingfish, high-grade shrimp) to be economically viable.

4. Integrated Multi-Trophic Aquaculture (IMTA): Ecological Engineering

Whereas RAS makes use of mechanical engineering to process waste, Integrated Multi-Trophic Aquaculture (IMTA) is an ecological engineering approach. IMTA is based on the view that the waste of one species forms a nutritional source for another. IMTA tries to recreate a balanced flow within an ecosystem by growing species of the same and different trophic levels next to each other, thus imitating natural nutrient cycling.

4.1 Trophic Balancing and Nutrient Recovery

The recovery of trophic balancing and nutrient recycling is attained through rocky layer decomposition and sedimentary rock existence (Li et al., 2007). The decompositions of rocky layers and the existence of sedimentary

rocks achieve the recovery of trophic balancing and nutrition (Li et al., 2007). An average IMTA system includes fed aquaculture (finfish or shrimp) mixed with organic extractive aquaculture (shellfish/detritivores) and inorganic extractive aquaculture (seaweed/macrophytes).

1. **Fed Species (Trophic Level +3):** These are the main economic powers and demand feed imports. They produce dissolved inorganic nutrients (ammonia, phosphate) as well as particulate organic matter (faeces, uneaten feed).
2. **Organic Extractives (Trophic Level- on average two):** the filter feeders, like mussels or oysters, will be placed down-current to extract fine particulate organic matter, whereas the deposit feeders, like sea cucumbers or polychaetes, may be deployed below cages to consume coarse settling solids.
3. **Inorganic Extractives (Trophic Level = -1):** Macrophytes (e.g., kelp, Gracilaria) take up dissolved inorganic nitrogen and phosphorus and transform potential atrophying substances into harvestable biomass.

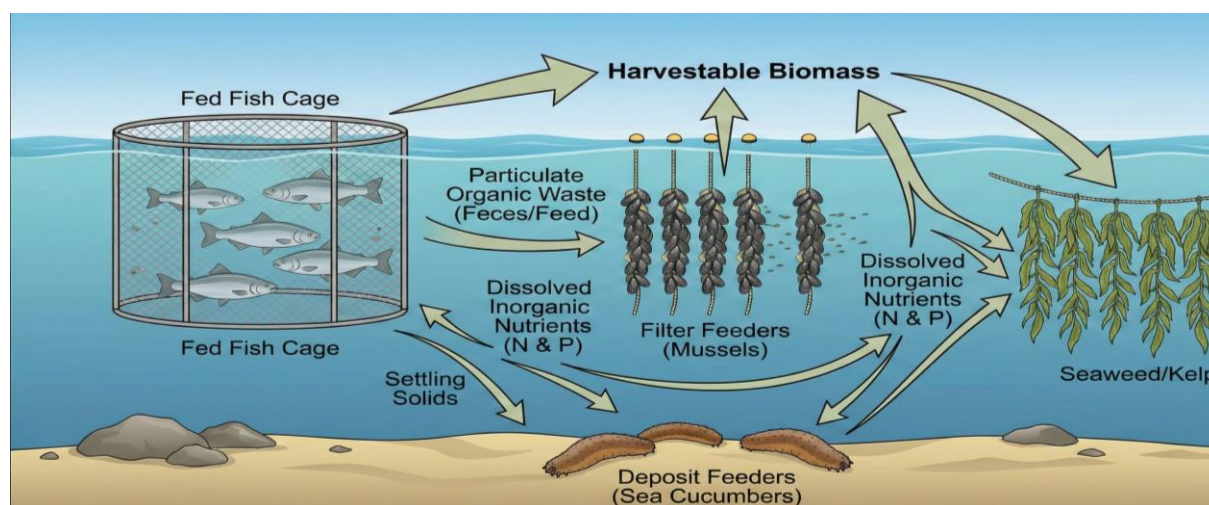


Figure 2 : Conceptual Nutrient Flow in a Coastal IMTA System

4.2 Benefits and Implementation Challenges

Bioremediation ensures the environmental integrity of IMTA; the extractive species have been shown to impact the nutrient plume generated by the fed species activities. Not only is it improved by the increase in the biomass of the main species, but revenue streams are diversified, and a resilient crop portfolio is developed. The primary IMTA challenge is the complex logistics of balancing the biomass ratios across trophic levels to achieve effective nutrient capture. Besides, the regulatory systems of most jurisdictions are not constructed to accommodate multiculturalism, and they also present an obstacle to combined operations. Additional development may also be needed to have co-cultured products that are accepted in the market.

5. Biofloc Technology (BFT): Microbial Management

Biofloc Technology (BFT) is a method that primarily targets the omnivorous species of warm waters, including tilapia and penaeid shrimp. In contrast to RAS, which uses external biofilters, or IMTA, which uses macro-co-culture, BFT alters the microbial community in the culture pond itself in order to regulate water quality and supplemental nutrition.

5.1 The Carbon-Nitrogen (C: N) Ratio

The biofloc technology (BFT) is based on the idea of stimulating the growth of heterotrophic bacteria. The accumulation of nitrogenous compounds, especially ammonia, is a form of toxification threat in the conventional recirculating aquaculture systems. BFT overcomes this by inoculating the culture medium with an exogenous carbonaceous substrate, e.g. low-cost agricultural byproducts like molasses, wheat bran or tapioca flour, increasing the Carbon: Nitrogen ratio, generally above 15:1. The ensuing carbon-rich environment is favourable to the quick proliferation of heterotrophic bacteria compared to autotrophic nitrifiers. These heterotrophs fix toxic ammonia- nitrogen directly onto microbial protein biomass. When adequately vigorous aeration occurs, the bacteria co-aggregate with algae, protozoa, zooplankton and detrital particles to bioflocs.

5.2 Dual Functionality: Waste Treatment and Feed

The growing biofloc has two important roles: increasing productivity and protecting the integrity of the environment.

1. In-situ water quality regulation: Ongoing microbial uptake of ammonia stabilises water parameters and allows the minimal amount of water exchange (frequently less than 10 per cent of a cycle) and, as a result, decreased water consumption and discharge of effluents.
2. Supplemental nutrition: The bioflocs are protein-rich aggregates (usually 30-50 per cent crude protein) that can be used as dietary supplements for filter-feeding organisms like shrimp or tilapia. This waste nitrogen reuse into the cultured organisms enhances the total protein-efficiency ratio and reduces reliance on commercial aquafeeds by 15-30 per cent.

BFT requires careful aeration control to achieve the high microbial oxygen requirements and needs strict control of water chemistry. Even though it is described as a high-intensity system, there is a low capital expenditure (CAPEX) alternative of recirculating aquaculture systems (RAS) to suitable species in the right climatic regimes.

6. Conclusion

Modern agricultural trends are moving towards models that recognise planetary limits. Being relatively young in comparison with terrestrial farming, aquaculture has a unique chance to avoid the most ecologically harmful stages of agricultural intensification and follow the ecologically integrated systems.

There is no single panacea of sustainable aquaculture; the choice of the system depends on the species, geographic area, capital and local environmental limitations. RAS provides unmatched biosecurity and geographic freedom to high-value species at a great expense of energy. Integrated multi-trophic aquaculture (IMTA) is an ecologically designed, advanced technology to be used in coastal settings, converting pollutants into effective products. The biofloc technology offers an avenue where highly efficient production of low water exchange omnivorous species can be achieved, which is highly relevant to food security around the globe.

Striking a balance between productivity and environmental integrity has become more of an aspiration goal than a necessary condition for the social licence and long-term sustainability of the aquaculture sector. Switching to extractive monocultures into integrated, circular systems is the maturation of the Blue Revolution that it requires.

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Vaccination Strategies and Immunoprophylaxis in Livestock Diseases



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1. Introduction

The health of the livestock population is essential to the resilience of global agricultural systems, as well as guaranteeing the presence of food security. Diseases that cause infections in animals raised as food sources impose high financial costs in terms of reduced food production, higher mortality rates, as well as trade bans and restrictions; they pose significant zoonotic risks to human morbidity and health. Among the arsenal of veterinary interventions, immunoprophylaxis, i.e., the active regulation of the host immune system to avoid illness, is the most cost-effective and effective intervention. Although the anti-pathogen barrier is formed by the combination of biosecurity actions, vaccination is the necessary biological fortification, which mitigates susceptibility on the individual animal and herd scales.

This review establishes the fundamental concepts of veterinary immunoprophylaxis, classifies the types of technologies of the available vaccines, and presents proposal strategies for their use in the livestock production systems. Moreover, it examines the major issues that are specific to the deployment of vaccines and considers the innovative technologies that will transform disease prevention in the future.

2. Principles of Veterinary Immunology and Immunoprophylaxis

Immunoprophylaxis involves everything that is done to prevent the disease by enhancing the immunity of an animal. It can be generally classified as passive and active immunisation, requiring specific mechanistic knowledge to be able to design effective vaccination regimens.

a) Passive Immunity

Passive immunity, exemplified by the excretion of pre-existing antibodies into an animal subject, causes immediate, though temporarily protective immunity without inducing endogenous immunological memory. The natural transfer of colostrum maternal antibodies in livestock is the most significant type of passive immunity. In contrast to human beings, the syndesmochorial or epitheliochorial placentation in the majority of farm animals, such as ruminants, swine, and equids, prevents the transplacental transfer of immunoglobulins. As a result, born neonates are agammaglobulinemic and reliant on the intestinal absorption and ingestion of colostral IgG within the first 24 hours of life. Failure of passive transfer (FPT) continues to be a significant etiologic cause of morbidity and mortality in the neonatal period. Artificial passive immunity may be induced by the application of hyperimmune serum or purified immunoglobulins, which is a common therapeutic approach to acute toxæmias such as tetanus.

b) Active Immunity

The basis of vaccination is active immunisation. It involves the introduction of a pathogen antigen or fragments of a pathogen, which have been modified to be non-pathogenic, to activate the adaptive immune system of the host. This phenomenon causes a complicated sequence of events, which is related to antigen-presenting cells, T lymphocytes, and B lymphocytes, and it ends in the production of definite antibodies and the creation of memory

cells. Following natural exposure to the virulent pathogen, a rapid, vigorous and specific immune response is induced, and thus clinical illness is prevented, or the severity and infectious shedding are significantly reduced.

3. Spectrum of Vaccine Technologies in Livestock

Advancements in veterinary vaccines have continued to be made in primitive empirical preparations through sophisticated molecular constructs. Vaccine modality is dependent on the target pathogen, the required immunological response (humoral or cell-mediated), safety, and economic viability.

Table 1: Comparative Overview of Major Livestock Vaccine Types

Vaccine Type	Mechanism of Action	Advantages	Disadvantages	Key Livestock Examples
Live Attenuated	Uses weakened, intact pathogens that replicate in the host, mimicking natural infection without causing severe disease.	Strong, long-lasting immunity (humoral & cell-mediated). Often requires only one dose.	Risk of reversion to virulence. Requires a cold chain. Cannot be used in immunocompromised or pregnant animals.	<i>Brucella abortus</i> Strain 19; Peste des Petits Ruminants (PPR) vaccine; Sheep Pox vaccine.
Inactivated (Killed)	Pathogens are killed using chemicals (formalin) or heat. They do not replicate in the host.	Safe, no risk of reversion to virulence. Stable in storage. Safe for pregnant animals.	Weaker immune response; primarily humoral. Requires multiple doses and adjuvants to boost immunogenicity.	Foot and Mouth Disease (FMD) vaccine; Blackleg (Clostridial) bacterins; Rabies vaccine.
Toxoids	Inactivated bacterial toxins (exotoxins) retain antigenicity but lose toxicity.	Highly effective against toxin-producing bacteria. Stable.	Protects against the toxin, not the bacterial infection itself. Requires adjuvants and boosters.	Tetanus toxoid (<i>Clostridium tetani</i>); Enterotoxemia vaccines (<i>C. perfringens</i> types).
Subunit / Recombinant	Contains only specific immunogenic protein fragments of the pathogen, often produced via genetic engineering.	High safety profile. Specific immune targeting. Allows for DIVA capabilities (see later section).	Often requires strong adjuvants. May not elicit broad protection if the pathogen mutates significantly.	Recombinant Bovine Herpesvirus 1 (BHV-1) marker vaccines.
Vector Vaccines	Uses a harmless virus or bacterium (the vector) engineered to express antigens from a pathogenic organism.	Induces strong cell-mediated and humoral immunity. The vector acts as its own adjuvant.	Potential for pre-existing immunity to the vector itself, reducing efficacy.	Recombinant poxvirus-vectored vaccines for avian influenza (poultry).

4. Strategic Approaches to Vaccination Implementation

There is no guarantee that the presence of a vaccine will guarantee the containment of the disease; the strategy of application is also compelling. The vaccination approaches to livestock are usually categorised based on epidemiological goals and the current situation with the disease in a certain area.

a) Preventive (Prophylactic) Routine Vaccination

Such a standard routine is used in endemic areas, the main purpose of which is to maintain a high minimum level of population immunity in order to prevent outbreaks and minimise the spread of pathogens. Vaccination programs are tailored based on the life stage of the animal (pre-breeding, pre-calving, weaning) to achieve a

maximum coverage at the phase of life when the animal is at risk and to achieve a maximum transfer to progeny of the colostral antibodies.

b) Emergency (Reactive) Vaccination

In the case of an outbreak of an exotic disease or a re-emergent disease, reactive vaccination is used to prevent the spread of an epidemic in space and time, reduce the clinical characteristics, and decrease the pathogen shedding.

a. Dampening Vaccination: Mass vaccination in the affected area to diminish the environmental viral load.

b. Ring Vaccination: Selective vaccination of all susceptible animals in a specific geographic area enclosing an infected focus, thus forming an immunologic firewall that prevents the outward transfer.

c) The Concept of Herd Immunity

Herd immunity is an epidemiological phenomenon in which an adequate number of people have protective immunity that reduces the likelihood of infection between infected and susceptible hosts. This passive immunisation is also exerted on animals (e.g., neonates, immunocompromised) that are not yet immunised or susceptible to infection (i.e., the susceptible animals), in effect breaking the chain of infection. The herd immunity threshold depends on the pathogen modularity, which is the basic reproduction number (R_0). The disease can be highly contagious, meaning that foot and mouth disease

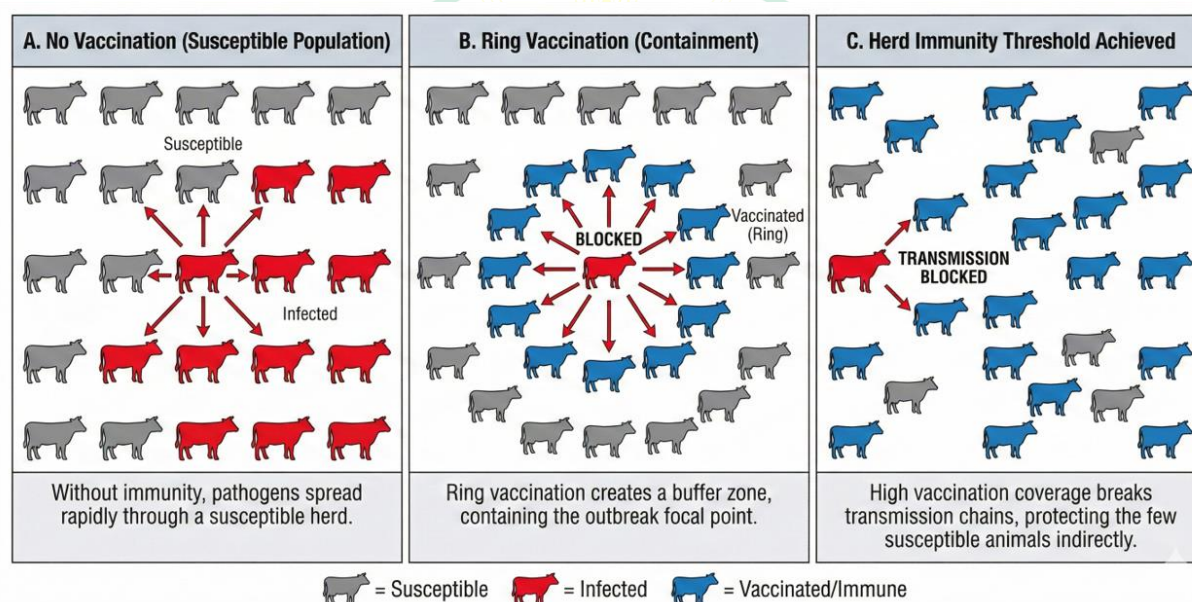


Figure 1. Strategic Vaccination Approaches and Herd Immunity Outcomes

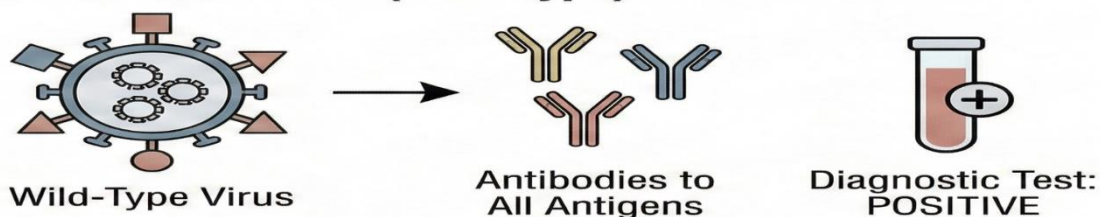
4. DIVA Strategy (Differentiating Infected from Vaccinated Animals)

Another important historical setback to successful vaccination, particularly with trade-sensitive agents such as foot and mouth disease or classical swine fever, has been that it has been impossible to serologically separate naturally infected and vaccinated animals; both produce antibody responses to the entire range of pathogen antigens. This prompted the creation of DIVA vaccines (also known as marker vaccines), which use an artificial deletion or an artificial omission of a non-essential protein of the wild-type pathogen. ELISA (e.g., companion diagnostic) assays are then designed to detect antibodies to the protein that is not present.

- Animals that are vaccinated develop antibodies against the vaccine antigens only (DIVA negative).
- Infected animals (field strains) produce antibodies to all pathogen proteins, including the deleted marker (DIVA positive).

Allowing countries to control outbreaks using vaccination, DIVA strategies allow the countries to maintain the disease-free status of trade without losing it, since surveillance can prove that there is no virus circulating even in a vaccinated population.

A. Natural Infection (Wild-Type)



B. DIVA Vaccination (Marker)

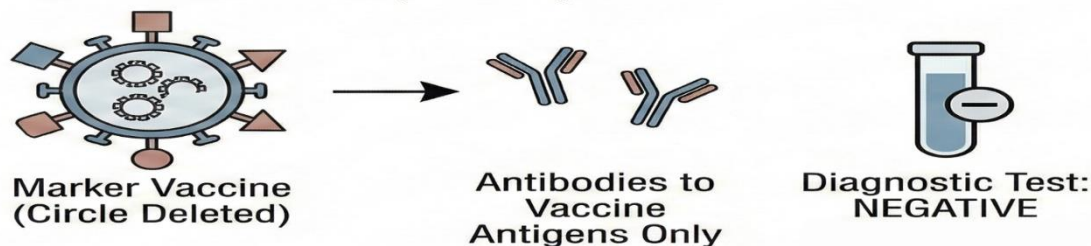


Figure 8. Principle of DIVA (Marker) Vaccines and Companion Diagnostics

5. Challenges and Considerations in Vaccine Failure

Immunoprophylaxis is still fallible. The failure of vaccines in preventing disease in target animals is termed vaccine failure. These two categories of failures can be systematically grouped as happening due to vaccine-related factors and host-related factors.

a) Vaccine-Related Factors:

- Cold -chain breach:** Most vaccines, especially live attenuated organism-based vaccines, are highly thermolabile. Poor conditions during storage or transportation lead to antigen denaturation and hence nullification of vaccine effectiveness.
- Misadministration:** Route of administration (such as subcutaneous administration instead of the advised intramuscular administration), inappropriateness of dosage, and the use of old vaccine preparations are all detrimental to immunogenicity.
- Mismatch of strains:** Strains of antigens circulating in the field- This can weaken the protective ability of antigenically mismatched vaccine strains; e.g. influenza virus serotypes and foot-and-mouth disease serotypes.

b) Host-Related Factors:

- Mother to child antibody interference:** Neonatal animal levels of colostral antibodies could counteract antigens in vaccines before they are detected by the emerging immune system. Accurate timing of the initial immunisation is thus important to maximize the period between the maternal antibody disappearance and the ontogenic development of active immunity, commonly known as the immunity gap.
- Nutritional condition:** Malnutrition of macronutrients (protein, energy), trace minerals (e.g., zinc, selenium), and micronutrients (vitamins A, E) impairs both innate and adaptive immunogenicity, which reduces the reactivity to vaccination.
- Parasitic burden and co-morbid infections:** Parasitic loads and chronic infectious diseases cause an immunological drain, thus resulting in an inappropriate vaccination response.
- Stress:** Stress, which is induced by physiological factors, includes transport, weaning, manual handling, and extreme weather conditions, increases the secretion of corticosteroids and has a suppressive effect on immunity.

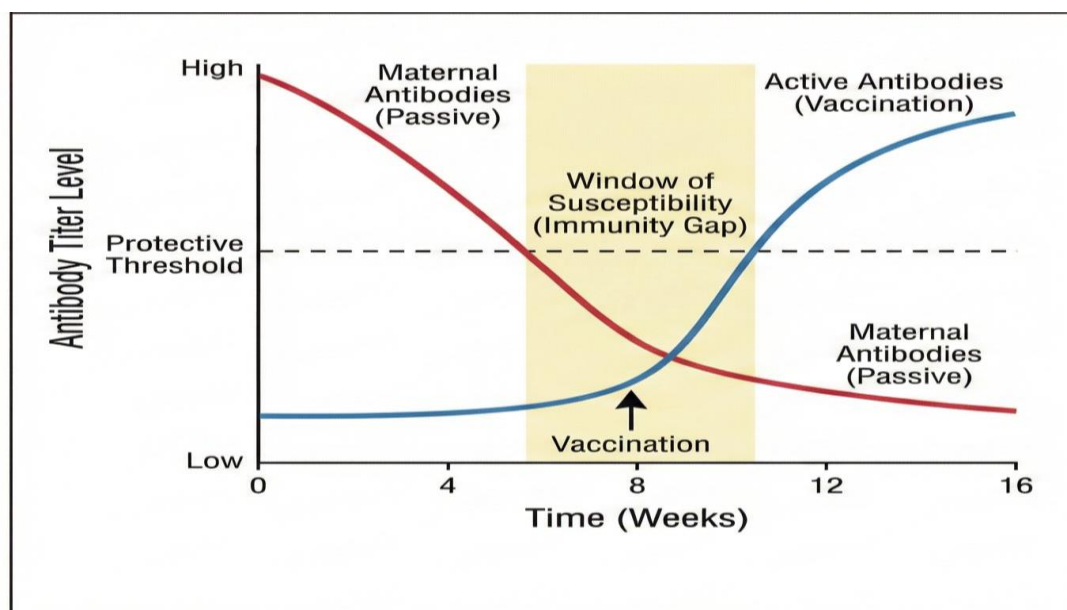


Figure 9. Dynamics of Neonatal Immunity and the Window of Susceptibility

6. Future Directions

The field is experiencing a frenzied development, which is driven by biotechnological innovations to overcome the existing constraints.

- **Nucleic acid vaccines (mRNA and DNA):** Due to the proven effectiveness of mRNA vaccinology in human therapeutics during the COVID-19 pandemic, there has been a rush of interest in similar use in veterinary science. These platforms can provide condensed development periods, which is a very important feature to counteract emergent transboundary pathogens. They cause strong immunogenicity and avoid the risks of live vaccines, and in some preparations, eliminate severe cold-chain requirements.
- **Mucosal vaccination:** The main route of entry to the body of most agents is through mucosal surfaces - respiratory and enteric pathways. Oral, nasal, or ocular vaccines are being developed to generate mucosal immunity, including secretory IgA, so as to prevent infection at the point of entry, and not only to prevent systemic manifestations. This can be applied particularly to respiratory disease complexes that plague bovine and porcine populations.
- **Nanoparticle delivery systems:** The encapsulation of vaccine antigens in nanoparticulate vehicles can be used to enhance antigen stability, antigen presentation to antigen-presenting cells and prolonged release kinetics, potentially eliminating the need to use booster administrations.
- **Plant-based edible vaccines:** GM crops like maize or alfalfa to express antigens of pathogens provide a possibly affordable method of mass animal feed vaccination. Nevertheless, the method is burdened with large regulatory and dosage-determination obstacles.

7. Conclusion

The basis of modern livestock disease management is immunoprophylaxis. It has helped to intensify animal rearing required to support the growing needs of the world population. However, vaccination is not a comprehensive remedy. Its efficacy should be incorporated in a holistic herd-health paradigm which includes effective biosecurity, accurate husbandry, optimal nutrition and environmental control. The course of livestock health will continually change to focus less on blanket immunisation approaches and more on specific, DIVA-conformant approaches involving the use of new vaccine platforms. The veterinarians and the producers should therefore be effective in navigating these changing modalities in order to ensure the resilience and productivity of the animal agricultural systems.

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Advances in Plant Breeding Techniques for Enhancing Quality and Stress Tolerance



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Abstract

Modern agriculture stands at a critical crossroads. On one side lies the immense pressure to feed a rapidly growing global population, while on the other stands the harsh reality of climate change, shrinking natural resources, and increasingly unpredictable environmental stresses. Droughts are becoming more frequent and prolonged, heat waves are intensifying, soils are turning saline, and new pests and diseases are emerging at an alarming rate. These challenges not only reduce crop yields but also compromise food quality, nutritional value, and shelf life, directly affecting farmers, consumers, and food industries alike. At the same time, consumer expectations have evolved significantly. Today's consumers are no longer satisfied with food quantity alone; they demand healthier, tastier, and more nutritious produce that can withstand transportation, storage, and processing with minimal losses. Traditional plant breeding has played a foundational role in shaping global agriculture, but on its own, it can no longer keep pace with these complex and interconnected demands. Over the past few decades, plant breeding has undergone a quiet but powerful revolution. By integrating classical breeding with advances in molecular biology, genomics, high-throughput phenotyping, and data science, scientists are now able to develop crop varieties that combine superior quality with enhanced tolerance to environmental stress. This article provides a clear and accessible overview of modern plant breeding techniques and explains how they are helping build a resilient, sustainable, and climate-ready food system for the future.

1. Introduction

Plants cannot walk away from danger. Unlike animals, they are fixed in one place and must endure whatever environmental challenges come their way. In natural ecosystems, plants survive through genetic adaptation over long periods of time. In agriculture, however, this biological limitation becomes a serious challenge because crops are expected to produce stable yields and high-quality food under constantly changing conditions. Crop plants are routinely exposed to a wide range of stresses, including drought, extreme heat, salinity, nutrient deficiencies, flooding, and attacks from insects, pathogens, and weeds. While the most visible impact of these stresses is reduced yield, their hidden effects on crop quality are equally damaging. Stress can shrink grain size, lower protein and oil content, alter starch composition, reduce flavour, and shorten shelf life. These quality losses often translate into economic losses for farmers and processors.

For centuries, farmers relied on simple selection, choosing seeds from the healthiest or highest-yielding plants. Over generations, this practice shaped the crops we grow today. The Green Revolution of the twentieth century demonstrated how targeted breeding could dramatically increase food production and prevent famine. However, these advances often depended heavily on irrigation, fertilizers, and pesticides, making modern agriculture more vulnerable to environmental stress and resource limitations. Today, plant breeding has entered a new phase. Scientists can now examine plant genomes directly, identify genes linked to desirable traits, and predict how plants will perform under future climate scenarios. This article explores how modern breeding tools are reshaping agriculture by improving both crop quality and stress tolerance in a sustainable way.

2. Understanding Crop Quality and Stress Tolerance

In the past, agricultural success was measured primarily by yield. While yield remains important, quality has become equally critical in modern food systems. Crop quality includes nutritional value—such as protein content, vitamins, minerals, and antioxidants—as well as processing characteristics like baking quality in wheat or oil

stability in oilseeds. Sensory traits such as taste, aroma, colour, and texture also influence consumer acceptance. In addition, post-harvest traits like shelf life, resistance to spoilage, and transportability play a major role in reducing food loss. Stress tolerance refers to a plant's ability to survive, grow, and reproduce under unfavourable conditions. Abiotic stresses such as drought, heat, and salinity disrupt photosynthesis, water balance, and nutrient uptake. Biotic stresses, including pests and diseases, activate complex defense responses that divert energy away from growth and reproduction. Importantly, stress tolerance and quality are closely interconnected. Drought stress, for example, may reduce grain size and protein accumulation, while heat stress during grain filling can change starch structure and affect milling or baking quality. Improving both traits simultaneously is challenging because they are usually controlled by many genes and are strongly influenced by environmental conditions. Modern plant breeding tools help overcome this complexity by allowing breeders to study these traits at genetic, physiological, and molecular levels, leading to more precise and reliable improvement.

3. Conventional Plant Breeding: The Strong Foundation

Despite the rapid rise of advanced technologies, conventional plant breeding remains the foundation of crop improvement. Methods such as selection, hybridization, backcrossing, and recurrent selection are still widely used across the world. Hybrid breeding is a classic example of conventional success. By crossing genetically distinct parent lines, breeders exploit hybrid vigour, resulting in crops that grow faster, yield more, and tolerate stress better than their parents. Many maize, rice, vegetable, and oilseed varieties grown today are hybrids that owe their success to this principle. Traditional breeding has also benefited greatly from the use of landraces and wild relatives of crops. These plants have evolved under harsh environmental conditions and often possess natural resistance to drought, diseases, or poor soils. By crossing them with modern varieties, breeders introduce valuable traits that might otherwise be lost. However, conventional breeding is time-consuming and heavily influenced by environmental variation. Selecting for stress tolerance in the field is particularly challenging because stress intensity can vary from year to year. These limitations created the need for more precise and faster breeding approaches.

4. Molecular Marker-Assisted Breeding

One of the most important breakthroughs in plant breeding was the development of molecular markers—small, identifiable DNA segments linked to specific traits. Marker-assisted selection (MAS) allows breeders to identify plants carrying desirable genes without waiting for those traits to appear in the field. MAS has been especially effective for traits controlled by one or a few major genes. Disease resistance in crops such as rice, wheat, and maize is a well-known example. Markers linked to grain quality traits, including starch composition or gluten strength, have also made selection faster and more reliable. Marker-assisted backcrossing enables breeders to transfer a specific gene from a donor plant into an elite variety while retaining most of the elite plant's genetic background. This approach saves time, reduces unwanted traits, and improves breeding efficiency.

Table 1. Major plant breeding techniques and their key contributions

Breeding Technique	Main Application	Key Advantages	Limitations
Conventional breeding	Yield, adaptation	Simple, affordable	Slow, environment-dependent
Marker-assisted selection	Disease resistance, quality	Accurate, faster	Less effective for complex traits
Genomic selection	Stress tolerance, yield	Handles many genes	Needs large datasets
Gene editing (CRISPR)	Precise trait improvement	Very high precision	Regulatory challenges

5. Genomic Selection: Breeding Meets Big Data

Many stress tolerance traits are controlled by hundreds of genes, each contributing a small effect. Genomic selection (GS) was developed to manage this complexity. Instead of focusing on individual genes, GS uses information from the entire genome to predict how a plant will perform. By analysing large datasets that link DNA profiles with observed traits, breeders can estimate the potential of new plants even before extensive field testing. This allows earlier, faster, and more accurate selection decisions. Genomic selection has proven particularly effective in improving drought tolerance, heat resilience, and yield stability in crops such as wheat, maize, and rice. By shortening breeding cycles, GS helps agriculture respond more quickly to climate change.

6. Gene Editing and Genetic Engineering

Gene editing, especially CRISPR-Cas technology, represents one of the most exciting developments in modern plant breeding. Unlike traditional genetic modification, gene editing introduces precise changes within a plant's own genome. Scientists can now disable genes that reduce stress tolerance or fine-tune genes responsible for quality traits. For example, editing drought-response genes can improve water-use efficiency, while modifying oil or starch biosynthesis genes can enhance nutritional value. Transgenic approaches remain important, particularly for traits not found naturally within a crop species. Insect-resistant and herbicide-tolerant crops are widely adopted examples. Advances in biosafety testing and gene stacking have improved their effectiveness and acceptance.

7. Speed Breeding: Saving Time Without Cutting Corners

Developing a new crop variety is a long-term endeavor, often requiring 8–12 years under conventional breeding systems. This extended timeline is mainly due to long generation cycles, seasonal constraints, and the need for repeated field evaluations. Speed breeding offers a transformative approach by drastically reducing generation time while maintaining the scientific rigor and selection accuracy of traditional breeding programs. Speed breeding works by precisely manipulating environmental factors such as extended photoperiods (often 20–22 hours of light per day), optimized light intensity, controlled temperature regimes, and humidity. These conditions accelerate physiological processes, leading to faster vegetative growth, earlier flowering, and quicker seed set. As a result, crops such as wheat, rice, barley, chickpea, and oilseeds can complete their life cycle in a significantly shorter time.

Under speed breeding protocols, it is possible to raise 4–6 generations per year compared to only one or two under field conditions. This rapid cycling enables breeders to advance segregating populations quickly, fix desirable traits at an early stage, and shorten the time required for variety stabilization. Importantly, this acceleration does not compromise plant health or genetic integrity when protocols are carefully optimized for each crop.

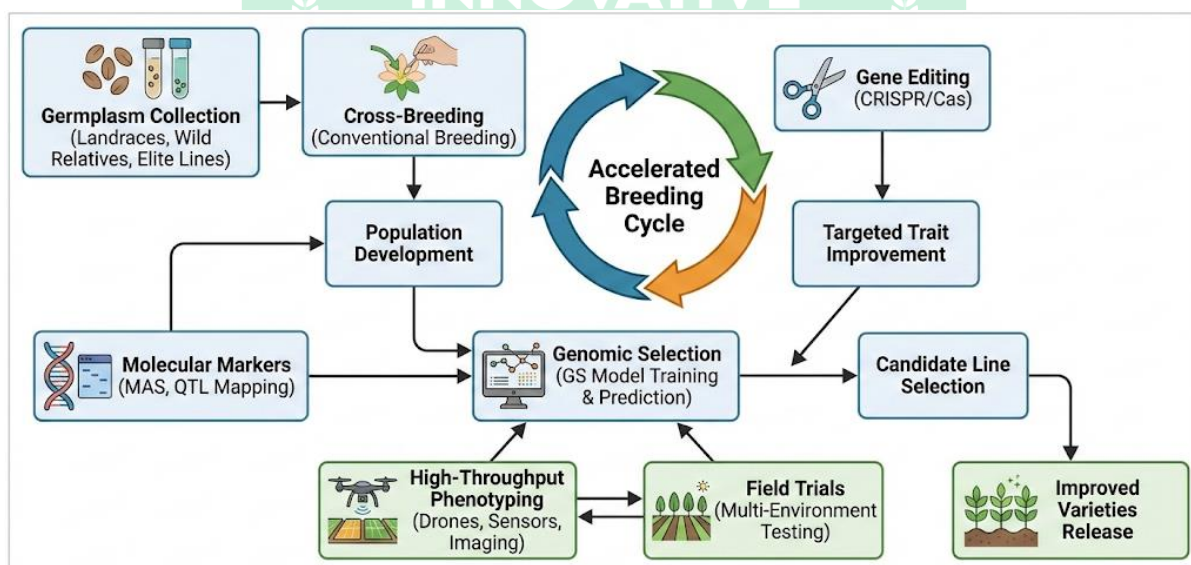


Figure 1. Integrated modern plant breeding pipeline

A schematic illustration showing how conventional breeding, molecular markers, genomic selection, phenotyping, and gene editing work together.

8. Enhancing Nutritional and Processing Quality

Modern breeding goes beyond yield and stress tolerance to address nutritional security. Biofortification programs have produced crops richer in iron, zinc, and vitamin A, helping combat hidden hunger in vulnerable populations. Processing quality is equally important. In wheat, gluten strength affects baking quality, while in oilseeds, fatty

acid composition determines nutritional and industrial value. Molecular tools help improve these traits without compromising yield or resilience.

Table 2. Examples of quality and stress tolerance traits improved through modern breeding

Crop	Target Trait	Approach	Outcome
Rice	Drought tolerance	Genomic selection	Stable yield
Wheat	Heat tolerance	MAS	Better grain filling
Maize	Vitamin A	Biofortification	Improved nutrition
Tomato	Shelf life	Gene editing	Reduced losses

9. Challenges and Ethical Considerations

Despite its promise, modern plant breeding faces challenges. Advanced technologies can be expensive and require skilled personnel, limiting access in developing regions. Regulatory frameworks for gene-edited crops vary widely across countries. Public trust is equally important. Transparent communication about safety, benefits, and ethical concerns will determine how widely these technologies are adopted.

10. Future Perspectives

The future of plant breeding lies in integration. Combining genomics, phenomics, artificial intelligence, and climate modelling will allow breeders to design crops tailored to specific environments and future conditions. Participatory breeding and open data sharing can ensure that smallholder farmers benefit alongside large producers. Resilient, nutritious crops will be essential for sustainable agriculture.



Figure 2. Crop performance under increasing environmental stress

A conceptual graph showing how improved varieties maintain yield and quality better than conventional crops.

11. Conclusion

Plant breeding has evolved from simple selection into a sophisticated science that blends genetics, technology, and data. These advances are enabling breeders to develop crops that are productive, nutritious, and resilient to stress. As climate change intensifies and global food demands grow, modern plant breeding will remain central to food security. By uniting innovation with sustainability, it offers practical solutions for the farms—and the future—of tomorrow.

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A Role of Drones Technology in Modern Farming



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Introduction

In Recent years, the use of drones in agriculture has been gaining increase attention as a promising approach for improving modern agriculture farming. the agricultural sector is increasingly adopting advanced digital technologies to address challenges related to food security, resource optimization, & environmental sustainability. Among these technologies, unmanned aerial vehicles (UAVs), commonly referred to as drones, have gained substantial attention for their capacity to support precision agriculture. Equipped with multispectral, hyperspectral, thermal, and RGB sensors, agricultural drones enable high-resolution spatial and temporal data acquisition for crop health assessment, soil analysis, irrigation management, and yield prediction. The integration of drone-generated data with geographic information systems (GIS), artificial intelligence (AI), and machine learning algorithms allows for data-driven decision-making at both field and farm scales. By enhancing input efficiency, reducing labor dependency, and minimizing environmental impact, drone technology represents a critical component of modern smart farming systems. This study explores the role of drone technology in contemporary agriculture, emphasizing its technical capabilities, applications, and potential to transform traditional farming practice.



History of Drones technology.

He uses of Drones dates back to 1849, when Austria deployed unmanned hot-air balloons. In 1983, Japan introduced remotely controlled aerial systems for spraying agrochemicals. Yamaha, a Japanese motor company, later developed the R-50, the world's first autonomous crop-dusting helicopter, capable of carrying a 20 kg payload. The potential of drones to revolutionize agriculture became widely recognized by 2015. Over the past two decades, drone technology has progressed rapidly, and its applications are expected to expand further in the coming years.

Drone Technology in India

- ❖ **Drone Rules, 2021** : One of the most important milestones was the introduction of the Drone Rules 2021, which simplified drone permissions and created the Digital Sky Platform for registration and flight planning. This dramatically lowered regulatory barriers and encouraged wider civilian use — including in farming.

- ❖ **Kisan Drone Scheme (2022):** The Indian government launched the Kisan Drone Scheme in 2022 aimed at supporting drone use in agriculture. It focused on activities like spraying, crop monitoring, and seeding, helping farmers adopt drones more easily.
- ❖ **Drone Didi / NaMo Drone Didi Initiative (2023–2024):** In 2023, the Drone Didi Scheme was introduced to empower women Self-Help Groups (SHGs) by providing drones (with 80% financial assistance), training, and support for operation and service delivery. This helped boost rural incomes and spread drone expertise in farming communities.
- ❖ **Growth and Adoption (2024–2025)** Adoption of drones in agriculture grew significantly, with reports showing ~35% year-on-year increases in 2024–25 due to government incentives, greater farmer awareness, and startup participation.
- ❖ **Government Support:** India expanded financial support under programs like the Sub-Mission on Agricultural Mechanization (SMAM) — offering subsidies for drone purchases to farmers, custom hiring centers, and farmer producer organizations (FPOs)

What do Modern Farming Drones do?

Agricultural drones help farmers observe crops from above, enabling early detection of problems and better field management. Based on the task, drones can be equipped with different tools like sensors, cameras, sprayers, hooks, or small containers for sample collection. The information collected is transmitted to computers or tablets, offering valuable insights and visuals of farmland, crops. These drones are used for several purposes in agriculture and agribusiness.

such as:

- Capturing land images.
- Mapping land features and field boundaries.
- Monitoring soil conditions.
- Tracking and counting insects & pests.
- Checking irrigation systems.
- Assessing spraying requirements.
- Collecting soil and water samples.
- Identifying and resolving field issues.

Classification of Unmanned Aircraft Systems (UAS)

According to the Directorate General of Civil Aviation (DGCA), unmanned aircraft are categorized based on their total weight, including payload:

- ❖ Nano: Weighs up to 250 grams
- ❖ Micro: Weighs more than 250 grams and up to 2 kg
- ❖ Small: Weighs between 2 kg and 25 kg
- ❖ Medium: Weighs between 25 kg and 150 kg
- ❖ Large: Weighs more than 150 kg

Used of drones in Modern farming: Drones are widely used in crop production to improve efficiency and farm management. They help monitor crop health through aerial imaging, allowing early detection of pests, diseases, and nutrient deficiencies. Drones are also used for precision spraying of fertilizers, pesticides, and herbicides, reducing chemical waste and labor costs. In addition, they assist in irrigation management by identifying water-stress areas and support yield estimation and crop mapping for better planning and decision-making.

Objective of Drone Technology in Modern Farming

The main objective of drone technology in modern farming is to improve agricultural productivity, efficiency, and sustainability through precise, real-time data collection and automated operations. Drones help farmers make better decisions while reducing costs and environmental impact.

- ❖ **Enhancing precision agriculture:** Collect accurate data on crop health, soil conditions, and moisture levels to optimize farming practices.
- ❖ **Monitoring crop growth and health:** Detect pest infestations, diseases, and nutrient deficiencies at an early stage.

- ❖ Optimizing resource use: Reduce wastage of water, fertilizers, and pesticides through targeted application.
- ❖ Increasing farm productivity: Improve yield quality and quantity by timely interventions.
- ❖ Reducing labor and time: Cover large areas quickly and minimize dependence on manual field inspections.
- ❖ Supporting sustainable farming: Lower chemical use and environmental damage while promoting eco-friendly practices.
- ❖ Improving decision-making: Provide data-driven insights for planning irrigation, fertilization, and harvesting.

Future of Drone Technology in Modern Farming

The future of drone technology in modern farming is expected to bring significant advancements, offering innovative solutions to meet the growing demands and challenges of modern farming. Several key developments highlight the potential role of drones in shaping the future of agriculture.

- ❖ **Advanced Sensing Technologies:** Future agricultural drones are likely to be equipped with sophisticated sensing tools such as hyperspectral and LiDAR (Light Detection and Ranging) sensors. These technologies will deliver highly detailed information on crop health, soil characteristics, and environmental factors. Enhanced data accuracy will help farmers make precise, data-driven decisions, improving productivity and efficient use of resources.
- ❖ **Autonomy and AI Integration:** Progress in artificial intelligence and machine learning will enable drones to independently process collected data and generate real-time insights. AI-enabled drones will be capable of identifying crop diseases, detecting pest infestations, and forecasting yields with improved accuracy. This automation will reduce manual labor, streamline farming operations, and increase overall efficiency.
- ❖ **Energy Efficiency and Sustainability:** Future drone systems are expected to feature improved battery performance, longer flight durations, and higher energy efficiency. Emphasis will also be placed on eco-friendly materials and cleaner propulsion systems to reduce environmental impact. The adoption of sustainable drone technologies will support environmentally responsible agricultural practices.
- ❖ **Integration with Farm Management Systems:** Drones will become an integral part of digital farm management platforms, providing farmers with real-time data access and analytical tools through centralized systems. This integration will support better planning, performance monitoring, and resource management. Additionally, drones will work in coordination with other precision farming technologies, such as GPS-guided machinery and automated irrigation systems, creating a fully interconnected agricultural ecosystem.
- ❖ **Regulatory Frameworks and Standards:** As drone adoption expands, well-defined regulatory guidelines and operational standards will be developed to ensure safe, efficient, and ethical use of drone technology in agriculture. As drone technology continues to develop, strong regulatory frameworks and industry standards will be essential to ensure safe and responsible use in agriculture. Governments and regulatory authorities will have a key role in setting clear guidelines for drone operations, particularly regarding airspace control, privacy protection, and data security. Well-defined regulations will encourage broader adoption of agricultural drones while ensuring adherence to legal and ethical requirements.

Advantages of Drone Technology in Modern Farming

Drone technology has brought significant improvements to Modern farming by modernizing traditional farming methods and helping farmers increase productivity, efficiency, and sustainability.

- ❖ **Precision Agriculture:** Drones support precision farming by gathering accurate information on soil conditions, moisture content, and crop health. This helps farmers plan planting, fertilization, and irrigation more effectively, ensuring optimal use of resources and higher yields.
- ❖ **Crop Monitoring and Management:** Equipped with advanced cameras and sensors, drones provide real-time data on crop growth, health status, and pest or disease presence. Early identification of problems enables timely action, reducing crop damage and limiting excessive chemical use.
- ❖ **Better Decision-Making:** Drone-generated data, including aerial photos, multispectral images, and thermal maps, allows farmers to make informed, data-based decisions. This information helps in identifying patterns, evaluating risks, and improving crop management strategies for better profitability.

- ❖ **Cost Effectiveness:** By automating activities such as field surveying, mapping, and spraying, drones reduce labor requirements and operational costs. They can quickly cover large areas, saving both time and money compared to conventional methods.
- ❖ **Environmental Sustainability:** Drones encourage eco-friendly farming by allowing precise application of fertilizers, pesticides, and herbicides only where required. This targeted approach lowers chemical usage, reduces runoff, and protects surrounding ecosystems and water resources.
- ❖ **Scalability:** Drone systems can be adapted to various farm sizes and agricultural activities. From small farms to large commercial operations, drones can be customized for tasks such as crop monitoring, spraying, and livestock management to meet individual farming needs.

Disadvantages of Drone Technology in Modern Farming

- ❖ **Technical Skill Requirements:** Effective use of agricultural drones demands technical knowledge in drone operation, data collection, and data interpretation. Many farmers may lack the required skills, leading to inefficient use or underutilization of the technology. Integrating drone-generated data with existing farm management systems also requires additional technical support.
- ❖ **Limited Battery Life and Operating Time:** Most agricultural drones operate for only 20–40 minutes per battery charge, which limits their coverage area. This constraint is particularly problematic for large farms. Addressing this issue would require improved battery technology or advanced solutions such as drone swarms and charging systems, which may not always be practical.
- ❖ **Data Handling and Privacy Issues:** Drones collect large volumes of data through sensors and imaging systems. Managing, storing, and analyzing this data can be challenging for farmers who lack data-processing skills or computing resources. Furthermore, concerns about data security and privacy may discourage adoption, especially in areas with strict data protection laws.
- ❖ **Weather and Environmental Constraints:** Unfavorable weather conditions like strong winds, rainfall, or fog can disrupt drone flights and reduce data accuracy. Environmental factors such as uneven terrain, dense vegetation, and altitude variations can also affect drone performance, limiting their reliability in certain agricultural settings.
- ❖ **Regulatory Challenges:** One major obstacle to using drones in agriculture is dealing with complex and frequently changing regulations. Rules related to flight altitude, airspace usage, and operator licensing differ across regions and countries. Compliance with these regulations increases operational complexity and creates uncertainty for farmers adopting drone technology.
- ❖ **High Investment Cost:** The cost of purchasing drones and related equipment can be very high, especially for small-scale farmers or those with limited financial resources. In addition to the initial purchase, expenses for maintenance, training, software, and insurance further increase the financial burden. As a result, achieving a profitable return on investment may take considerable time.
- ❖ **Public Acceptance and Social Concerns:** The acceptance of drones by local communities plays an important role in their adoption. Issues such as noise, safety risks, and visual disturbance may raise concerns, particularly in populated areas. Increasing awareness and maintaining transparent communication are necessary to gain public trust and support for drone use in modern farming.

Conclusion

In summary, the application of drones in agriculture presents substantial advantages, including enhanced operational efficiency, lower labour requirements, and improved environmental sustainability. Although their adoption faces certain challenges—such as technological constraints, regulatory complexities, and concerns related to data privacy—continuous technological advancements and the integration of artificial intelligence are expanding their capabilities. These developments enable more accurate decision-making and higher levels of automation. Consequently, drone technology holds considerable promise for helping farmers and agribusinesses optimize productivity while supporting sustainable agricultural practices. It should be emphasized that agricultural drone technology is still in an emerging stage, with many aspects yet to be fully explored. Ongoing research and development are crucial to unlocking its full potential and effectively addressing existing challenges, thereby ensuring its long-term success in modern agriculture.

Artificial Intelligence in Fisheries: Bridging the Gap Between Data, Decisions, and Sustainability



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Abstract

The global fisheries and aquaculture sectors face mounting pressure from climate change, overexploitation, biodiversity loss, and rising food demand. Conventional monitoring and management approaches are often costly, labor-intensive, and limited in spatial and temporal coverage. Recent advances in artificial intelligence (AI)—including machine learning, deep learning, reinforcement learning, and the artificial intelligence of things (AIoT)—offer transformative opportunities to enhance data collection, analysis, and decision-making across fisheries value chains. This article synthesizes recent progress in AI applications spanning fisheries genetics and monitoring, precision aquaculture, fisheries management, and sensing infrastructure. It highlights how AI-driven systems are transitioning from experimental prototypes to operational tools that support sustainable and equitable aquatic resource management. At the same time, critical challenges related to domain shift, data scarcity, uncertainty quantification, governance, and equity persist. Addressing these limitations through standardized datasets, robust evaluation frameworks, and inclusive governance mechanisms is essential to realizing the full potential of AI in fisheries.

Keywords: Artificial intelligence, Fisheries monitoring, Data, Electronic monitoring, IUU fishing, Digital twins

Introduction

Fisheries and aquaculture are essential for the livelihoods and nutrition of millions globally, but the sustainability of these systems faces increasing threats. Traditional methods—such as trawl surveys, onboard observers, and manual species identification—are limited by high costs, restricted coverage, and observer bias. With aquaculture now accounting for over half of global seafood production and a significant portion of wild stocks being overexploited, there is an urgent need for scalable and adaptive management tools. Artificial intelligence has emerged as a significant enabler in this field. Developments in computer vision, acoustic analysis, satellite remote sensing, and genomic technologies facilitate automated perception, short-term forecasting, and real-time control. Instead of replacing established practices, AI systems enhance their effectiveness by increasing observation density, speeding up analysis, and connecting data streams directly to operational decisions. This article examines the application of AI in fisheries science and management, assesses its current limitations, and highlights priorities for moving from experimental applications to dependable decision-support infrastructure.

AI in Fisheries Genetics and Monitoring

AI-powered monitoring systems are transforming the observation of wild fish populations and aquatic ecosystems. Advanced computer vision models facilitate the automated detection and classification of species from underwater images, even in challenging environments marked by turbidity and occlusion. Techniques such as transfer learning and domain adaptation lessen the reliance on large labeled datasets, although performance can often suffer for rare or protected species and during habitat transitions. In addition to visual data, environmental DNA (eDNA) metabarcoding offers a non-invasive approach to evaluating biodiversity and seasonal community dynamics. When paired with AI-driven analytics, eDNA can closely match traditional survey indices, although difficulties persist in correlating read abundance with actual biomass and in accounting for hydrological transport. Acoustic monitoring further broadens the scope by allowing extensive assessments of fish abundance and behavior, with machine learning increasingly employed to automate echo-trace classification and minimize the need for expert annotation. Genomic technologies, bolstered by AI-based inference, are enhancing

our understanding of stock structure, connectivity, and adaptive traits. Trait-based and mixed-effects statistical models combine life-history traits with environmental factors, providing deeper insights into population dynamics. Collectively, these methods indicate a shift towards integrated, multi-sensor monitoring systems capable of ongoing, ecosystem-wide assessments.

AI in Precision Aquaculture

In aquaculture, artificial intelligence is facilitating a shift from reactive to adaptive management of farms. Supervised learning models improve feed rationing by incorporating behavioral signals, growth histories, and environmental factors, which enhances feed conversion efficiency and minimizes waste. Researchers are investigating reinforcement learning controllers to optimize feeding and water quality in recirculating aquaculture systems, although significant challenges such as safety constraints and data requirements persist. Vision-based systems broaden the application of AI to welfare and disease monitoring, allowing for the real-time detection of abnormal behaviors, lesions, and stress indicators. Forecasting models are capable of predicting dissolved oxygen levels, ammonia concentrations, and growth trajectories, which supports proactive interventions and better harvest planning. New concepts like digital twins are merging these elements into cohesive decision-support dashboards that simulate various management scenarios. Despite encouraging outcomes, numerous AI applications in aquaculture are still confined to short-term or single-farm experiments. Wider implementation will rely on multi-site validation, decision rules that account for uncertainty, and explainable AI tools that foster farmer trust and enable human-in-the-loop management.

AI in Fisheries Management and Governance

AI is increasingly influential in fisheries governance, especially in ensuring compliance and facilitating risk-based management. The analysis of Automatic Identification System (AIS) trajectories allows for the identification of unusual vessel activities linked to illegal, unreported, and unregulated (IUU) fishing. When paired with satellite-based technologies like synthetic aperture radar and nighttime light imagery, AI systems can uncover non-broadcasting "dark" fleets and enhance the mapping of global fishing efforts. Electronic monitoring (EM) systems that utilize computer vision automate the documentation of catch and bycatch, extending coverage beyond what human observers can provide. These technologies hold potential for standardizing the monitoring of interactions with protected species, although their effectiveness for rare events is limited by the availability of training data. AI-driven decision support systems are also being incorporated into stock assessment models, assisting managers in evaluating different strategies amidst uncertainty. For AI-generated outputs to be practical, they need to be validated against enforcement and management results, such as inspection reports and observer data. Clear thresholds, estimates of uncertainty, and human oversight are crucial to ensure the legitimacy and effectiveness of these systems.

Sensing Infrastructure and Emerging Technologies

The operational success of AI in fisheries depends on robust sensing and computational infrastructure. Advances in edge computing enable near-real-time analysis on power-constrained platforms such as buoys and vessels, reducing data transmission costs. Lightweight object detection models, particularly YOLO-based architectures, facilitate rapid inference for underwater imagery and echograms. Foundation models, including domain-specific large language models and vision-language systems, represent a new frontier. These models offer potential for cross-task generalization, open-vocabulary recognition, and knowledge synthesis. However, their deployment in safety-critical fisheries contexts requires careful governance, transparent training data, and rigorous evaluation to avoid biased or unreliable recommendations.

Challenges and Future Directions

Despite rapid progress, significant challenges remain. AI models often suffer from performance degradation under domain shifts caused by changes in environment, seasonality, or gear type. Standardized, multi-region datasets—particularly for rare and protected species—are scarce. Moreover, many studies emphasize accuracy metrics without assessing how model errors propagate into management decisions. Equity and governance issues are equally important. Small-scale fishers and farmers may lack access to data, infrastructure, or capital required for AI adoption. Privacy, data-sharing incentives, and cybersecurity must be addressed to build trust and collaboration. Future priorities include developing standardized benchmarks with uncertainty quantification,

integrating AI outputs into decision-relevant frameworks, and fostering inclusive data partnerships. By aligning technological innovation with transparent governance and stakeholder participation, AI can evolve from isolated prototypes into a reliable infrastructure for sustainable fisheries.

Conclusion

Artificial intelligence is reshaping fisheries and aquaculture by enhancing monitoring, optimizing production, and supporting governance. While current applications demonstrate substantial promise, their real-world impact depends on robust data foundations, transparent evaluation, and adaptive management frameworks. A coordinated effort involving researchers, managers, policymakers, and producers is required to ensure that AI-driven tools contribute to resilient, equitable, and sustainable aquatic food systems.

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Direct Seeded Rice with Drum Seeder: The Best Solution to Labour Shortage in Paddy



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Abstract

Rice cultivation in India is increasingly challenged by acute labour shortages, rising wage rates and high water demand under traditional puddled transplanting. Timely transplanting has become difficult, leading to higher costs and yield losses. In this context, Direct Seeded Rice (DSR) using a drum seeder has emerged as an efficient and practical alternative. Drum seeder based DSR eliminates nursery raising, seedling uprooting and manual transplanting, reducing planting labour by nearly 90 percent. The method enables rapid sowing of one hectare within a few hours using minimal manpower, ensuring timely crop establishment. DSR also saves 15-30 percent irrigation water by avoiding repeated puddling and continuous flooding, making it suitable for water-scarce regions. Direct establishment promotes better root growth, faster early tillering and absence of transplanting shock. Although weed pressure is a major concern, effective use of herbicides and mechanical weeder ensures successful crop performance. Overall, drum seeder based DSR is a labour-saving, cost-effective, water-efficient and climate-smart technology for sustainable rice production.

Keywords: Direct Seeded Rice, drum seeder, labour scarcity, water saving, sustainable rice farming

1. Introduction

Rice is the staple food of India and the backbone of national food security. Traditionally, rice is grown by raising seedlings in nursery beds and transplanting them manually into puddled fields. This system requires huge amounts of labour, water and time. Today, farmers across India face an acute labour crisis due to migration of rural youth to cities, rising wage rates and lack of workers during peak agricultural seasons. Because of this, many farmers are unable to transplant rice on time, resulting in delayed planting, higher costs and yield loss. Under these conditions, Direct Seeded Rice (DSR), especially using a drum seeder, has emerged as the most practical and efficient solution.

2. What is Direct Seeded Rice?

Direct Seeded Rice is a method in which rice seeds are sown directly in the main field, without raising seedlings in a nursery and without transplanting. In drum seeder based DSR, pre-germinated rice seeds are placed inside a manually pulled drum seeder and sown in straight rows on puddled or moist soil. This ensures uniform spacing, better crop stand and easy weed management.

DSR can be practiced as:

- **Wet DSR** (using drum seeder or broadcasting on moist soil)
- **Dry DSR** (seeds drilled into dry soil)

This method completely eliminates nursery raising, seedling uprooting and manual transplanting.

3. Why Labour Shortage is a Major Threat in Rice Farming

Rice transplanting is one of the most labour intensive farm operations. Traditionally, 30-40 labourers are required per hectare for several days just for transplanting.

This causes serious problems:

- Labour is not available when needed
- Wages rise sharply during transplanting season
- Delayed planting reduces yield
- Small farmers cannot afford high labour costs

In many villages, transplanting has become the biggest bottleneck in rice cultivation.

4. How Drum Seeder Based DSR Solves the Labour Crisis

The drum seeder revolutionizes rice sowing.

Traditional Transplanting

- 30-40 labourers needed per hectare
- 3-5 days of continuous work
- Separate nursery sowing, uprooting and transplanting

DSR with Drum Seeder

- Only 2-3 persons required
 - One person pulls the drum seeder
 - One or two refill seeds
- 1 hectare can be sown in 5-6 hours
- No nursery, no uprooting, no transplanting

This results in nearly 90% saving in planting labour, making DSR ideal for labour-scarce areas.

Labour is Not Eliminated - It is Used More Smartly

In drum-seeded DSR, labour shifts from hard transplanting work to:

- Weed management
- Herbicide application
- Occasional mechanical weeding (cono weeder)

This means labour is spread over the season instead of being concentrated in one costly peak period.

5. Water Saving Advantage

Traditional puddled transplanting uses enormous amounts of water. DSR avoids repeated flooding and puddling and saves 15-30% irrigation water, making it perfect for groundwater-depleted and drought-prone areas.

Lower Cost and Higher Profit

Drum-seeded DSR saves money on:

- Labour
- Nursery raising
- Transplanting
- Irrigation pumping

On average, farmers save ₹5,000-8,000 per hectare, while yields remain equal or better than transplanted rice.

Faster and Stronger Crop Establishment

Since plants grow directly where they are sown, there is:

- No transplanting shock
- Better root growth
- Faster early tillering
- Stronger crop stand

6. Climate-Smart Technology

DSR reduces continuous flooding, which lowers methane emissions and helps in climate change mitigation, making it an environmentally friendly practice.

7. Weed Management - The Key to Success

Weeds are the main challenge in DSR, but this can be easily controlled by:

- Pre-emergence and post-emergence herbicides
- Row sowing using drum seeder
- Cono or mechanical weeders

With proper weed control, DSR performs excellently.

Direct Seeded Rice (DSR) with Drum Seeder: The Best Solution to Labour Shortage in Paddy



Traditional Transplanting
30-40 Labourers
3-5 Days

DSR with Drum Seeder
2-3 Workers
5-6 Hours

How Drum Seeder DSR Works
Drum Seeder-Based DSR
Pre-Germinated Rice Seeds
Seed Drum
No Nursery → No Transplanting

Wet DSR
• Puddled Field

Dry DSR
• Dry Soil

Key Advantages of DSR

- 90% Labour Saving
- ₹5,000-3,000 /Ha Savings
- 15-30% Less Water Use
- Lower Methane Emissions

Smart Weed Management

- Herbicide Spray
- Row Sowing with Drum Seeder
- Cono Weeder

DSR with Drum Seeder: The Future of Rice Farming!

Conclusion

In today's era of labour shortage, rising costs and water stress, Direct Seeded Rice with a drum seeder is the future of paddy farming. It reduces labour by nearly 90%, cuts costs, saves water and ensures timely sowing. DSR is not just a method, it is a smart, sustainable and profitable revolution in rice cultivation.

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Bacteriophages: Based Strategies for Sustainable Plant Disease Control



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Introduction

Bacterial diseases pose a serious threat to agricultural productivity worldwide, causing heavy yield losses in important crops such as tomato, banana, rice, citrus and kiwifruit. Conventional disease management practices rely largely on copper compounds and antibiotics. However, the continuous use of these chemicals has led to the development of resistant bacterial strains, environmental contamination and concerns for human health. In this context, scientists are increasingly exploring eco-friendly and sustainable alternatives. One such promising solution is the use of bacteriophages, commonly known as phages. Bacteriophages are naturally occurring viruses that specifically infect and kill bacteria. Because of their high specificity and self-replicating nature, bacteriophages are emerging as powerful biological control agents against bacterial plant pathogens. Their application offers a novel, environmentally safe strategy for plant disease management.

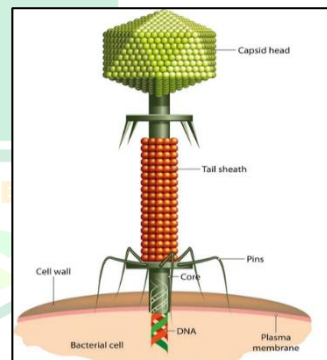
What are Bacteriophages?

The term bacteriophage is derived from Greek words meaning “bacteria eater.” Phages are viruses that infect only bacteria and are incapable of reproducing independently without a bacterial host. Once inside the bacterial cell, phages multiply rapidly and ultimately destroy the host bacterium through cell lysis. Their discovery dates back to the early 20th century, but renewed interest in phages has emerged due to increasing antibiotic resistance and the need for sustainable agriculture.

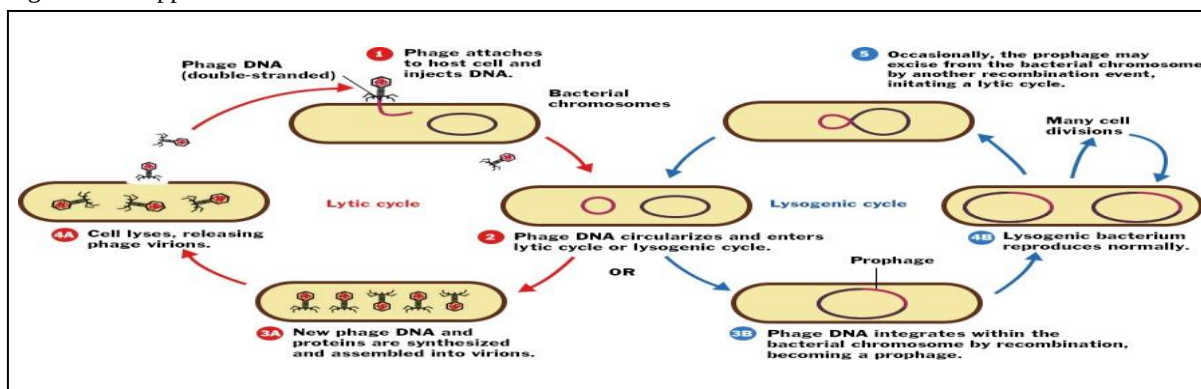
Structure and Life cycle of Bacteriophages

A typical bacteriophage consists of:

- An icosahedral protein head (capsid) that contains genetic material
- A tail structure with sheath, base plate, tail fibers and pins,
- Functionally, the tail and its components that help the phage attach to and inject its genome into the bacterial cell.



The bacteriophage life cycle is central to its effectiveness as a biological control agent. Phages follow either a lytic or lysogenic cycle, but only lytic phages are suitable for disease management. In lytic cycle, the phage first adsorbs on bacterial cell surface using its tail fibers and injects its genome into the host. The phage then takes control of the bacterial metabolic machinery, directing it to synthesize phage proteins and replicate phage nucleic acid. As the infection progresses, newly formed phage particles assemble within the bacterial cell. Finally, phage-encoded enzymes such as holins and endolysins degrade the bacterial cell wall, leading to cell lysis and release of progeny phages. These newly released phages can infect neighboring bacterial cells, resulting in rapid suppression of pathogen populations at the infection site. This self-amplifying property makes bacteriophages attractive for agricultural applications.



Why Bacteriophages are Ideal Biocontrol agents

For successful phage therapy in plant disease management, ideal bacteriophages should:

- Phage should be exclusively lytic
- Have a broad host range within the target pathogen species
- Multiply rapidly and persist under field conditions
- Suppress bacterial populations without completely eliminating beneficial microbes.

An important advantage is that phages can coexist with their bacterial hosts in soil ecosystems, maintaining a natural balance while reducing pathogen virulence.

Applications of Bacteriophages in Plant Disease Management

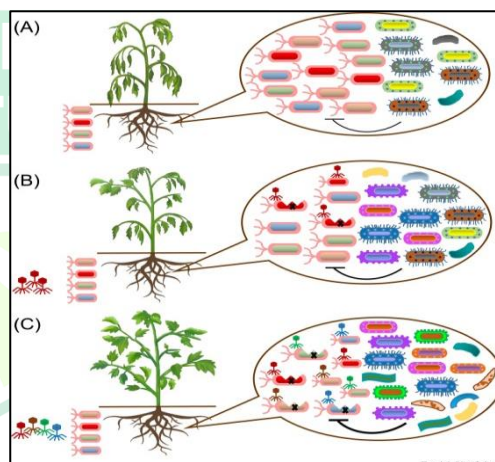
Bacteriophages have emerged as an innovative and sustainable tool for the management of bacterial plant diseases. Their ability to selectively infect and lyse bacterial pathogens, coupled with their safety to plants, humans and beneficial microorganisms, makes them attractive alternatives to conventional chemical bactericides. The applications of bacteriophages in plant disease management can be broadly categorized based on their mode of use, formulation and integration with other control strategies.

1. Application of Individual Lytic Bacteriophages

The direct application of individual lytic bacteriophages is one of the simplest and most widely studied approaches for controlling bacterial plant diseases. These phages are applied specifically against a target pathogen and rapidly multiply at the site of infection. In agricultural systems, individual bacteriophages can be applied through soil drenching, foliar spraying, seed treatment or plant tissue infiltration, depending on the disease and pathogen involved. Soil drenching is highly effective for soil-borne pathogens such as *Ralstonia solanacearum*, the causal agent of bacterial wilt in crops like tomato, potato and banana. When introduced into the rhizosphere, phages infect bacterial cells present in soil and root zones, reducing pathogen populations and suppressing disease development. Similarly, foliar application of phages has shown significant success in controlling leaf and fruit diseases caused by *Xanthomonas* and *Pseudomonas* species by directly targeting bacteria present on plant surfaces.

2. Use of Bacteriophage cocktails

One of the major limitations of using single bacteriophages is their narrow host range and the potential for bacteria to develop resistance. To overcome this limitation, researchers have developed bacteriophage cocktails, which consist of two or more lytic phages. Phage cocktails broaden the spectrum of activity and ensure effective control of diverse strains of same pathogen present under field conditions. Phage cocktails have been particularly successful in managing complex bacterial diseases such as bacterial wilt of banana, bacterial blight of rice and bacterial canker of kiwifruit. By simultaneously attacking bacteria through multiple receptors, phage cocktails significantly reduce the chances of resistance development and provide more consistent disease suppression. Field and greenhouse studies have demonstrated that phage mixtures are more reliable and durable than individual phage applications.



3. Integration of Bacteriophages with Chemical and Biological agents

Bacteriophages can be effectively integrated with other plant disease management strategies to enhance their efficacy. Combined applications of phages with plant defense activators, antibiotics, or reduced doses of chemical bactericides have shown synergistic effects in controlling bacterial diseases. This integrated approach allows for a reduction in chemical inputs while maintaining or improving disease control efficiency. For example, the combination of bacteriophages with acibenzolar-S-methyl (ASM) and SAR inducer, has been shown to significantly reduce disease severity in tomato bacterial spot and onion bacterial leaf blight. Such combinations not only improve disease suppression but also help to delay the development of bacterial resistance to antibiotics and copper compounds.

4. Application of Phage-Derived Antimicrobial proteins (Endolysins)

An advanced and promising application of bacteriophages in plant disease management involves the use of phage-derived proteins, particularly endolysins. Endolysins are enzymes produced by bacteriophages during the late stage of the lytic cycle that degrade the peptidoglycan layer of bacterial cell walls, leading to rapid cell lysis.

Endolysins show strong bactericidal activity against Gram-positive bacterial plant pathogens such as *Clavibacter michiganensis*. Exogenous application of purified endolysins has been shown to effectively suppress bacterial populations, while transgenic expression of endolysin genes in plants has conferred enhanced resistance to bacterial diseases. Although Gram-negative bacteria are protected by an outer membrane, recent strategies involving enzyme modification and combination with membrane-permeabilizing agents are expanding the applicability of endolysins in plant disease control.

Target diseases and pathogens	Bacteriophages	Hosts	Treatment methods	Test conditions	Reduction of disease incidence, %	Reference
Bacterial wilt: <i>Ralstonia solanacearum</i>	Single (RsPod1EGY)	Tomato	Soil drench	Greenhouse	100	Elhalag <i>et al.</i> , 2018
	Cocktail (NJ-P3, NB-P21, NC-P34, NN-P42)	Tomato	Soil drench	Greenhouse	80	Wang <i>et al.</i> , 2019
				Field	80	
	Cocktail (M5, M8)	Banana	Soil treatment	Greenhouse	100	Ramírez <i>et al.</i> , 2020
Bacterial blight: <i>Xanthomonas oryzae</i> pv. <i>oryzae</i>	Cocktail (P4L, P43M, P23M1)	Rice	Spray	Field	50.8	Chae <i>et al.</i> , 2014
Black rot: <i>X. campestris</i> pv. <i>Campestris</i>	Single (XcpSFC211)	Broccoli	Spray	Greenhouse	60	Nagai <i>et al.</i> , 2017
Soft rot: <i>Pectobacterium carotovorum</i>	Cocktail (φMA11, 12, 13, 14)	Onion	Immersion and spray	Field	2.5-15	Zaczek-Moczydlowska <i>et al.</i> , 2020

Challenges in Field application

Despite their advantages, phage therapy faces certain challenges:

- Reduced persistence in soil and phyllosphere due to UV radiation, temperature and pH fluctuations
- Adsorption to soil particles and biofilms
- Development of phage resistance in bacteria
- Limited availability of commercial phage-based products.

Addressing these challenges requires improved formulations, UV protectants and standardized protocols for phage selection.

Conclusion

Bacteriophages represent a highly promising, eco-friendly alternative to chemical bactericides for managing bacterial plant diseases. Their specificity, safety, compatibility with other control methods, and ability to target resistant bacterial strains make them ideal tools for sustainable agriculture. Although their practical use is still limited, increasing research evidence strongly supports their potential to reduce dependence on antibiotics and copper-based chemicals. With further field validation, improved formulations and regulatory support, bacteriophage-based disease management can play a crucial role in the future of plant protection and sustainable crop production.

Nanotechnology for Diagnosis and Management of Plant Diseases



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Introduction

Plant diseases pose a serious threat to global agricultural productivity and food security, causing significant yield and economic losses. Conventional disease diagnosis and management practices largely depend on visual symptom observation and extensive use of chemical pesticides, which are often inefficient, environmentally unsafe and increasingly challenged by pathogen resistance. These limitations highlight the need for innovative, precise and sustainable approaches for effective plant disease management.

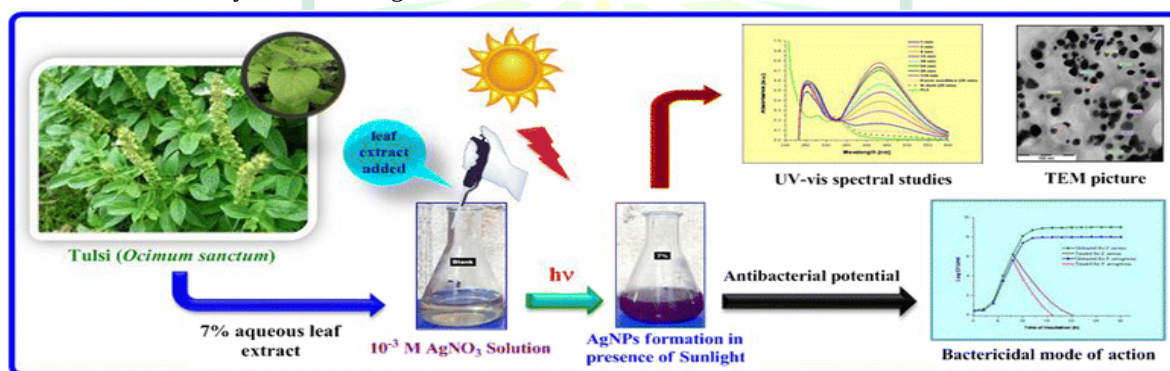
Nanotechnology, involving the manipulation of materials at the nanoscale (1–100 nm), has emerged as a powerful tool in plant pathology due to the unique physicochemical properties of nanomaterials, including high surface area, enhanced reactivity and altered optical and magnetic behavior. These properties enable the development of highly sensitive diagnostic tools and advanced disease control strategies. In plant disease diagnosis, nanotechnology enables rapid and accurate detection of pathogens through nano-biosensors and nanoparticle-based assays, allowing early intervention and reduced crop losses. For disease management, nano-formulated pesticides, metal and metal oxide nanoparticles and nano-carrier systems improve the efficacy, stability and targeted delivery of antimicrobial agents while minimizing chemical dosage and environmental impact. Furthermore, green synthesis of nanoparticles supports environmentally sustainable plant protection. Overall, nanotechnology provides a next-generation platform for precise diagnosis and efficient management of plant diseases, offering promising solutions for sustainable agriculture.

Biological synthesis of Nanoparticles

It is the method of producing nanoparticles using living systems such as plants, bacteria and fungi, which act as natural reducing and stabilizing agents.

- Metal ions are reduced into nano-sized particles by biomolecules (proteins, enzymes, flavonoids).
- Biological agents act as capping agents, preventing aggregation and stabilizing nanoparticles.

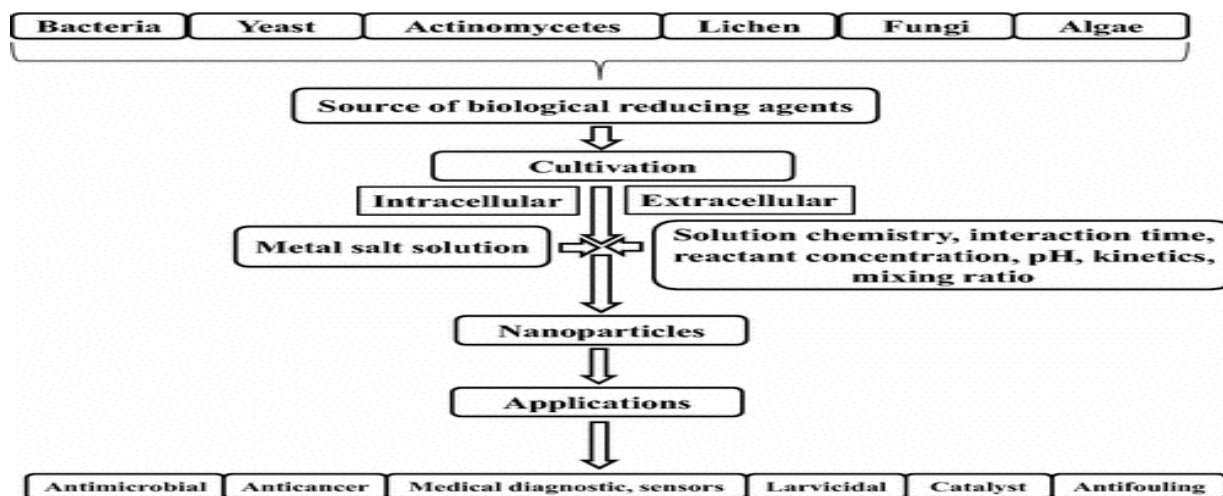
1. Plant-Mediated Synthesis: Using leaf, root, seed, flower or fruit extracts



Examples of Plant-Mediated of Nanoparticles:

Nanoparticle (NPs)	Plant source	Size (nm)	Application	Reference
Silver NPs	<i>Azadirachta indica</i> (Neem)	10–50	Antifungal and antibacterial activity against plant pathogens	Rai <i>et al.</i> , 2012
Copper NPs	<i>Coriandrum sativum</i>	40–80	Fungicidal activity and disease management	Jo <i>et al.</i> , 2009

2. Bacterial and Fungal mediated Synthesis of Nanoparticles:



Examples of Bacterial-Mediated of Nanoparticles:

Nanoparticle (NPs)	Plant source	Size (nm)	Application	Reference
Silver NPs	<i>Pseudomonas aeruginosa</i>	10–30	Antibacterial and antifungal activity	Klaus <i>et al.</i> , 1999
Gold NPs	<i>Bacillus subtilis</i>	15–45	Diagnostic probes and antimicrobial action	Kalimuthu <i>et al.</i> , 2008

Examples of Fungal-Mediated of Nanoparticles:

Nanoparticle (NPs)	Plant source	Size (nm)	Application	Reference
Silver NPs	<i>Trichoderma viride</i>	10–40	Biocontrol and plant disease management	Elamawi <i>et al.</i> , 2018
Gold NPs	<i>Verticillium spp.</i>	20–100	Nano-diagnostics and pathogen inhibition	Mukherjee <i>et al.</i> , 2002

Nanotechnology-Based Detection of Plant Diseases

Early and accurate detection of plant diseases is a critical challenge in effective disease management, as most disorders are identified only after symptom development, when control becomes difficult. Conventional diagnostic methods are time-consuming, laboratory-dependent and impractical for large field-scale monitoring. Nanotechnology offers promising solutions through nano-biosensors capable of rapid, real-time and highly specific detection of viral, bacterial and fungal pathogens directly in the field. These portable systems require minimal sample preparation and enable site-specific disease surveillance, reducing unnecessary pesticide applications and environmental risks. Advances in nanofabrication also improved understanding of pathogen–host interactions, particularly fungal surface recognition and infection processes. In viral diseases, nano-based diagnostic tools enable detection of specific viral strains and infection stages before symptom appearance. Such early-stage diagnosis supports timely and targeted disease management strategies. Therefore, nanotechnology-based detection systems represent a powerful approach for precision plant disease diagnosis and sustainable crop protection.

Nanoparticles in Plant Disease Management:

Silver Nanoparticles (AgNPs): They are most widely studied nanomaterials for plant disease management due to their strong and broad-spectrum antimicrobial activity. They are effective against a wide range of fungal, bacterial and viral plant pathogens. AgNPs inhibit pathogens by disrupting cell membranes, denaturing proteins, generating reactive oxygen species (ROS) and interfering with DNA replication. Their **multi-target mode of action** reduces the risk of resistance development. AgNPs successfully used in seed treatment, foliar application and post-harvest disease control, offering an eco-friendly alternative to conventional chemical fungicides when used at low concentrations.

Zinc Nanoparticles (ZnNPs): Particularly zinc oxide nanoparticles, play important role in plant disease management due to their antimicrobial and micronutrient properties. ZnNPs suppress plant pathogens by damaging cell membranes, inducing oxidative stress and inhibiting enzyme activity. In addition to disease control, zinc nanoparticles improve plant growth, enhance enzyme function and strengthen plant defense mechanisms. Their dual role as a nutrient and antimicrobial agent makes them highly valuable in sustainable agriculture. ZnNPs are effective against fungal and bacterial diseases and are commonly used in nano-formulations for controlled release and reduced toxicity.

Copper Nanoparticles (CuNPs): Exhibit strong fungicidal and bactericidal properties and are considered an advanced form of traditional copper-based fungicides. CuNPs act by disrupting pathogen cell walls, inactivating enzymes and generating ROS. Due to their nanoscale size, copper nanoparticles are more effective at lower doses compared to conventional copper compounds, thereby reducing environmental accumulation and phytotoxicity. They are particularly effective against fungal pathogens causing leaf spots, blights and wilts. Copper nanoparticles provide enhanced disease control with reduced chemical load on the environment.

Silica Nanoparticles (SiNPs): play a unique role in PDM by strengthening plant defense rather than directly killing pathogens. SiNPs enhance mechanical strength of cell walls, form physical barriers against pathogen entry and stimulate the plant's natural defense responses. They also induce the production of defense-related enzymes and phenolic compounds, increasing resistance to fungal and bacterial infections. Silica nanoparticles improve plant tolerance to both biotic and abiotic stresses and are widely used as plant defense enhancers in integrated disease management.

Advantages	Limitations
➤ Improved targeted action on pathogens ➤ Reduced environmental toxicity ➤ Helps plants tolerate biotic and abiotic stresses ➤ Early and rapid disease detection ➤ Effective against chemical-resistant pathogens ➤ Restoration of degraded soil and land ➤ Minimizes post-harvest losses	➤ Health issues like could be inhaled, swallowed, absorbed through skin and interfere with regulatory mechanism of protein and enzymes ➤ Environmental issues like accumulation in soil, water, plants etc. ➤ Excess uses lead to disturbing physiology of plants

Conclusion

Nanotechnology offers a transformative and sustainable approach for the diagnosis and management of plant diseases by overcoming the limitations of conventional methods. Nano-based diagnostic tools enable early, rapid and precise detection of pathogens, supporting timely and targeted interventions. The use of biologically synthesized and metal-based nanoparticles enhances antimicrobial efficacy while reducing chemical load and environmental toxicity. Despite concerns related to biosafety and environmental accumulation, careful regulation, optimized dosages and green synthesis can mitigate associated risks. Therefore, nanotechnology represents a promising next-generation strategy for precise PDM and sustainable agricultural productivity.

Emerging Sequencing Platforms: Shaping the Future of Plant Pathology



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Introduction

Plant diseases continue to pose serious challenges to global agriculture by reducing crop yield, quality and farmers' income. Early, accurate and reliable detection of plant pathogens is essential for effective disease management and sustainable crop production. Conventional diagnostic methods, such as symptom-based identification, culturing and serological assays, are often time-consuming and limited in their ability to detect latent, mixed or emerging infections. In recent years, sequencing technologies have emerged as powerful tools in plant pathology, revolutionizing pathogen detection, identification and characterization. Emerging sequencing platforms are now shaping the future of plant pathology by enabling rapid, precise and comprehensive disease diagnostics. Furthermore, advances in high-throughput and real-time sequencing have made it possible to detect plant pathogens directly from infected tissues without prior isolation or culturing. These technologies provide deeper insights into pathogen diversity, evolution and host pathogen interactions at the molecular level. As sequencing becomes faster and more affordable, it is expected to play a central role in early disease surveillance and precision plant pathology.

Sequencing in Plant Pathology?

Sequencing refers to the determination of the precise order of nucleotides (DNA or RNA) in a genetic material. In plant pathology, sequencing is used to identify and study plant pathogens such as fungi, bacteria, viruses, viroids and nematodes at the molecular level. Unlike traditional diagnostic tools that target specific pathogens, sequencing-based approaches provide an unbiased and holistic view of all organisms present in a sample. This makes sequencing especially valuable for detecting unknown, emerging and complex pathogen populations.

Types of Sequencing Technologies

1. First-Generation Sequencing (Sanger Sequencing)

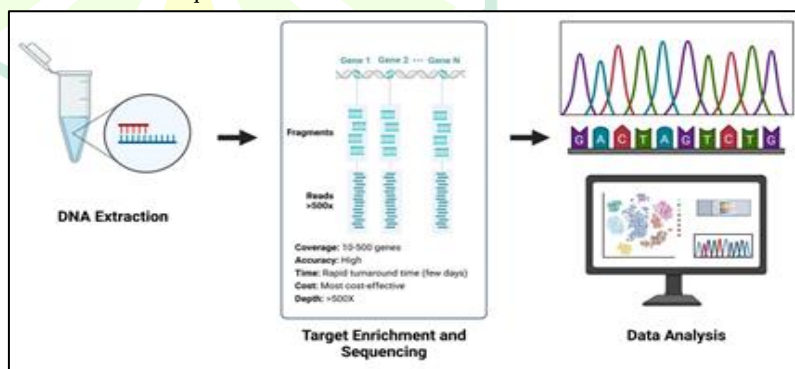
First-generation sequencing, also known as Sanger sequencing, was developed in 1977 and is based on the chain termination method. In this technique, DNA polymerase incorporates normal nucleotides along with special dideoxynucleotides (ddNTPs) that terminate DNA chain elongation. The resulting DNA fragments of different lengths are separated and read to determine the DNA sequence.

Key Features

- High accuracy
- Low throughput
- Suitable for short DNA fragments (up to ~1000 bp)

Applications

- Confirmation of PCR products
- Identification of known pathogens
- Gene sequencing and mutation validation



2. Second-Generation Sequencing (Next-Generation Sequencing – NGS)

Second-generation sequencing, commonly called Next-Generation Sequencing (NGS), allows massively parallel sequencing of millions of DNA fragments simultaneously. DNA is fragmented, adapters are added and fragments are sequenced in parallel on a solid surface. This results in rapid and high-throughput data generation.

Key Features

- Very high throughput
- Faster and cheaper per base than Sanger sequencing
- Short read lengths (50–300 bp)

Example Platforms:

Illumina Sequencing: These platforms use sequencing-by-synthesis with fluorescently labeled nucleotides to generate highly accurate, high-throughput short reads. They are widely used for whole-genome, transcriptome and metagenomic studies.

Ion Torrent Sequencing: Ion Torrent detects hydrogen ions released during DNA synthesis instead of fluorescence, enabling fast and cost-effective sequencing. It is mainly used for targeted sequencing and microbial genome analysis.

SOLiD Sequencing: SOLiD uses sequencing-by-ligation with two-base encoding, providing very high accuracy. It generates short reads and is mainly applied in precise variant detection studies.

Applications of NGS (Next Generation Sequencing)

Whole-Genome Sequencing: Whole-genome sequencing involves decoding the complete DNA sequence of a plant pathogen. It helps in accurate identification, strain differentiation and understanding of pathogen evolution and virulence factors. This approach supports epidemiological studies and tracking of disease outbreaks. It also aids in developing targeted disease management strategies.

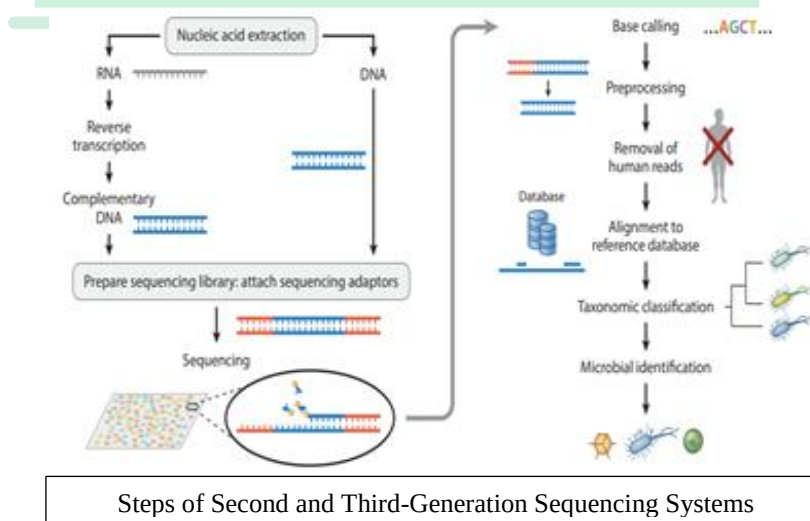
Transcriptome (RNA-Seq) Analysis: RNA-Seq analyzes the complete set of RNA transcripts expressed during plant-pathogen interactions. It provides insights into genes involved in pathogenicity, host defense and stress responses. RNA-Seq is especially useful for studying RNA viruses and host response mechanisms. This information helps in identifying key genes for resistance breeding.

Metagenomics: Metagenomics involves sequencing of total DNA or RNA directly from plant, soil or vector samples without culturing. It enables simultaneous detection of known, unknown and unculturable microorganisms. This approach is highly effective in diagnosing complex and mixed infections. Metagenomics improves early and accurate disease diagnosis.

Detection of Plant Pathogens (Viruses and Bacteria): Sequencing-based approaches allow rapid and precise detection of plant viruses and bacteria directly from infected tissues. They overcome limitations of conventional diagnostics by identifying pathogens at very low concentrations. These methods are highly sensitive and reduce false-negative results. Early detection supports timely disease management and prevents pathogen spread.

3. Third-Generation Sequencing (Long-Read Sequencing)

Third-generation sequencing sequences single DNA or RNA molecules directly without amplification. It generates long reads in real time, making it ideal for assembling complex genomes and detecting structural variations.



Steps of Second and Third-Generation Sequencing Systems

Key Features

- Long read lengths (up to kb or Mb)
- Real-time sequencing
- Slightly lower accuracy

Applications

- Complete genome assembly
- Detection of structural variants
- Identification of novel plant viruses

Feature	First GS	Second GS (NGS)	Third GS
Throughput	Low	Very high	Moderate
Read length	Long (~1000 bp)	Short (50–300 bp)	Very long (kb or Mb)
Speed	Slow	Fast	Real-time
Accuracy	Very high	High	Moderate–High
Cost per base	High	Low	Moderate
Field use	No	No	Yes (portable)

Conclusion

Emerging sequencing technologies have transformed plant pathology by providing powerful tools for accurate, rapid and comprehensive disease detection. Approaches such as whole-genome sequencing, transcriptome (RNA-Seq) analysis and metagenomics enable in-depth understanding of plant pathogens, their interactions with hosts and their evolutionary dynamics. These sequencing-based methods allow early detection of viruses, bacteria and other pathogens, even in complex or mixed infections, where conventional diagnostics often fail. With continuous advancements, sequencing platforms will play a crucial role in shaping the future of plant disease surveillance, management and sustainable crop protection.

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Wilt Diseases in Plants: An Overview

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Introduction

Wilt diseases constitute a major constraint to global crop production and food security. The term “wilt” refers to a physiological condition in which plant tissues lose turgidity due to impaired water uptake or translocation, leading to drooping and collapse of leaves and stems. Although wilting is a common symptom, it represents the outcome of diverse underlying causes both abiotic and biotic. Wilt diseases are particularly challenging to manage because most causal agents are soil-borne, possess long-term survival structures and exhibit wide host ranges. Crops such as tomato, potato, banana, cotton, chickpea, pigeon pea, brinjal and several ornamentals suffer heavy losses due to wilt diseases. In many cases, yield losses range from 30 to 80% and under favorable conditions, total crop failure may occur. The persistence of wilt pathogens in soil, combined with climate variability and intensive mono-cropping, has increased the incidence and severity of wilt diseases worldwide. Understanding the nature, classification and mechanisms of wilting is therefore essential for accurate diagnosis and effective disease management.

I. Wilt diseases

Wilt diseases are broadly classified into physiological wilt and pathological wilts. Pathological wilts include fungal, bacterial and nematode-induced wilts.



Wilt Type	Causal Agent	Nature	Vascular Discoloration	Reversibility
Physiological	Abiotic factors	Non-infectious	Absent	Often reversible
Fungal	<i>Fusarium</i> , <i>Verticillium</i>	Infectious	Present	Irreversible
Bacterial	<i>Ralstonia solanacearum</i>	Infectious	Present	Irreversible
Nematode	<i>Meloidogyne</i> spp.	Infectious	Absent/Indirect	Partially reversible

Physiological wilt

Physiological wilt is caused by drought, salinity, high temperature, waterlogging or nutrient imbalance. Water loss exceeds water uptake leading to temporary or permanent wilting. Plants often recover when favorable conditions return.

Fungal wilt

Fungal wilts are among the most widespread and economically important wilt diseases. These are caused by soil-borne fungi that invade plant roots and colonize the vascular system.

Fusarium wilt:

Fusarium oxysporum is a species complex comprising numerous formae speciales, each adapted to specific host plants. Important examples include *F. oxysporum* f. sp. *lycopersici* (tomato), f. sp. *cubense* (banana), f. sp. *vasinfectum* (cotton), and f. sp. *ciceris* (chickpea). Initial symptoms include yellowing of lower leaves, followed by wilting, defoliation, stunting and plant death. A characteristic diagnostic feature is brown discoloration of vascular tissues when stems are cut longitudinally. The pathogen survives in soil and plant debris as chlamydospores for many years. Infection is favored by warm soil temperatures, continuous cropping and poor drainage.

Verticillium wilt:

Verticillium wilt is caused by *Verticillium dahliae* and *V. albo-atrum* and affects crops such as potato, cotton, sunflower, and woody perennials. Symptoms include unilateral wilting, chlorosis, stunting and vascular browning. The pathogen survives as microsclerotia in soil and infects plants through roots under cool to moderate temperatures.

Pathological wilt	Physiological wilt
Loss of turgidity and dropping of plant parts due to infection by microbes resulting in blockage of water transport or toxicity is known as pathological wilt.	Loss of turgidity and dropping of plant parts due to insufficient water in plant body is known as physiological wilt.
It is a type of soil borne pathogenic disease.	It is a physiological imbalance.
Pathogens like fungi, bacteria, etc. can be isolated from diseased samples.	No pathogens are found in disease samples.
Original healthy stages do not come again generally.	Original healthy stages may come again if proper measures taken.
In case of bacterial wilt, ooze test can be performed.	No oozing can be seen

Bacterial wilt

Bacterial wilt is caused by *Ralstonia solanacearum*, a highly aggressive soil and water-borne vascular pathogen with a wide host range, particularly among solanaceous crops. Sudden wilting of leaves without yellowing, rapid plant collapse and brown discoloration of vascular tissues are typical. Bacterial streaming from cut stems placed in water is a key diagnostic feature.

Nematode-Induced wilt

Nematode wilts are primarily associated with root-knot nematodes (*Meloidogyne* spp.) and lesion nematodes (*Pratylenchus* spp.). Symptoms include gradual wilting, stunting, chlorosis and poor root systems with galls or lesions. Nematode feeding damages root tissues, reduces water and nutrient uptake and predisposes plants to secondary infections by fungi and bacteria.

Pathogen	Primary Symptoms	Root Damage	Vascular Browning
<i>Fusarium</i> spp.	Yellowing, wilting	Moderate	Yes
<i>Verticillium</i> spp.	Unilateral wilt	Low	Yes
<i>Ralstonia solanacearum</i>	Sudden wilt	Low	Yes
<i>Meloidogyne</i> spp.	Gradual wilt	Severe	No

II. Mechanism of wilting

Physiological wilt: Wilting occurs when rate of transpiration exceeds the rate of water uptake by roots. This leads to loss of turgor pressure in parenchyma cells, causing leaves and stems to droop. Prolonged stress may result in permanent damage and plant death.

Pathological wilts:

- **Xylem blockage:** Fungal hyphae, spores, bacterial cells, gums and tyloses physically obstruct xylem vessels, preventing the upward movement of water. This disruption in water transport leads to loss of turgidity and wilting.
- **Toxin production:** Pathogens produce toxins that alter cell membrane permeability and disrupt normal physiological processes. These toxins impair water balance and accelerate wilting symptoms.
- **Enzymatic degradation:** Cell wall degrading enzymes break down structural components of roots and vascular tissues. This damage facilitates pathogen spread and interferes with water conduction.
- **Root dysfunction:** Pathogen invasion or nematode feeding damages root tissues, limiting water absorption from the soil. Reduced root efficiency directly contributes to plant water stress and wilting.
- **Host defense responses:** Plants respond by forming tyloses, gums, and gels within xylem vessels to restrict pathogen movement. While defensive, these responses also restrict water flow, thereby enhancing wilting.

III. Management of wilt diseases

Management of wilt diseases is challenging due to the soil-borne nature and long-term survival of most wilt pathogens. An integrated disease management (IDM) approach combining cultural practices, host resistance, biological control and chemical use is considered most effective.

Cultural management: Cultural practices form the first line of defense against wilt diseases by minimizing the survival and spread of soil-borne pathogens. Crop rotation with non-host crops reduces the build-up of wilt pathogens such as *Fusarium*, *Verticillium*, *Ralstonia* and nematodes in the soil. Use of disease-free seeds and planting material prevents the introduction of pathogens into new fields. Proper field sanitation, including removal and destruction of infected plant residues, helps lower inoculum levels. Soil solarization, balanced fertilization, proper drainage and avoidance of waterlogging further create unfavorable conditions for pathogen survival and infection, thereby reducing disease incidence.

Host resistance: The use of resistant or tolerant varieties is the most effective, economical, and environmentally safe approach for managing wilt diseases. Resistant cultivars restrict pathogen colonization and multiplication within plant tissues, thereby reducing yield losses without additional input costs. Host resistance has been successfully exploited against both fungal wilts (e.g., *Fusarium* and *Verticillium* wilts) and bacterial wilts (e.g., *Ralstonia solanacearum*). This strategy is particularly valuable for smallholder farming systems, as it provides season-long protection and fits well into sustainable agriculture and integrated disease management programs.

Biological management: Biological control involves the use of beneficial microorganisms to suppress wilt pathogens through mechanisms such as antibiosis, competition, mycoparasitism, and induced systemic resistance. Biocontrol agents like *Trichoderma* spp. are effective against fungal wilt pathogens by colonizing the rhizosphere and inhibiting pathogen growth, while *Pseudomonas* spp. and *Bacillus* spp. reduce both fungal and bacterial wilt incidence by producing antibiotics and siderophores. In addition, these microbes enhance plant growth and soil health, making biological management an eco-friendly and sustainable component of wilt disease management.

Chemical management: Chemical control is generally considered a supportive measure in wilt disease management due to the soil-borne nature of pathogens, high costs, environmental concerns, and the risk of resistance development. Fungicides, bactericides, and nematicides may provide temporary reduction of pathogen populations, particularly when used as seed treatment, soil drenching, or nursery treatment. However, their effectiveness in field conditions is often limited, and indiscriminate use can negatively affect beneficial soil microorganisms. Therefore, chemical methods are best used judiciously and in combination with cultural, biological, and host resistance strategies under an integrated disease management framework.

Strategy	Approach	Target Wilt Type	Remarks
Cultural	Crop rotation	All	Reduces inoculum
Host resistance	Resistant varieties	Fungal/Bacterial	Most effective
Biological	<i>Trichoderma</i> , <i>Pseudomonas</i>	Fungal/Nematode	Eco-friendly
Chemical	Fungicides/Nematicides	Specific	Limited use

Conclusion:

Wilt diseases constitute a major threat to agricultural productivity due to their complex etiology, soil-borne nature and persistent survival of causal agents and mechanisms. The mechanisms of wilting involve xylem blockage, toxin production, root damage and host defense responses that impair water transport. Both physiological and pathological wilts disrupt plant water relations, ultimately leading to severe yield losses. Integrated disease management is essential for reducing crop losses and ensuring sustainable agriculture.

Climate Resilient Horticulture for Sustainable Fruit and Vegetable Production



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Abstract

Climate change poses great challenges in horticultural production. It causes fluctuations in the growth, yield, and even the quality of fruits, vegetables, and ornamental crops. Climate Resilient Horticulture involves sustainable horticultural practices that enhance productivity, mitigate risks, and reduce greenhouse gas emissions. In this way, the productivity can be maintained even with the changing weather patterns. Such steps contribute to lessening the risks arising from extreme weather situations, stabilizing yields, and making sure of sustainable farmer incomes while at the same time conserving resources. Facilitating training, technology dissemination, research, and well-organized policy and institutional support, in fact, fuel adoption and impact even more. Therefore, resilience building is a pre-requisite for sustainable, productive, and climate-smart horticulture in a changing world.

Introduction

Climate change refers to the changes in the Earth's average weather patterns such as temperature, rainfall, and humidity that persist for many years or decades. In the last one hundred years, the average surface temperature of the Earth has gone up by about 0.74⁰ C (Shah *et al.*, 2024). As a result, climate change is being considered as a primary source of various risks that range from the level of a single individual to the whole planet, as it is the main factor that exacerbates numerous other risks. The changing climate also has a very strong effect on the nature of the horticultural cropping system. The worldwide climate change is altering the production of fruits, vegetables, and ornamental crops in every region. Higher average seasonal temperatures, unexpected precipitation, and the increasing frequency of extreme weather situations that affect all horticultural growing systems are the main causes of these changes that have a significant impact on the crop growth, flowering, pest and disease cycle patterns, as well as, the final yield and quality. Farmers, due to the increased effects, have to change their farming methods to produce enough food and at the same time, maintain their living in the climate that is still changing. The IPCC report indicates that developing countries will require 127 billion US dollars per year by 2030 and 295 billion US dollars per year by 2050 for climate change adaptation (Shah *et al.*, 2024).

What is Climate Resilient Horticulture

Climate resilient horticulture is an approach to withstand the adverse impacts of climate on horticultural crops such as fruits, vegetables and ornamental crops and to ensure their sustainable production through practices and technologies such as crop diversification, better soil management, water management, use of climate suitable crops and varieties, genetically modified crops to better suit the particular climate, use of controlled environments etc. The process entails the amalgamation of cutting-edge technology, eco-friendly farming methods, and flexible approaches to maximize resource efficiency, reduce ecological footprints, and guarantee the sustained prosperity of horticulture production networks (Jain *et al.*, 2024). Climate resilient horticulture helps in mitigating the risks from extreme weather events, enhances sustainability and hence ensures food security.

Major climate challenges in Horticulture

Horticultural crops are highly sensitive to climatic variations, hence make them a vulnerable object to climate change. Some of the weather events affecting horticultural crops include:

- **Temperature stress:** Increased temperature disturbs respiration and photosynthesis and reduces the transfer of food materials to the harvestable parts of the plant, leading to poor yield and quality. Low temperatures would lead to freezing, chilling injury, etc. For instance, a heat wave in North India reduced tomato and onion yields by 15-20% in 2022, thus hiking their prices in the market (Indian Meteorological Department, 2023).

- **Erratic rainfall:** Erratic rainfall during the development and harvesting stages of the horticultural crops greatly affects the quality of the produce. The fluctuations in the moisture also leads to many disease and pests outbreaks which ultimately affects the quality and quantity of the crops. The Maharashtra grape industry suffered a ₹700 crore loss in 2021 due to excess pre-harvest rainfall that led to fungal infections (National Horticulture Board, 2023).
- **Water Stress:** Low rainfall and high evapotranspiration could lead to water stress during the critical stages of the crops, thus affecting their growth and development. In fruit crops, water stress often causes shedding fruits; the “June Drop” of apples and citrus are the best examples (TNAU Agritech Portal, n.d.).
- **Extreme weather events:** Hailstorms, cyclones, floods damages the horticultural crops including water erosion affecting the quality of the soil which serves as the growing base for all the crops, thus deteriorating the quality and yield of the horticultural crops.

Climate-Resilient Practices in Horticulture

- **Use of heat resistant and drought tolerant varieties:** Stress-tolerant cultivars sustain crop performance under high temperature and low moisture conditions, thereby minimizing yield reduction during climatic extremes. Examples include Solar Fire (tomato) and Tasty Green (cucumber) for heat tolerance, public sector tomato varieties such as Arka Rakshak and Arka Samrat from ICAR-IIHR, and drought-adapted grape clones of Thompson Seedless recommended for dry regions.
- **Use of salt tolerant varieties:** Growing salinity-tolerant cultivars helps reduce crop losses in salt-affected soils and irrigation water under changing climate conditions. Public sector varieties such as Pusa Sadabahar (tomato), COHB-1 (bhendi) from TNAU, and salt-tolerant rootstocks of citrus and guava recommended by ICAR institutes are suitable for saline regions.
- **Water management strategies:** Climate resilient horticulture heavily relies on water management during periods of excess as well as stress, thus making water management a very important part of it. Micro-irrigation practices such as drip irrigation ensures water availability to crops by directly providing water into the root zone, thus ensuring proper availability of water to crops as per their needs in addition to reducing loss from evaporation and runoff thereby helping during periods of water stress. Similarly practices such as rain water harvesting and soil moisture conservation practices helps in storing water when they are available in excess, thus helping when required during dry spells. Together these approaches reduces the vulnerability of horticultural crops during periods of stress.
- **Soil management strategies:** Mulching and conservation tillage are two of the most significant climate-resilient measures in horticulture as they extend the protection of crops against various climate hazards such as heat stress, heavy rainfall, flooding, and moisture loss. Through organic and inorganic mulches, farmers can reduce water loss from their fields, improve the soil temperature, enhance weed management, improve soil health, and drastically lower irrigation needs while increasing the quantity and quality of their crops. Benefits may also flow from the adoption of conservation tillage and the retention of permanent soil cover. By these methods, soil organic matter is increased, and erosion is reduced, the soil becomes more resistant to extreme weather events, and its carbon storage potential is increased due to the lowering of carbondioxide emissions. So, all these measures help farmers to obtain the necessary means to climate change adaptation through continued soil and water conservation, stable productivity levels, and the provision of sustainable horticultural production systems.
- **Precision Horticulture:** Precision horticulture is a key tool in climate-resilient horticulture. Through use of technologies such as remote sensing, drones, GIS, GPS, vegetation indices like NDVI, one can go for site specific nutrient management, timely application of water and pesticides according to the needs of the horticultural crops, enabling higher yields while minimizing environmental impacts. Such practices increase the efficiency of the agricultural system as a whole.
- **Controlled environment agriculture:** CEA can modify various factors like light, temperature, humidity, carbon dioxide etc. as per the requirements of the horticultural crops and thus increase the crop production. These are basically technology interventions which include utilization of polyhouse, greenhouse, shade nets

along with methods such as hydroponics, aeroponics, aquaponics etc. Greenhouse and shade nets gives protection from harsh weather conditions, while hydroponics, aquaponics and aeroponics make efficient use of water and nutrients, help in reduction of soil-borne diseases as well as serve as a suitable method for urban farming.

Benefits to Farmers

Climate-resilient horticulture can help farmers sustain stable yields during periods of unpredictable weather events. Farmers will have fewer risks of drought, flooding, pest pressures, and extreme heat or cold; therefore, climate-resilient horticulture is a way of safeguarding farmers crops and their livelihoods. Farmers would be promised a stable income through the use of such technologies as they would ensure better crop production. Last but not least, farmers, through climate-resilient horticultural practices, can harness natural resources (e. g. , water, nutrients, and energy) in a more efficient way, thus saving the production cost. Ultimately, these types of agricultural practices will help improve farm adaptability and resilience against climate change challenges.

Role of Extension and Research

Training, demonstrations and technology dissemination can go a long way helping farmers adopt climate-resilient horticultural practices more. By training the farmers more about these practices, farmers become more knowledgeable and well informed about these, allowing them to believe in such practices more. At the same time farmers if trained by extension agents using on-site demonstrations, the practices and technologies become easier to the farmers, boosting their confidence in using these technologies, leading to more adoption. Technology dissemination through extension agents, mobile apps, farmers fields schools ensures these practices reach quickly and effectively to the farmers. Further research in these fields would also lead to the development of suitable varieties and technologies that can help overcome the impending challenges. Together, these approaches accelerate the adoption of climate-resilient practices, improve productivity, reduce risks from climate variability, and enhance farmers' long-term livelihoods.

Stability analysis for identifying climate resilient varieties:

Stability analysis is very useful in climate resilient horticulture, especially under increasing climate variability.

What is stability analysis?

It helps to evaluate how consistently a genotype performs across different environments (locations, season, years or stress conditions). It focuses on

- Genotype $\times$ Environment interaction
- Yield, quality and stress tolerance consistency
- Adaptability under variable climate conditions

Key contribution to climate resilience:

1. Identification of stable genotypes:
2. Selection for wide or specific adaptation
3. Stress tolerance assessment
4. Efficient breeding for climate resilience

Common models of stability are:

1. Eberhart and Russell model
2. AMMI (Additive main effects and multiplicative interaction)
3. GGE biplot analysis
4. Regression and variance stability model

Policy and institutional support

Policy and institutional support are very essential for scaling up climate resilient horticultural systems. Proper incentives and financial assistance from the government side would help scaling up the technologies in the field of climate resilience more. Similarly better researches in the institutions is also a necessary tool as it would help take the studies further and hence help in knowing the needs and further developing the technologies according to these needs. Another dimension to these supports would be dissemination to the farmers through extension agents who would ultimately be the drivers of change. These three frameworks should work in hand in hand in

the field of climate-resilience horticulture to make the system more efficient, more sustainable and ultimately more resilient to climate change.

Conclusion

Resilience is the future of horticulture, as climate change continues to test the conventional farming systems. The climate-resistant measures implemented include deploying resistant crop varieties, precision horticulture, efficient water and soil management, and controlled environment agriculture, which have ensured farmers stable yields, lower risks, and kept their incomes sustainable. Moreover, such measures supported by training, research, technology dissemination, and a strong policy enable horticultural systems to be climate, resilient. Resilience building, in the end, is not simply an adaptation measure, rather it is the way to sustainable, productive, and climate, resilient horticulture in a world of changing climates.

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Precision Horticulture: Improving yield and quality through smart practices



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Abstract

Horticultural production is under pressure from increasing input prices, limited resources, and the demand for top quality produce. Precision horticulture is a solution to these problems by using technologies such as GIS, GPS, drones, sensors, and decision support systems, which allow site-specific management of water, nutrients and crop monitoring. The major advantages are the optimized input use, lesser costs, greater yield and quality, and less environmental impact. There are some problems when it comes to using the technology but the progress being made in Artificial Intelligence, IoT and automation will still help to make the horticulture sector better.

Introduction

Horticulture today faces a major challenge of producing high-quality vegetables, fruits, and flowers while coping with rising input costs such as water, fertilizers, labor, and energy. At the same time farmers also face the pressure of efficient resource management while reducing wastage. The traditional concept that “one-size-fits-all” has often proved to be inefficient, resulting in excess of inputs in one place while shortage in the other. In this context, precision horticulture is gaining immense importance. Through the use of various tools of precision horticulture like GIS, GPS, sensors, drones, data analytics etc., it allows farmers to manage the crops according to their needs at right time, right place and right dose. This kind of targeted management helps farmers optimize input use, reduce production costs while also ensuring better quality and yield of produce along with reducing detrimental effects to the environment. As the prices of inputs continue to rise along with demand of horticultural crops, precision horticulture serves as a practical solution for efficient resource management and long-term sustainability.

What is Precision Horticulture?

Precision horticulture is the application of technologies and principles to manage spatial and temporal variability associated with all aspects of horticultural production. It is a cutting-edge farming method, focusing on increasing crop yields and quality while minimizing environmental impact (Kumar *et al.*, 2024). In contrast to this, traditional farming embodies age-old agricultural practices that have been passed down through generations which rely heavily on manual labor, traditional planting and harvesting methods, where farmers work tirelessly in fields employing techniques like broadcasting, ploughing, visual monitoring, etc. The key difference observed is the shift from experience-based approach in traditional farming to targeted data informed approach in precision horticulture.

Key components of precision horticulture

Precision horticulture revolves around the site-specific management of crops through the use of modern technologies with the aim of optimizing inputs and raising productivity. One of its main components is precision irrigation and the main aspects of the precision irrigation involve use of soil moisture sensors, weather data, and micro-irrigation systems to apply the correct amount of water at the right time and place and, thus, to make water use more efficient. The site-specific or variable rate irrigation is considered as a necessary or essential component of precision irrigation. It has been reported that variable rate irrigation (VRI) could save 10 to 15% of water used in conventional irrigation practice (Yule *et al.*, 2008). Second important component include precision nutrient management which is also closely linked to soil and plant analysis, DRIS, SSNM, GIS mapping, and variable rate fertilizer application in order to provide nutrients in a way that corresponds to the demand of the crop and to lower the losses. Monitoring crops is also one of the components and it is realized through the use of remote sensing, drones, NDVI, and ground-based sensors for the continuous

assessment of crop growth, health, and stress conditions. The integration of these elements results in the availability of timely data-driven decisions that lead to the reduction of input costs, the increase of yield and quality, and the conservation of the environment in horticultural production.

Technologies supporting precision horticulture

Precision horticulture encompasses advanced technologies that help farmers know the variability within their fields, hence helping them with going forward with their cultivation practices with utmost precision. Technologies include:

- **Computer systems and software:** This forms the backbone of precision horticulture. Computers store, analyze and interpret large amounts of data related to soil, climate, and crops-both spatial and temporal. The Decision Support System for the farmers is highly helpful software for farmers which help them to go for site specific resource management, making computers a very important tool in precision horticulture.
- **Remote sensing:** Remote sensing employs satellites, aircraft, or drone, mounted sensors to gather data about the health, growth, and stress of crops as well as soil conditions by analyzing the light that is reflected and the heat that is radiated. One of the most popular vegetation indices is the NDVI which can be used to monitor crop vigor, nutrient status, water stress, and yield potential in horticultural crops.
- **Geographic Information System (GIS):** GIS is employed to generate, maintain, and analyze spatial maps representing soil properties, nutrient status, moisture, pest incidence, and crop performance. Incorporating several data layers together, GIS facilitates the identification of management zones and the production of prescription maps for the site-specific application of inputs.
- **Global Positioning System (GPS):** GPS allows farmers to correctly navigate to specific locations in the field, year after year to collect soil samples or monitor crop conditions. Location information is collected by GPS receivers for mapping roads, boundaries and irrigation systems.
- **Variable Rate Technology:** VR means that the appropriate rates of inputs will be applied leading either to reduced inputs, costs and environmental effects or improved yields and quality (Das *et al.*, 2018).
- **Soil and Crop Sensing Technologies:** Modern sensors are capable of measuring soil properties (such as texture, moisture, and electrical conductivity) and crop parameters (chlorophyll content, nitrogen status, water stress) instantly. Such devices lessen the need for slow laboratory analysis and encourage fast, location-specific decision-making.
- **Diagnosis and Recommendation Integrated System (DRIS) and Site-Specific Nutrient Management (SSNM):** DRIS and SSNM use information from the soil and the plants to find out which nutrients are missing. This helps farmers to figure out how much fertilizer and manures to use in order to fulfill the nutritional requirements of the crops. Using DRIS and SSNM makes sure that the plants get the nutrients they need which means the plants grow better and are healthier.
- **Yield Mapping Technology:** Yield mapping technology is also a very important technology of precision horticulture, providing farmers with valuable insights into the spatial variability of crop yields across their fields, enabling the creation of detailed yield maps (Rana *et al.*, 2023).

Some examples where precision farming aligns with horticulture crops:

1. Drip irrigation + Soil moisture sensors in tomato and pepper.

In this irrigation is only triggered when soil moisture drops below a set threshold and helps in water saving, reduced blossom end rots in tomatoes and uniform fruit size.

2. Variable rate fertilization (Fertigation) in leafy greens.

In this nutrients are applied based on crop growth stage and real time nutrient status. It helps in reduced nitrate accumulation in leaves and faster growth cycles.

3. Canopy and growth monitoring using remote sensing in onion and garlic.

It monitors plant vigor and identifies nutrient stress zones. This helps in early detection of nitrogen deficiency and yield increase upto 10-15 %.

4. Precision post-harvest quality monitoring.

It monitors temperature and humidity during storage and transport and help to reduce post-harvest losses and improved shelf life.

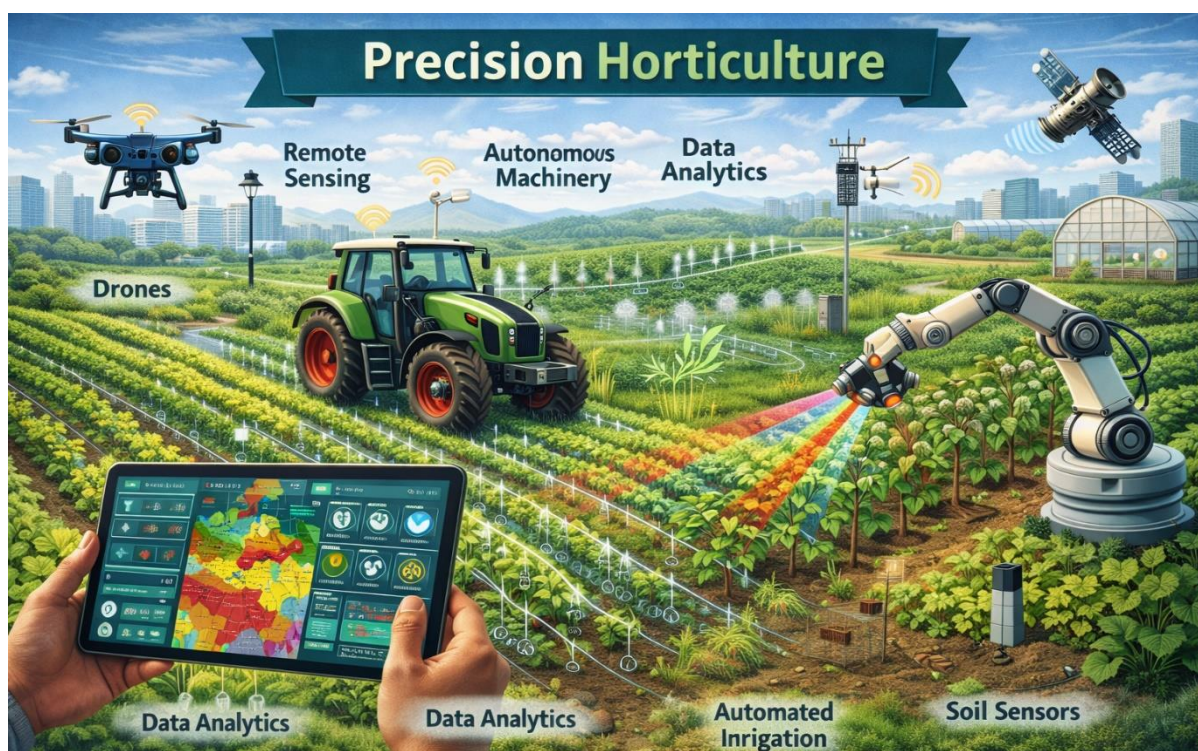


Fig. 1. Conceptual Illustration of Precision Horticulture (Source- AI Generated)

Benefits to Horticulture Growers

- Aids in site specific nutrient management according to crop needs saving inputs and time.
- Reduces inputs cost through resource optimization
- Improves water use efficiency
- Aids in early detection of pests and diseases, hence saving the crops
- Improves yield and quality of produce through optimum use of resources in right time, place and dose.
- Minimizes environmental pollution by reducing chemical overdose in soil.

Challenges in adoption

- High initial cost of investment of the required technologies
- Limited technical knowledge and skills among farmers
- High cost of maintenance and calibration of the equipments
- Limited awareness and confidence among farmers regarding the technology
- The management of the large database by the farmers is a tough job to be accomplished.
- Poor access to reliable soil and weather data

Future scope

The new technologies and sensor-based digital solutions for precision horticulture that has been developed quickly in recent years are creating a promising future for precision farming. Artificial intelligence, machine learning, IoT based sensors, drones, and high resolution remote sensing will be used more and more to monitor crops in real time and make decisions based on data. There will be more development of low-cost and easy to use tools for farmers and farmer groups or schemes of custom hiring which will help the adoption of small and fragmented farms. In a world which is facing water scarcity, labor shortages, and rising input costs, precision irrigation, fertigation, automation, and robotics will be the solution while big data analytics and cloud-based advisory platforms will make crop and resource management more efficient. In summary, precision farming will be a major contributor to climate-resilient horticulture aiding in better resource use efficiency and higher productivity and profitability in the future.

Conclusion

Precision horticulture represents a shift from conventional farming to data driven smart practices, enabling farmers to act according to the needs of the specific crops. These smart practices for smart farming help in optimization of resources and building a sustainable future in the field of horticulture. As technologies are becoming more efficient and farmer friendly, precision horticulture has the power to transform the scenario of today's horticulture, supporting both economic and environmental growth.

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Urban and Peri-Urban Horticulture for Nutrition and Livelihood Security



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Abstract

Rising urbanization and the increasing demand for food in cities have led to the necessity of new food production methods. Urban and peri-urban horticulture is a new concept involving methods like rooftop, balcony, terrace, and vertical gardening, which is an environment friendly way of cultivating horticultural crops in limited spaces in the cities. It contributes to nutritional security, income and employment generation, environmental sustainability and urban youth and women empowerment. Although there are challenges such as limited space, high costs and lack of awareness, support systems, training and awareness programs can help overcome them. Horticulture going beyond rural areas is a strong tool for its capacity to ensure food security, improve livelihoods and create greener urban environments.

Introduction

Urbanization is rapidly reshaping how people live, work and eat in today's world resulting in rapid surge in food demands within cities. According to an estimate, India's total population will be more than 1.5 billion, the largest in the world, with the urban population of around 600 million, by 2030 (Singh and Malhotra, 2013). It has been seen that there is a huge lot of rural people who have been migrating from rural to urban areas in search of better opportunities for their livelihood, it has created extra pressure on the food system to deliver fresh and healthier nutrient rich fruits, vegetables and other produces to them. This is because rapid industrialization in urban areas has led to a lack of agricultural land, making it difficult for people to adopt traditional methods of growing agricultural and horticultural crops. In this regard urban and peri-urban horticulture has emerged as a vital strategy to reduce the gap between demand and supply of horticultural products in the urban areas, as it provides ways for the people to go for growing their own crops in limited availability of land and other factors of production.

Concept of urban and peri-urban horticulture

The concept of urban and peri-urban horticulture is rising immensely with rise in the demand of fresh fruits and vegetables in the urban areas. Urban and peri-urban horticulture essentially means growing horticultural crops within cities and its surroundings through practices such as rooftop and balcony gardening, terrace farming, community gardens, small farms nearby cities, vertical farming in walls, container gardening and kitchen gardening. Urban and peri-urban horticulture has a long way to go as it serves as a means to fulfill the demand of fresh, nutritious food to the people living in the cities in an easier way. Urban horticulture also contributes to strengthening social sustainability and increasing ecological sustainability by transforming wastes, conserving natural resources, preventing soil erosion, and reducing pollution (Bon *et al.*, 2015). Not only this, urban and peri-urban horticulture also help in employment generation and can contribute to greener cities, thus also serving environmental benefits in this ever-changing climate. It also has climate resilience cropping to offer as some innovative practices like hydroponics, aeroponics, aquaponics, vertical gardening is done in environmentally controlled conditions which offer resistance to environmental extremities thus maintaining optimum production.

Crops suitable for urban horticulture

According to Bon *et al.* (2015) crops suitable for urban and peri-urban horticulture may include:

Vegetables: Amaranth, Beans, Beetroot, Bitter leaf, Broccoli, Cabbage, Cauliflower, Chinese cabbage, Chinese mustard, Cucumber, Eggplant, French bean, Garlic, Indian mustard, Leek, Lettuce, Mung bean, Okra, Onion, Palak, Pea, Potato, Squash, Sweet pea, Sweet pepper, Tomato etc.

Fruits: Banana, Melons, Orange, Papaya, Peach, Pineapple, Strawberry

Ornamental plants: Bougainvillea, Chrysanthemum, Kumquat, Rose

Benefits of urban horticulture

Urban horticulture has lots of benefits to offer. First of all, urban horticulture can enhance nutritional security by allowing residents to cultivate fresh produce of their own, thus reducing dependence on produce from distant places. It serves as a way of producing food to meet the demands of the constantly rising world population. This can also enhance employment opportunities by allowing urban people to get involved in farming jobs and hence acts as a source of income for such people. Thus, it can be said that it enhances income generation of the people involved with the horticulture sector. Urban and peri-urban horticulture also has environmental benefits to offer as it leads to the creation of greener cities, thus improving the urban scenery along with improving the air quality in such areas. It also helps in creating a calm scenario for the people residing in the busy cities, thereby helping them in relaxing and reducing stress levels. Thus, it can be said that urban and peri-urban horticulture proved to be very beneficial for people.

Role of urban youth and women

Urban youth and women play a very pivotal role in in urban horticulture. The youth bring innovation and entrepreneurship to the sector by adopting digital tools, modern technologies as well as some innovative ways of marketing, thus strengthening the horticultural value chain. The youth can create agribusiness opportunities thus improving income generation of the youth. The women through their involvement in cultivation, nursery management and processing of the produce also play a very important role in improving the supply chain. Women also by means of getting involved in self help groups earn a stable source of income by themselves. Together, their participation enhances productivity, generates income and employment, improves nutrition and food security, and empowers women socially and economically.



Fig. 1. Different Methods of Urban Horticulture (Source- AI Generated)

Challenges in urban horticulture

Urban horticultural opportunities get hindered by varieties of challenges which are as follows:

- Limited availability of land and growing space.
- High costs of inputs
- Competition for water with domestic and industrial uses.
- Improper waste management
- Some of the urban horticulture techniques need high cost of installation and technical expertise which sometimes can be a problem.
- Growing medium can sometimes get contaminated by construction wastes.
- Limited awareness among people.
- Less support from the government.
- Poor market linkages

Support systems and future scope

Urban horticulture can be improved with suitable support systems and has a bright future if adequate training and awareness are prioritized. If supported by government schemes, policies, NGOs and urban local bodies, the urban residents can get access to quality inputs, technical guidance, be aware of its benefits and also get financial assistance along with market linkages. Through training programs and campaigns people become more aware of the concepts about rooftop gardening, terrace farming, hydroponics, vertical farming etc. Given the rising urban food demand, climate issues, and the popularity of green spaces, urban horticulture is a viable solution with a strong future potential for creation of jobs, entrepreneurship, environment enrichment, and improvement of food and nutritional security.

Conclusion

Horticulture is no longer limited to rural boundaries; it has extended its reach beyond that. Through practices such as rooftop gardening, balcony gardening, vertical gardening, terrace farming etc. horticulture has transformed itself from large fields in villages to limited spaces in urban areas. These practices has increased food and nutritional security, encourages urban youth participation in farming activities, promotes nutrition gardens and enhances environmental sustainability in the urban areas. Urban horticulture thus is a tool for sustainability-both economic and environmental in the long run.

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Importance Scope and of Protected Cultivation of Fruit Crops



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Introduction:

Agribusiness and related sectors have a significant impact on the Indian economy. A few new biotic and abiotic stressors have emerged as an enormous issue following the Green Revolution. Protected cultivation reduces weed infestation and promotes efficient use of resources, such as water and fertilizer. It ensures a steady and reliable supply of fresh produce by enabling the production of plant crops throughout the year even at sluggish times. Additionally, it increases germination rates and disease resistance by promoting the growth of good planting material. Protected cultivation has become a fundamental aspect of modern agriculture, providing a number of benefits and addressing various challenges in crop production. The definition of protected cultivation for horticultural crops is examined in this essay. Growing crops in controlled environments such as greenhouses, polyhouses, and shade net houses that allow precise guidelines for aspects like temperature, humidity, and light is known as protected farming. This method is essential for protecting plants from unfavorable weather, pests, and diseases, which enhances yield efficiency and quality. However, there are drawbacks to protected cultivation adaption, such as the expensive initial capital costs, the need for professional staff, and maintenance requirements. Given the substantial resource investment, it is crucial to guarantee a stable market for the produce.

Importance of Protected Cultivation

Even while agriculture has always been the foundation of India's economy, our experience over the past 50 years shows a connection between agricultural practices and economic well-being. The agricultural growth trajectory suggests a combination of noteworthy successes and lost chances. New and efficient production technologies that can consistently raise the agricultural sector's productivity, profitability, and respectability are needed if India is to maintain its independence, ensure food security for the underprivileged, and export high-quality fruits and vegetables. One such field is protected cultivation technique, which is used sparingly in India but extensively in wealthy nations. Numerous farming patterns are made possible by the considerable variances in climate seen throughout the country's varied geography.

Climate extremes including floods, droughts, and other anomalies that frequently result in crop losses or damage that costs 'farmer's money are also experienced in India. Simultaneously, the demand for quality agricultural produce has increased over the last decade. This provides better opportunities for the Indian farmers to adopt protected cultivation technologies as per region and suitability of the crops. Greenhouses are being commercially used for production of exotic (non-native) and off-season vegetables, export-quality cut flowers and also for raising quality seedlings. Economic returns from the high value agricultural produce can be increased substantially when grown under greenhouse conditions. For the crops under protected environment, the use of chemical pesticides and insecticides can be kept minimal to avoid their residues on the crop produce. Greenhouses are mostly used as rain shelters, particularly in high rainfall areas of India such as North- eastern states and coastal regions

Objectives of Protected Cultivation:-

(i) Protection of plants from abiotic stress (physical or by non-living organism) such as temperature, excess/deficit water, hot and cold waves, and biotic factors such as pest and disease incidences, etc. Do you know? Greenhouse effect When short wave radiation from the Sun enters the greenhouse structure, it refracts through the surface and gets transformed into long wave radiations. These long wave radiations do not escape the greenhouse in entirety, thereby trapping the heat and thus, continually increase the temperature inside. This is known as the greenhouse effect. Thus, the enclosed space builds higher temperature

than the ambient environment. However, after sunset it starts losing stored heat through conduction, convection and radiation.

- (ii) Efficient water use with minimum weed infestation.
- (iii) Enhancing productivity per unit area.
- (iv) Minimising the use of pesticides in crop production.
- (v) Promotion of high value, quality horticultural produce.
- (vi) Propagation of planting material to improve germination percentage; healthy, uniform, disease free planting material and better hardening.
- (vii) Year-round and off-season production of flower, vegetable or fruit crops.
- (viii) Production of disease-free and genetically better transplants.

Depending on their ability to make investments and the availability of local markets, small and medium-sized farmers in India have begun growing flowers and vegetables under various modular covered structures. Greenhouse growing offers the greatest advantages of all the protected cultivation techniques. Floriculture crops like rose, gerbera, carnation, anthurium, lily, orchids, chrysanthemum, etc. and vegetable crops like tomato, yellow and red bell peppers (from the capsicum family), cucumber, green and exotic vegetables, etc. are among the main crops planted under protected structures.

Protected Cultivation: Scope

A. Cultivation in Problematic Agro-Climate: in India, most of the crude space is underneath hazardous circumstances like barren, uncultivated lands and deserts. Indeed, even a small part of this space brought under greenhouse cultivation could yield significant returns for the local inhabitants.

B. Greenhouse Enormous Urban Areas:

- The significant interest continues for ongoing vegetables and ornamentals round the year in gigantic urban areas.
- Interest in off-season and excessive-cost crops also exists in enormous urban areas. In this manner, greenhouse cultivation is elevated to satisfy the metropolitan necessities.

C. Export of Horticultural Produce:

- There are fair global demands for farming produce, mainly cut flowers
- Advancements in greenhouse cultivation of commodity export homeward crops are going to be of distinct facilitating towards trade advancement.

D. Greenhouse for Plant Propagation

- Greenhouse cultivation innovation is by and is currently a day's considered a suitable methodology for the raising of seedlings, cuttings and grafted plants.
- Greenhouse offices could build the ability and nature of assembling the stuff.

E. Greenhouse Technology for Biotechnology: Materials developed through the tissue culture area unit will be proliferated up to speed. Hydroponics is likewise expected to control environmental conditions for raising and developing plants. Greenhouse for The Cultivation of Endangered and Medicinal Plants: India has a great many energizing spices and endangered plant species like orchids that are known for huge-scope cultivation. The greenhouse could offer the appropriate style of environmental conditions for the intensive cultivation of those plants

Limitations of Protected Cultivation:

- Significant upfront infrastructure costs pose a hurdle in terms of initial investment.
- A lack of skilled labor and limited local replacements present challenges.
- Inadequate technical knowledge in cultivating crops within sheltered settings.
- Labour-intensive operations demanding sustained dedication.
- Requires meticulous oversight and continuous vigilant monitoring.
- Control of specific pests and soil-borne pathogens poses challenges.
- Overcoming obstacles related to repairs and maintenance.
- Necessitates a secure market guarantee due to substantial investment of resources, including time, effort, and finances.

Conclusion:

Environmental change is turning into an inexorably critical worldwide issue that can at this point not be disregarded. The basic reason is anthropogenic, i.e., impractical utilization of petroleum derivatives, backwoods debasement for industrialization, and quick urbanization with overpopulation. Protected cultivation involves a complex set of practices and technologies which require elaborate planning, fabrication, management and maintenance of quality production of horticultural crops to take advantage of season, demand and choice of market. It gives opportunities for the cultivation of horticultural crops in an entrepreneurial form for the up-markets in urban and semi-urban areas, besides empowering youth, and technology-led traditional ways of crop cultivation to such modern methods. There are various types of protected cultivation practices. Some of the commonly used practices are — forced ventilated greenhouse, naturally ventilated polyhouse, insect- proof net house, shade net house, plastic tunnel and mulching, raised beds, trellising and drip irrigation. These practices can be used independently or in combination, to provide favourable environment to save plants from harsh climate and extend the duration of cultivation or off-season crop production. Adoption of drip irrigation under raised beds (you will read about it in Unit 4) covered with mulch films not only eradicates weeds but also maintains moisture in the soil for a prolonged period by minimising evaporation losses.



Genetic Complexity: The Octoploid Challenge

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Genomic Prediction and Computational Breeding

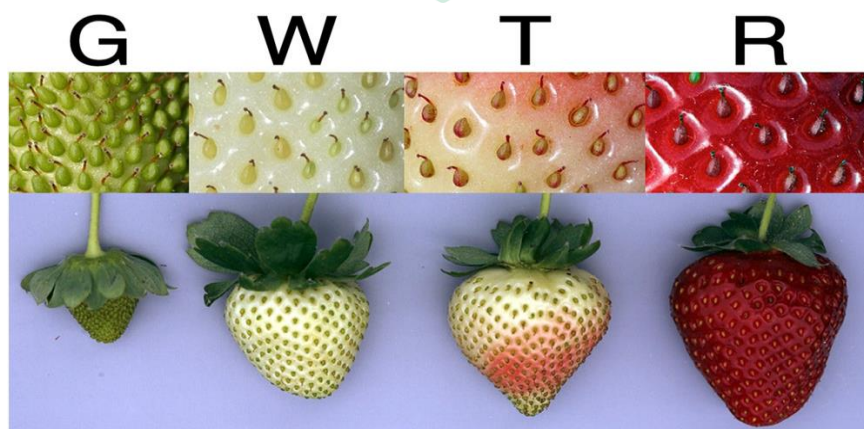
The integration of modern computational models is currently revolutionizing the process of selection for complex traits in polyploids such as strawberries. The intricate genetic interactions found in the octoploid strawberry genome, such as dominance and epistasis, are challenging for conventional linear models to handle.

Studies comparing deep learning models with conventional Bayesian linear models have shown that while linear models are extremely efficient for additive traits, deep learning models such as Convolutional Neural Networks (CNNs) are more accurate when non-additive genetic factors are important (Zingaretti et al., 2020).

The development of telomere-to-telomere phased genome assemblers, such as the recent high-quality assembly of the "Seolhyang" variety, which provides a comprehensive roadmap for the identification of resistance genes like the Mildew Locus O (MLO) gene for powdery mildew, further contributes to this computational advancement (Kim et al., 2025).

Cultivar Identification and Genetic Mapping

For breeding and production to be successful, germplasm identification must be precise. Molecular technologies have been developed in nations like the Philippines to combat the high rate of cultivar misidentification among farmers. Scientists found notable differences between the identities of plants as reported by farmers and their actual identities using single nucleotide polymorphism (SNP) markers from the anthocyanin reductase (ANR) gene (Ledesma et al., 2020).



Gene Expression atlas of fruit ripening and transcriptome

Effective strategies against harmful pathogens, particularly the *Colletotrichum* species complex, which causes anthracnose and bitter rot illnesses, must be developed in order to sustain strawberry farming. The similar traits and varying fungicide resistance of the species, including *C. acutatum* and *C. gloeosporioides*, make managing this "complex" difficult (Dowling et al., 2020). Current approaches center on integrated pest management (IPM), which includes the development of non-destructive detection techniques and the use of marker-assisted selection for resistance genes like *Rca2* (Dowling et al., 2020; ResearchGate, 2021).

Advancements in Functional Genomics and Gene Validation

The functional verification of genes in strawberries has been significantly enhanced by recent developments in transient expression technology. Researchers have refined *Agrobacterium*-mediated temporary expression in a variety of tissues, including fruits, leaves, and even roots, because steady genetic transformation in octoploid strawberries (*Fragaria × ananassa*) is a time-consuming and arduous operation (Jang et al., 2024).

The study of disease resistance proteins, like *RPW8.2*, which strengthens the defense system against powdery mildew when paired with external salicylic acid treatment, has been made possible by the application of CRISPR/Cas9 and reverse genetics methods (Jang et al., 2024).

Genetic Diversity and Marker-Assisted Selection

Numerous markers for fruit quality and disease resistance have been found through the examination of huge panels of genetic diversity. The 50K FanaSNP array has been utilized in a comprehensive study of a European-focused strawberry diversity panel to find markers and candidate genes for fruit quality attributes in a wide range of cultivars released from the 19th century to the present (Prohaska et al., 2024).

Genomic Architecture of Resistance and Polyploid Evolution

Understanding the polyploid nature of the strawberry genome is essential for managing pathological problems like anthracnose and *Phytophthora* crown rot disease. Studies on the genomic organization of the *RPC2* gene have revealed insights into the inheritance of resistance in the octoploid genome (Han et al., 2024).

Furthermore, the use of telomere-to-telomere (T2T) phased genome assemblies has made it possible to gain hitherto unheard-of insights into the subgenome evolution and domestication history of *Fragaria* species (Kim et al., 2025; Prohaska et al., 2024). In order to predict performance in complex traits using deep learning models, the precise location of Quantitative Trait Loci (QTL) and the identification of non-additive genetic effects like dominance and epistasis are made possible by the high-quality assemblies (Zingaretti et al., 2020; Kim et al., 2025).

Genomic Architecture and Evolutionary Diversity

High-quality genome assemblies and modern phylogenomics have shed light on the history of the domesticated strawberry (*Fragaria × ananassa*). Although nucleotide variety has decreased in some chromosomal locations under strong selection, the genetic resource is nonetheless diversified, according to recent research conducted on a European-focused diversity panel spanning 160 years of breeding (Prohaska et al., 2024).

Advancements in Genomic Prediction and Breeding Efficiency

Precision breeding currently focuses on sophisticated computational techniques that take into consideration the polygenic nature of fruit quality. Numerous research have demonstrated that while machine learning and deep learning models, like Convolutional Neural Networks (CNNs), are more accurate for traits impacted by dominance and epistasis, linear models are effective for additive traits (Zingaretti et al., 2020). More than 70 correlations have been effectively found by genome-wide association studies (GWAS) that are linked to important fruit quality characteristics as weight, firmness, and gloss (Prohaska et al., 2024).

Functional Gene Validation and Disease Management

Transient expression systems mediated by *agrobacterium*. These technologies enable the immediate validation of gene activities in leaves, fruits, and roots without having to wait for the long period needed for the generation of transgenic plants (Jang et al., 2024). For instance, the role of the *LRK10* gene in providing resistance to *Neopestalotiopsis* spp., a significant emerging pathogen, was confirmed using transient gene knockdown and overexpression techniques (Jang et al., 2024).

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