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Emerging Threat of Spider Mites in Climate-Changed Agriculture

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Abstract

It has long been known that spider mites, especially the invasive tomato red spider mite (Tetranychus evansi) and the two-spotted spider mite (Tetranychus urticae), are serious agricultural pests that cause large financial losses all over the world. However, the growing speed of climate change is transforming these controllable concerns into systemic agricultural vulnerabilities. The confluence of higher climatic variability, longer growing seasons, and rising global temperatures is examined in this paper. These conditions boost the possibility for mite reproduction while also jeopardizing plant defense mechanisms and undercutting conventional management methods. We examine the temperature-mediated suppression of jasmonic acid plant defense pathways, the thermal acceleration of mite development and fecundity, and the emerging trade-offs between pesticide resistance and heat tolerance that complicate chemical control, based on recent research published in prestigious entomological and plant science journals. Predictive modeling has shown that invasive species' optimal habitat has expanded geographically, indicating a general northward spread of mite concerns across several continents. Additionally, the decline in phytoseiid predatory mite performance under climate stress scenarios suggests that biological control methods need to be significantly revised. This study suggests adaptive integrated pest management systems including climate-informed monitoring, thermotolerant biocontrol agents, and regionally coordinated responses. As an indicator species, the spider mite signals the larger ecological changes that will characterize agricultural productivity in the upcoming decades. Rather of making little tweaks to current procedures, addressing this danger necessitates fundamental changes in pest control paradigms.

Keywords – Spider mites, climate change, integrated pest management, agriculture adaptation

I. Introduction

It has long been known that spider mites are economically significant agricultural pests, especially the invasive tomato red spider mite (*Tetranychus evansi*) and the two-spotted spider mite (*Tetranychus urticae*). But these controllable risks have become systemic agricultural vulnerabilities due to the quickening pace of climate change. According to current research, conditions that boost mite reproductive potential while simultaneously undermining traditional control methods are being created by warmer temperatures, longer growth seasons, and increased climatic variability. This convergence of elements reflects a fundamental shift in pest ecology rather than just an incremental challenge, necessitating new strategic responses from academics, politicians, and agricultural professionals. By penetrating plant cells and removing their contents, these microscopic arachnids which are hardly noticeable to the unaided eye cause harm that results in decreased photosynthetic ability, slowed development, and, in extreme situations, total crop failure. For decades, farmers and researchers have developed and refined management strategies chemical acaricides, biological control agents, cultural practices, and integrated pest management programs that have kept these pests substantially in check in most agricultural systems. Although epidemics have occasionally happened, they have usually been controllable under the current control frameworks. Another sign of climate change is longer growing seasons, which give spider mites more opportunity to complete many generations annually. Higher population densities and more cycles of reproduction result from longer warm weather. Crops that traditionally enjoyed a reprieve during cooler months now endure continuous strain. Drought circumstances, which are becoming more widespread in many agricultural locations, further complicate the situation by stressing plants and making them more prone to mite infestation.

There are significant ramifications. For farmers, this entails more crop losses, higher input costs, and greater unpredictability in production planning. It necessitates that researchers reevaluate models of pest ecology and create new control methods that are appropriate for a warming planet. Policymakers must give trade regulations,

agricultural adaptation, and support for research and extension services top priority. The instance of the spider mite is not unique. It is an indicator species, signifying the greater ecological processes ongoing in agricultural systems globally. The techniques established to manage this danger will provide a framework for controlling the cascade of climate-amplified pest concerns that will define the future of food production. The question is not whether agriculture will experience additional insect outbreaks in the future decades that much is certain. The question is whether the agricultural community can adjust rapidly enough to secure global food security.

This paper investigates the rising problem of spider mites in climate-changed agriculture, discusses the mechanisms driving their growth, evaluates the consequences for present management approaches, and offers strategic actions for agricultural professionals, researchers, and legislators.

II. The problem nobody saw coming

On a sweltering July afternoon, you are strolling through your field. Rain hasn't fallen in weeks, and the temperature has been close to 38°C for days. As you examine the underside of a leaf, you notice something: a slight bronzing that resembles a sunburn. You take a closer look. There is a smooth, fine webbing with tiny, scarcely perceptible particles crawling all over it. If you've been farming long enough, you are familiar with the emotion that ensues. Spider mites are those specks. And here's the bad news: they're growing worse. Both the tomato red spider mite (*Tetranychus evansi*) and the two-spotted spider mite (*Tetranychus urticae*) have long existed. However, they have a huge edge due to climate change. These pests are taking full advantage of the ideal conditions being created by warmer temperatures, longer growing seasons, and more frequent droughts.

III. Why Warmer Weather Means More Mites

Spider mites have a frigid heart. This implies that when temperatures rise, their metabolism, reproduction, and eating rates all accelerate. Simply said, it's biology. Mite strains were found to cause far greater harm at 32°C than at 25°C, according to research published in the Journal of Pest Science. At warmer temperatures, their ability to lay eggs increased dramatically. Mite populations go into overdrive when the temperature rises. Doubling times are reduced from roughly a week to a few days. Consider the implications for your operation. On a Tuesday, you could notice a few mites. You might have a full-blown infestation by Friday. Before you knew it was open, the window for intervention had already closed. However, things worsen.

Not only is climate change benefiting mites, but it is also impairing the natural defenses of your crops. A 2025 study in Plant, Cell & Environment demonstrated that warm temperatures decrease the plant's jasmonic acid pathway, which is one of its key defense mechanisms against herbivores. In basic terms: when it's hot, your plants can't fight back as efficiently.

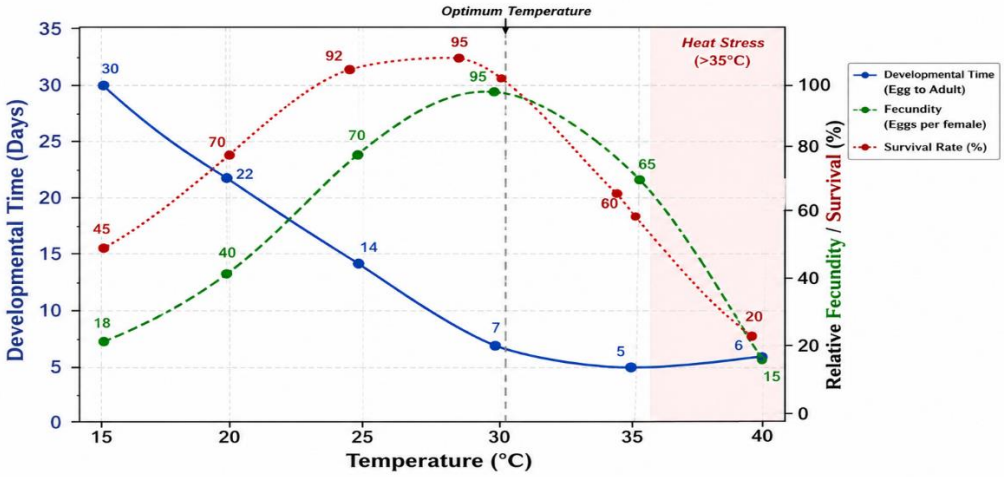


Figure. Temperature significantly influences the development, reproduction, and survival of the two-spotted spider mite (*Tetranychus urticae*). Increasing temperatures accelerate egg-to-adult development and enhance fecundity up to an optimum of approximately 30°C. However, temperatures exceeding 35°C reduce survival and reproductive performance due to heat stress.

And when drought and heat are combined? Your crops are especially vulnerable as a result of that one-two punch. Mild drought can sometimes induce defensive reactions, but the combination of drought and heat overwhelms the plant's ability to protect itself.

IV. How Mites are Winning the Arms Race

Farmers are battling a pest that not only multiplies quicker but is also adapting to outsmart the technologies we've relied on for decades.

They're made for heat. The two-spotted spider mite has unique genes that activate during thermal stress, helping it counteract damage that would kill its natural predators. These mites are activating their internal heat shields when you perspire on the field.

They are becoming resistant. There's a serious trade-off emerging in mite populations. Even though resistant males exhibit decreased fecundity, resistant female mites are resilient in the face of heat stress, according to research published in Evolutionary Applications. Because your pesticides are losing their effectiveness just when you need them most, pesticide resistance may continue to exist in populations even as temperatures rise.

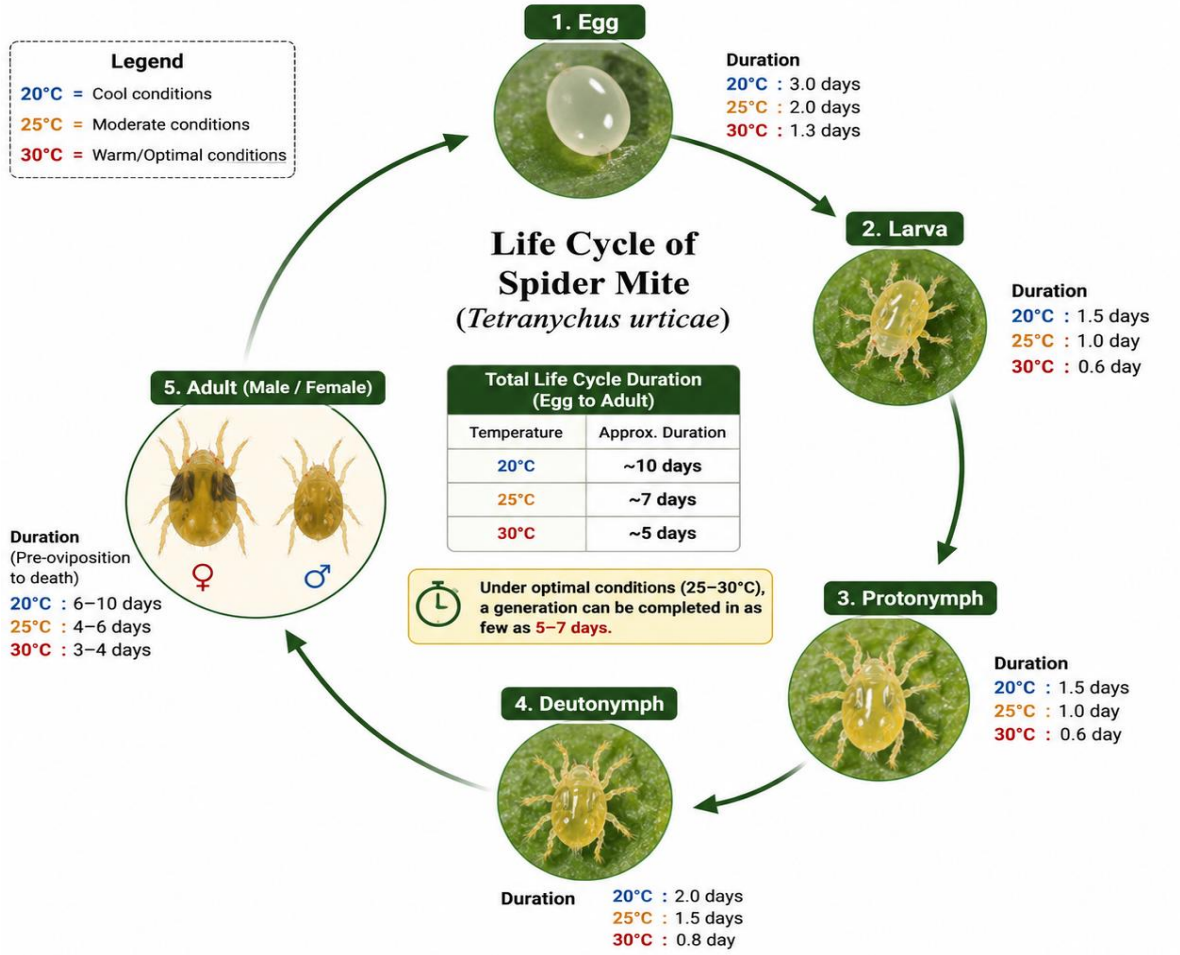


Figure 3. Spider mites complete their life cycle rapidly under warm conditions, with multiple generations occurring in a single growing season. This rapid reproduction makes population control extremely challenging.

Their life strategy is perfect for the new situations. Acarologists categorize mites into various "life types" according to how they behave. The two-spotted spider mite belongs to the "complicated web" type—a method excellently fitted to warm, dry environments. These mites develop webbing that forms a protective microclimate, preserving moisture and sheltering them from predators and chemicals. They quickly procreate and readily adjust to new crops.

V. The New Mite species nobody Saw Coming

Two previously unidentified species of spider mites were found in West Africa. This shows that climate change isn't just spreading existing pests, it's generating conditions for totally new threats to arise.

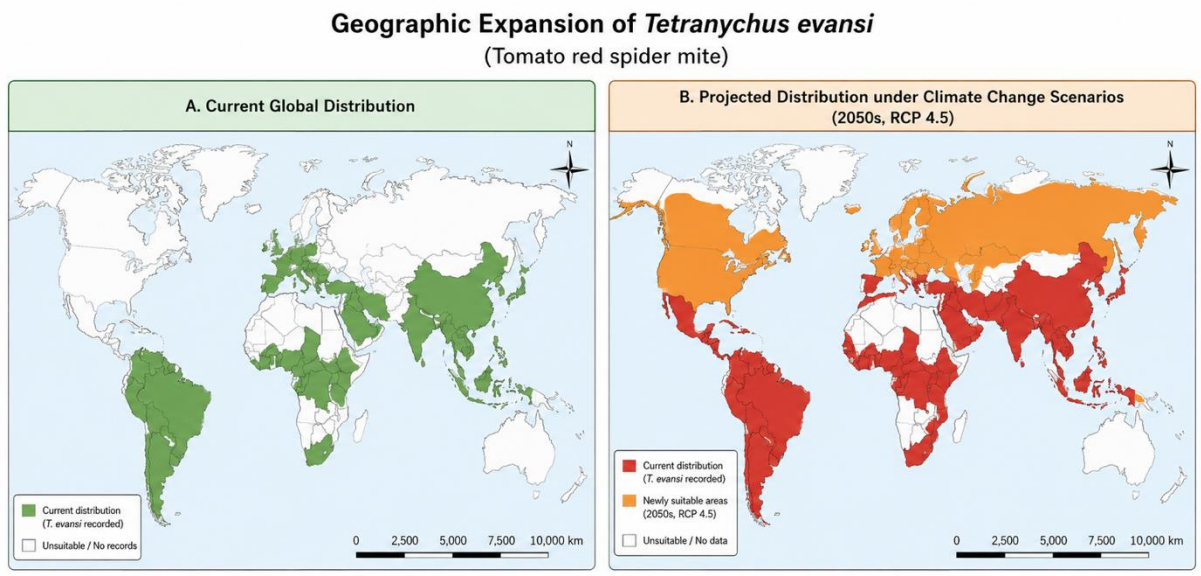
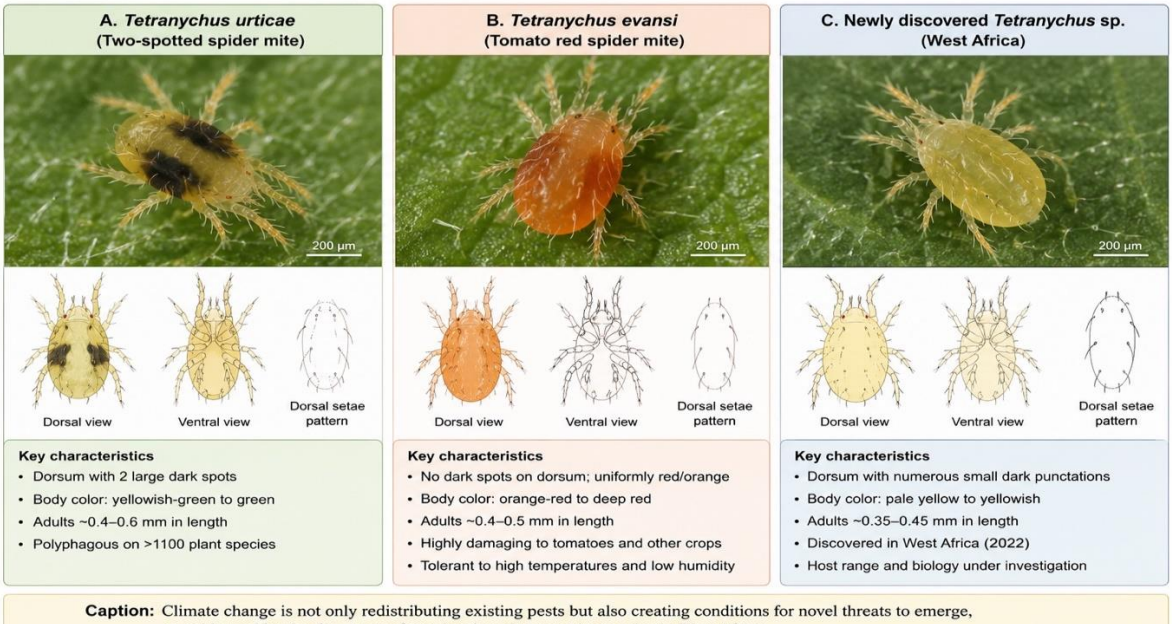


Figure 7. Predictive modeling indicates a general northward expansion of suitable habitat for the tomato red spider mite (*T. evansi*) under climate change scenarios.

On solanaceous crops, the invasive *T. evansi* has taken over, and local predatory mites like *Neoseiulus barkeri, Amblyseius swirskii,* and *Amblyseius tamatavensis* have been unable to manage their populations. Even when producers introduced new predators like Phytoseiulus longipes, the outcomes have been varied.

Figure 8. Species Comparison: Major *Tetranychus* Mites of Agricultural Importance



Caption: Climate change is not only redistributing existing pests but also creating conditions for novel threats to emerge, as evidenced by the discovery of previously unknown mite species in West Africa.

The lesson is clear: we can't expect the old remedies will work in the new climate.

VI. Adaptive Integrated Pest Management

Climate-amplified mite stresses necessitate significant modifications to traditional IPM frameworks:

Cultural Controls:

1. **Humidity control:** Maintaining higher humidity levels in regulated settings by misting or dampening down lowers the rates at which mites reproduce.
2. **Optimizing ventilation:** Better airflow lessens the hot, dry conditions that encourage the growth of mites.

3. **Fertilization adjustment:** Balanced nutrient applications reduce the higher vulnerability associated with excessive nitrogen fertilization.
4. **Protocols for sanitation:** Source populations are decreased when weed hosts and infested plant waste are removed.

Biological Controls (Updated Methods):

i. Predatory mites should be introduced early before an infestation develops (biological control agents take time to establish populations).
ii. Predator species that are more thermotolerant should be chosen; at the moment, N. californicus is performing better at high temperatures.
iii. Timed augmentative releases to prevent periods of severe temperature preservation of predator populations' habitat refugia

Chemical Restraints:

1. Preferential use of acaricides having translaminar characteristics to reach mites on leaf undersides.
2. Judicious application of abamectin, which remains effective in many locations though resistance monitoring is needed.
3. Integration of organic possibilities (plant oils, fatty acids) where applicable, with knowledge of their limited residual activity.
4. Systematic rotation of chemical classes to delay resistance development

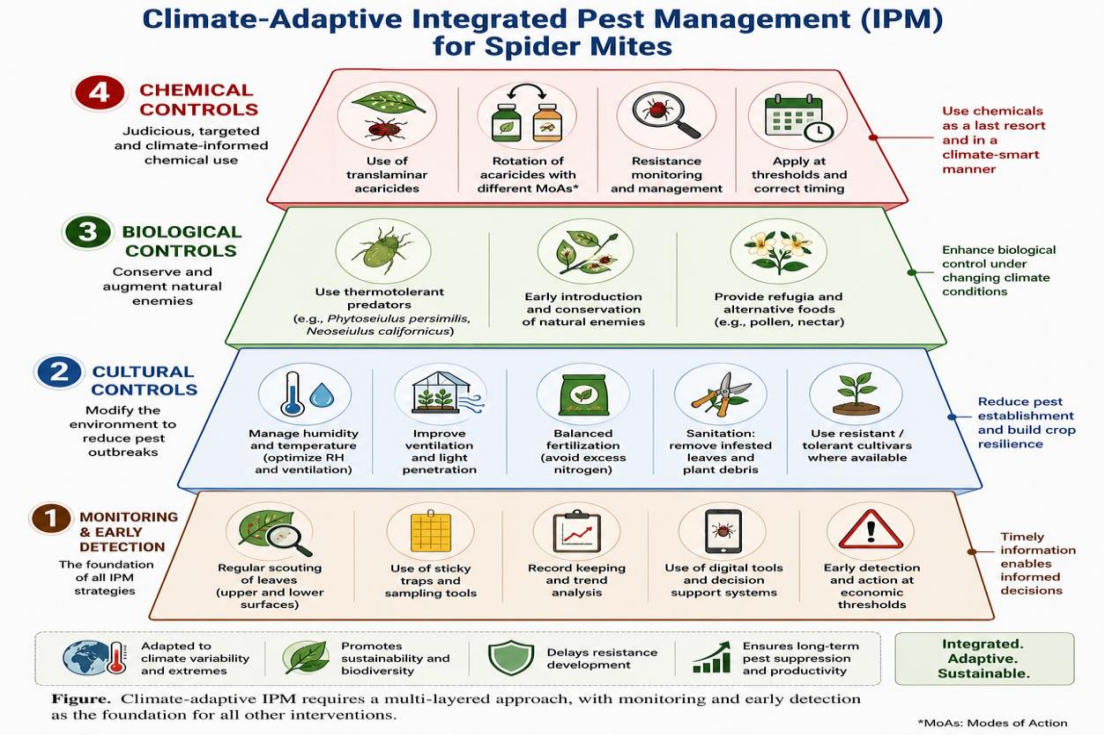


Figure. Climate-adaptive IPM requires a multi-layered approach, with monitoring and early detection as the foundation for all other interventions.

VII. Research priorities

Targeted research funding is needed in a number of crucial areas to address the growing threat posed by spider mites:

1. **Climate-informed pest modeling:** Creating forecasting tools including temperature, precipitation, and humidity forecasts to estimate the time and intensity of outbreaks
2. **Biocontrol agents that are thermotolerant**: Predatory mite strains with improved temperature tolerance are screened for and bred. Crop resistance breeding: Identification of genetic markers related with climate-resilient resistance to spider mite feeding
3. **Monitoring of pesticide resistance:** Systematic monitoring of resistance prevalence to inform chemical rotation methods

4. **Ecological impact assessment**: Evaluation of climate-mediated changes in predator-prey dynamics across agricultural settings

VIII. Conclusion

Global food production systems face a serious threat from the growing threat of spider mites in climate-changed agriculture. Warming temperatures, greater climatic variability, and the spread of exotic species are converging to generate conditions that favor mite multiplication while also undermining existing management approaches. The necessary answer is a significant shift in pest control concepts rather than little adjustments. Agricultural experts must adopt climate-informed monitoring techniques, deploy adaptive IPM tactics that account for thermal effects on both pests and predators, and engage in regional coordination to manage transboundary concerns. The study of crop resistance mechanisms and thermotolerant biological control agents must be given top priority by research organizations. The spider mite is a species that serves as an indication of the larger ecological changes occurring in agricultural systems across the globe. The strategy created to counter this threat will serve as a model for handling the series of insect problems exacerbated by climate change that will shape agricultural production in the future.

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Managing Soil Compaction and Improving Water Infiltration in Agricultural Fields

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Agricultural productivity depends fundamentally on the physical architecture of the soil profile. Heavy precipitation events frequently expose a persistent and costly physical barrier in agricultural fields: standing water, surface sealing, and severe surface runoff. While casual observation often attributes these drainage failures solely to excessive rainfall volume, the root cause invariably traces back to the structural degradation of the soil matrix. The combined mechanical forces of intensive tillage operations and the raw atmospheric energy of intense rainfall systematically destroy natural pore networks, impede vertical drainage, and leave crops vulnerable to simultaneous waterlogging and physiological drought stress. Restoring structural integrity, managing mechanical traffic, mitigating atmospheric impacts, and maximizing water infiltration require a rigorous examination of the physical, chemical, and biological mechanisms governing the soil profile.

1. The Atmospheric and Mechanical Collision: Tillage Intensity and Raindrop Physics

The structural stability of an agricultural field is constantly challenged by the interplay between mechanical soil management and atmospheric forces. The specific manner in which a seedbed is prepared and subsequently exposed to the elements dictates whether incoming water enters the profile or runs off the surface.

The Kinetic Energy of Raindrops

When severe storms strike bare or structurally compromised topsoil, unmitigated raindrops function as microscopic ballistic impacts. A single heavy raindrop strikes the soil surface at velocities reaching up to 30 miles per hour, generating localized shockwaves. The explosive kinetic energy shatters surface soil aggregates, breaking them apart into primary mineral components: sand, silt, and clay particles.

Surface Sealing and Crust Formation

Once aggregates shatter, the dislodged fine clay and silt particles are set into motion by flowing water. These micro-particles migrate into surrounding interstitial spaces, physically plugging surface macropores as water begins to pool. Upon the cessation of rain, solar radiation and atmospheric drying bake this suspended slurry into a hard, impermeable surface crust. This layer physically blocks emerging seedlings from breaking through, restricts vital gaseous exchange between the root zone and the atmosphere, and forces subsequent precipitation to run off rather than infiltrate.

The Tillage Disruption Cycle

Conventional intensive tillage practices such as mouldboard plowing, heavy offset disking, and frequent secondary cultivation temporarily loosen the topsoil, but they exact a severe long-term structural toll. Mechanical inversion and pulverization oxidize soil organic matter rapidly, shatter delicate fungal hyphae networks, and break down natural soil aggregates. Over successive crop cycles, this intensive mechanical manipulation leaves the soil highly vulnerable to structural collapse, surface sealing, and accelerated erosion during major storm events.

2. Subsurface Compaction: Creating Pans and Puddling Water

While surface crusting restricts water entry at the topmost boundary, subsurface degradation blocks drainage deeper within the profile, creating persistent hydrological bottlenecks.

Traffic Pans and Plow Pans

The repeated passage of heavy modern agricultural machinery including large tractors, self-propelled sprayers, and fully loaded grain carts exerts immense downward and shear pressure upon the soil. When these heavy passes occur while the soil profile contains high moisture levels, the applied pressure forces soil particles into tighter spatial arrangements, expelling air and destroying macro-aggregates. This process creates a dense, severely compacted layer situated directly beneath the normal tillage depth, typically occurring between 4 and 12 inches below the surface.

Impeded Percolation and Perched Water Tables

This compacted plow pan acts as a nearly impermeable physical barrier. Roots struggle to penetrate the high mechanical resistance of the pan, forcing them into shallow horizontal growth patterns. Simultaneously, downward-moving gravitational water is halted by the dense layer, creating a temporary perched water table. Consequently, fields remain saturated and waterlogged long after storm events cease, creating anaerobic conditions that starve roots of oxygen, stunt nutrient uptake, and encourage root rot pathogens.

3. Mechanical Remediation: Shattering Pans and Opening Pathways

When sub-surface compaction restricts vertical drainage, biological amendments alone cannot instantly resolve the physical bottleneck. Targeted mechanical intervention becomes necessary to re-establish structural pathways through dense layers.

Deep Tillage and Subsoiling

Operating a specialized subsoiler or in-row ripper below the depth of the compacted pan physically shatters the dense horizontal layers. To maximize the effectiveness of this intervention, subsoiling must be executed when the soil profile is relatively dry. Dry soil fractures cleanly along natural cleavage planes under mechanical stress, whereas wet soil merely smears, creating elongated cavities that fail to provide genuine structural relief.

Precision Zone Tillage and Traffic Management

Modern conservation systems emphasize minimizing total soil disturbance while fracturing localized traffic lanes, preserving organic matter and structural aggregates in undisturbed crop rows. Furthermore, restricting heavy machinery passes to permanent, designated traffic lanes, a strategy known as controlled traffic farming prevents random compaction across the entire field, protecting the vast majority of the root zone from structural degradation.

4. Biological Armor: Roots, Microbes, and Organic Carbon

Mechanical fracturing provides immediate physical relief, but long-term structural stability relies entirely on biological reinforcement. Without living roots and organic cementing agents, mechanically loosened soils rapidly re-compact under subsequent rainfall events.

Root-Driven Biopores

Deep-rooting cover crops, such as forage radishes, cereal rye, and daikon radishes—act as biological drills within the soil profile. Vigorous taproots penetrate dense, compacted subsoil layers, creating continuous vertical macropores. When these roots senesce and decompose, they leave behind stable biopores that serve as permanent conduits for water infiltration and air movement during heavy storms.

Glomalin and Aggregate Stability

Arbuscular mycorrhizal fungi play an indispensable role in maintaining soil structure by secreting glomalin, an exceptionally stable, hydrophobic glycoprotein. Glomalin acts as a biological glue, binding mineral soil particles and organic matter together into stable macro-aggregates. These stable aggregates resist raindrop dispersion, preventing the breakdown of surface structure and keeping infiltration pathways wide open.

Surface Residue Protection

Maintaining a high volume of crop residue or cover crop mulch on the soil surface absorbs the kinetic energy of falling raindrops. By intercepting raindrops before they strike the soil matrix, residue blankets protect surface aggregates from shattering and prevent the formation of impermeable crusts.

5. Water Management: Enhancing Infiltration and Reducing Runoff

Mitigating standing water requires optimizing the continuous pore network from the surface down to the deep subsoil, transforming dense, crust-prone fields into resilient, well-drained production environments.

- **Enhancing Macropore Continuity:** Continuous macropores, formed by earthworms, decayed root channels, and biological activity, allow water to move rapidly via gravity through the profile, bypassing dense matrices.
- **Surface Roughness and Micro-relief:** Maintaining appropriate surface residue and contour farming techniques slows down overland water velocity, providing additional time for moisture to infiltrate rather than pool in low spots.

- **Balancing Tillage Intensity:** Transitioning away from intensive, continuous moldboard plowing prevents the destruction of natural soil architecture, fostering a resilient sponge-like matrix capable of absorbing heavy storm events.

6. The Economics of Drainage: Long-Term Soil Resilience and Yield Protection

Evaluating the financial return of managing soil compaction and water infiltration reveals that physical soil restoration is fundamentally an economic risk-management strategy. Unmanaged surface crusting and subsurface compaction impose severe, recurring costs on agricultural operations that extend far beyond immediate crop stunting.

Quantifying the Hidden Costs of Compaction

When heavy precipitation events result in standing water and poor infiltration, multiple economic losses accumulate simultaneously:

- **Input Inefficiency:** Fertilizer nutrients, particularly mobile nitrogen and applied herbicides, are washed away in surface runoff rather than infiltrating into the root zone, resulting in wasted chemical expenditures and potential environmental contamination.
- **Machinery and Fuel Penalties:** Tilling and planting compacted, poorly drained soils demands significantly higher drawbar pull from tractors, which translates directly into elevated fuel consumption and accelerated mechanical wear on equipment.
- **Yield Suppression:** Subsurface pans restrict root volume, preventing crops from accessing stored subsoil moisture during mid-season dry spells. This premature drought susceptibility causes severe yield depression even when seasonal rainfall totals are adequate.

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Pollination Services: The Hidden Economic Value of Honey Bees

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Abstract

Honey bees (*Apis mellifera* and related *Apis* species) are the most widely managed pollinators in the world, and their activity underpins the production of many fruits, nuts, oilseeds, vegetables and forage crops. Unlike honey, wax and other hive products, whose value is traded openly, the pollination service that bees provide is largely invisible in market accounts, which is why its worth is frequently described as hidden. This review synthesises current knowledge on the biological basis of honey bee pollination, the dependence of global agriculture on animal pollination, the methods used to value pollination services, and published estimates of their economic magnitude at global and regional scales. Evidence indicates that animal pollinators contribute to roughly one third of global crop production by volume and that the annual market value of pollinator-dependent crops lies in the hundreds of billions of US dollars, far exceeding the value of honey itself. Pollination also improves crop quality and yield stability and sustains wild plant communities, benefits that are seldom captured in price. However, demand for pollination is growing faster than the supply of managed colonies, while colonies are challenged by parasites, pathogens, pesticides, poor nutrition and climate change. We discuss the market failures that keep this value hidden and outline policy and research priorities for securing pollination services.

Keywords: pollination services; honey bees; *Apis mellifera*; ecosystem services; economic valuation; pollinator-dependent crops; food security; beekeeping

1. Introduction

Pollination is the transfer of pollen from anthers to receptive stigmas, and it is a prerequisite for seed and fruit set in the great majority of flowering plants. An estimated 87.5% of flowering plant species depend, at least in part, on animals for pollination (Ollerton et al., 2011), and among these animals bees are the most important group. Within the bees, the western honey bee *Apis mellifera* has a special standing in agriculture: it can be kept in movable-frame hives, transported to crops at bloom, and deployed in large numbers on demand. As a result, honey bees are often described as the workhorse of commercial pollination (Delaplane & Mayer, 2000).

The value that society derives from honey bees is conventionally associated with honey, beeswax, propolis and royal jelly. These products have clear prices and are easy to count. The pollination service, by contrast, is a benefit that accrues to farmers, consumers and ecosystems rather than to the beekeeper, and it is not usually recorded in national accounts. This asymmetry explains why the economic contribution of honey bees is widely regarded as hidden: it is real, large and measurable in principle, but it is embedded in the value of other goods.

The question of how much this service is worth has practical importance. Pollination services are described in the ecosystem-services literature as a classic example of a benefit supplied by nature that is rarely priced (Costanza et al., 1997; Costanza et al., 2014). Reliable valuation helps to justify investment in beekeeping, habitat protection and pesticide regulation, and it allows policymakers to weigh the cost of pollinator decline against the cost of conservation. At the same time, valuation is contested, because the results depend heavily on the method, the crops included and the assumptions made about the role of wild pollinators.

This article reviews the evidence on the economic value of pollination services provided by honey bees, supported by illustrations of bee biology and global data. Section 2 describes the biology, castes, life cycle and behaviour of honey bees that underlie their pollination role. Section 3 examines their effectiveness as pollinators in relation to wild species. Section 4 summarises global beekeeping and the market for hive products. Section 5

examines the dependence of world agriculture on animal pollination. Sections 6 and 7 describe valuation methods and summarise published estimates, including crop case studies. Section 8 considers benefits beyond yield, Section 9 discusses threats to the service, and Section 10 analyses why the value remains hidden and what can be done about it. Section 11 concludes with research priorities.

2. Honey Bee Biology Relevant to Pollination

2.1 Taxonomy, distribution and morphology

The genus *Apis* contains around ten recognised species, depending on the classification followed, but only two of them are managed on a large scale in hives: the western honey bee *Apis mellifera* and the eastern honey bee *Apis cerana* (Engel, 1999; Winston, 1987). The remaining species, including the giant honey bee *A. dorsata*, the dwarf honey bee *A. florea* and the Himalayan cliff bee *A. laboriosa*, build single open combs and are harvested rather than kept. *Apis mellifera* is native to Europe, Africa and western Asia, where it has differentiated into some two dozen geographic subspecies, such as *A. m. ligustica*, *A. m. carnica* and *A. m. mellifera*, that differ in temperament, brood cycles and winter hardiness (Ruttner, 1988). Humans have since carried the species to every inhabited continent, and it is now the most widely distributed managed pollinator on Earth. *Apis cerana* is native to Asia and is the traditional hive bee of the Indian subcontinent, where it is valued for its tolerance of local conditions and its foraging on scattered bloom.

Several morphological features explain the effectiveness of honey bees as flower visitors (Figure 1). The head carries a pair of large compound eyes, three simple eyes (ocelli) and a pair of antennae that are rich in olfactory and tactile receptors. Mouthparts form a tongue-like proboscis that is used to lap and draw up nectar. The thorax bears two pairs of wings, which are coupled in flight by a row of small hooks called hamuli, and three pairs of legs. The body is covered with branched (plumose) hairs that catch pollen grains, and the hind legs are fitted with a concave basket-like structure, the corbicula, in which moistened pollen is packed and carried to the hive. The abdomen houses the honey stomach (crop), in which nectar is carried, the wax glands of young workers and, in females, the sting (Snodgrass, 1956; Winston, 1987).

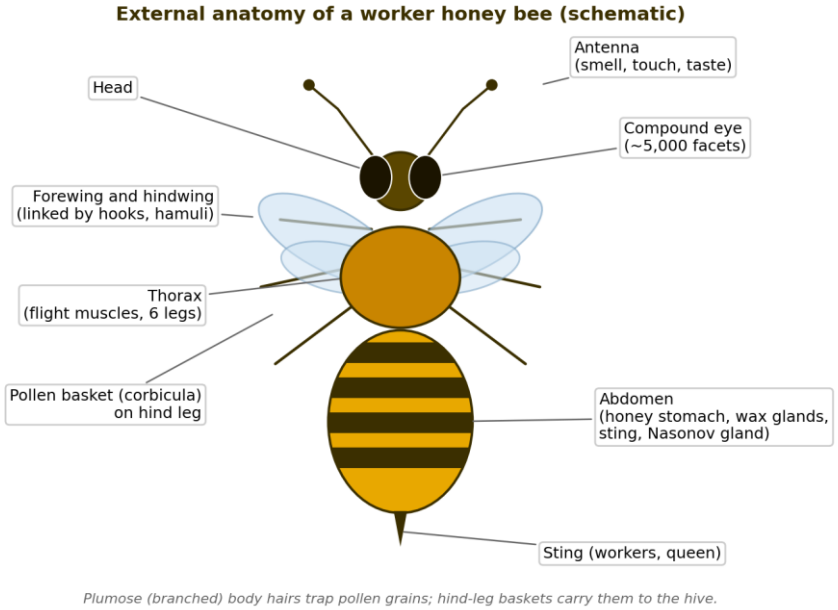


Figure 1. External anatomy of a worker honey bee (schematic illustration), showing structures that are important for foraging and pollination.

2.2 Castes and the colony life cycle

A honey bee colony is a eusocial superorganism composed of three castes (Figure 2). A single queen is the only fertile female and may lay well over a thousand eggs a day in the peak season. Workers, which are sterile females, make up the bulk of the colony and carry out all the tasks of nest construction, brood care, defence and foraging. Males, called drones, develop in spring and summer and have a single function, which is to mate with virgin

queens. Because a colony can contain from ten to fifty thousand workers at its peak, the foraging workforce that can be directed to a flowering crop is far larger than that of any solitary bee (Winston, 1987; Seeley, 1995).

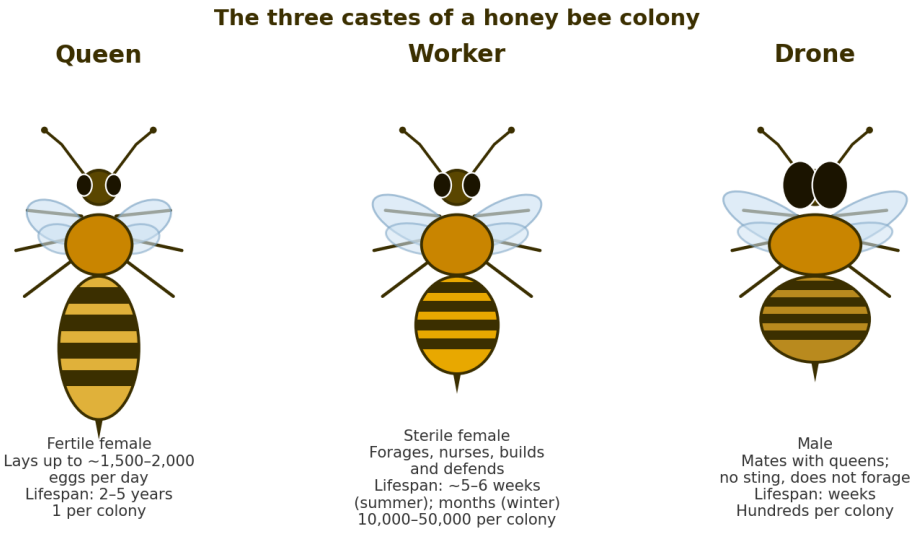


Figure 2. Queen, worker and drone: the three castes of the honey bee colony and their main characteristics (schematic illustration; values approximate).

Honey bees undergo complete metamorphosis, passing through egg, larval, pupal and adult stages (Figure 3). The egg is laid by the queen at the base of a wax cell and hatches after about three days. Nurse bees feed the larva intensively on glandular secretions and later on a mixture of honey and pollen; after roughly six days the cell is capped with wax and the larva pupates. A worker emerges about 21 days after the egg is laid, a queen after about 16 days and a drone after about 24 days (Table 1). The brood nest is held at a nearly constant temperature of about 34–35 °C, a requirement that links colony biology closely to the thermal environment (Winston, 1987).

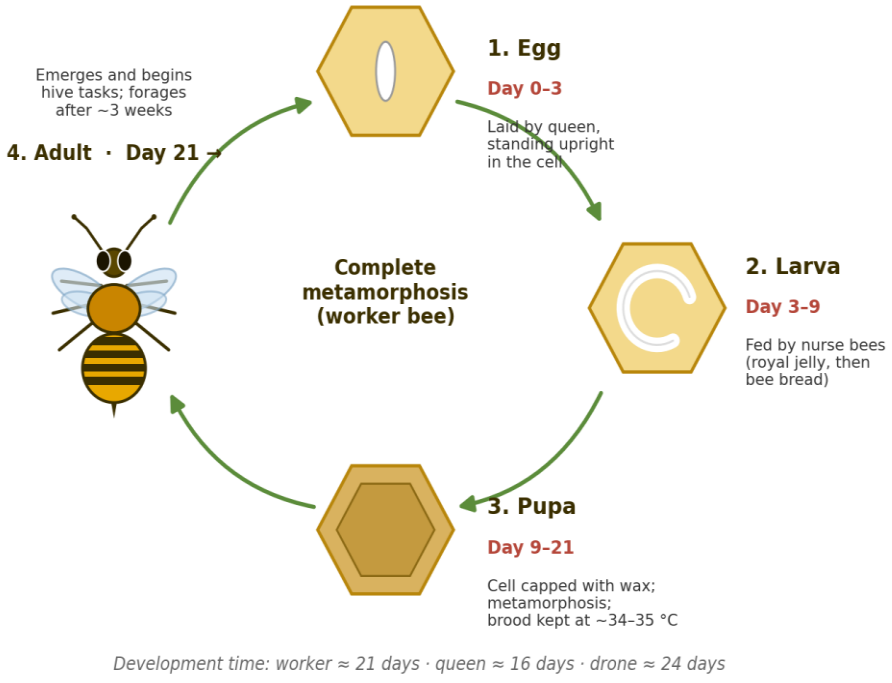


Figure 3. Life cycle of the worker honey bee from egg to adult, illustrating the sealed-brood stage and typical durations (schematic illustration).

Table 1. Approximate developmental times and characteristics of the honey bee castes (after Winston, 1987).

Parameter	Queen	Worker	Drone
Egg stage (days)	≈ 3	≈ 3	≈ 3
Larval stage (days)	≈ 5–6	≈ 6	≈ 6–7
Pupal stage (days)	≈ 7–8	≈ 12	≈ 14–15
Total development (days)	≈ 16	≈ 21	≈ 24
Typical adult lifespan	Years (commonly 2–3 or more)	Weeks in summer; months for winter bees	Weeks
Number per colony	1	Thousands to tens of thousands	Zero to hundreds
Main role	Egg laying; pheromonal regulation	Foraging, brood care, defence, nest building	Mating

Note: values are typical textbook figures and vary with race, season and conditions.

2.3 Division of labour and foraging

Workers do not perform all tasks at once. Instead, they pass through an approximate sequence of jobs as they age, a pattern called temporal polyethism (Seeley, 1982). In the first days of adult life a worker cleans cells; she then feeds larvae, handles incoming nectar and builds comb, and later guards the entrance and ventilates the hive before becoming a forager at about three weeks of age (Figure 4). This schedule is flexible, however, and colonies can accelerate or reverse it in response to losses of foragers or nurses. The practical significance for pollination is that only the oldest workers, a fraction of the colony, are foraging at any time, so the strength of the colony and the age structure of the population strongly affect the pollination service delivered per hive.

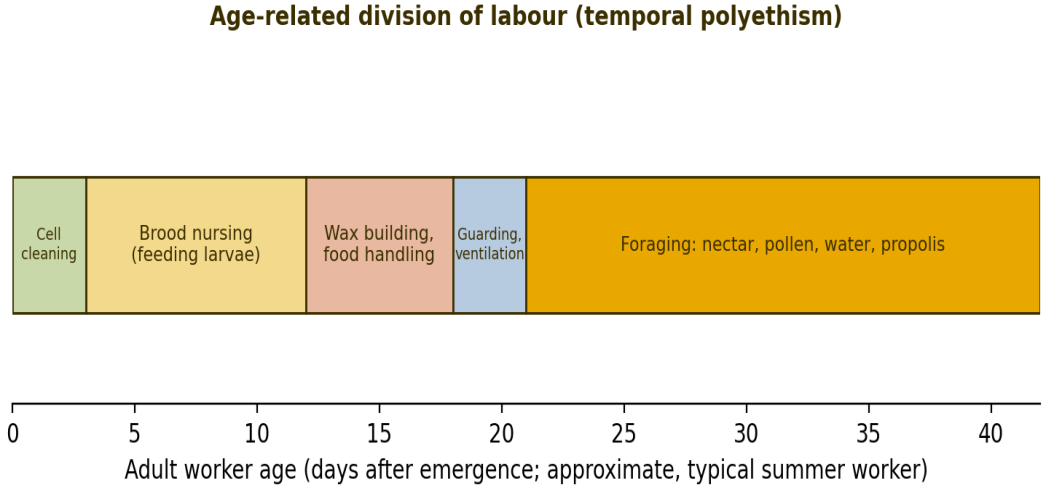


Figure 4. Age-related division of labour in a typical summer worker honey bee (approximate).

Foragers locate and communicate profitable food by a dance language. A successful forager returning to the hive performs a waggle dance on the vertical comb in which the angle of the waggle run relative to the vertical indicates the direction of the food source relative to the sun, and the duration of the run encodes the distance (von Frisch, 1967; Seeley, 1995) (Figure 5). Nestmates that follow the dance leave to search at the indicated location. This recruitment mechanism concentrates foragers on the richest patches, including crops in full bloom, and is a major reason why honey bee colonies are effective at exploiting mass-flowering crops. Foragers regularly travel several kilometres from the hive, and in landscapes with sparse resources, distances approaching ten kilometres have been recorded (Beekman & Ratnieks, 2000), which means that one apiary can influence pollination over a wide area.

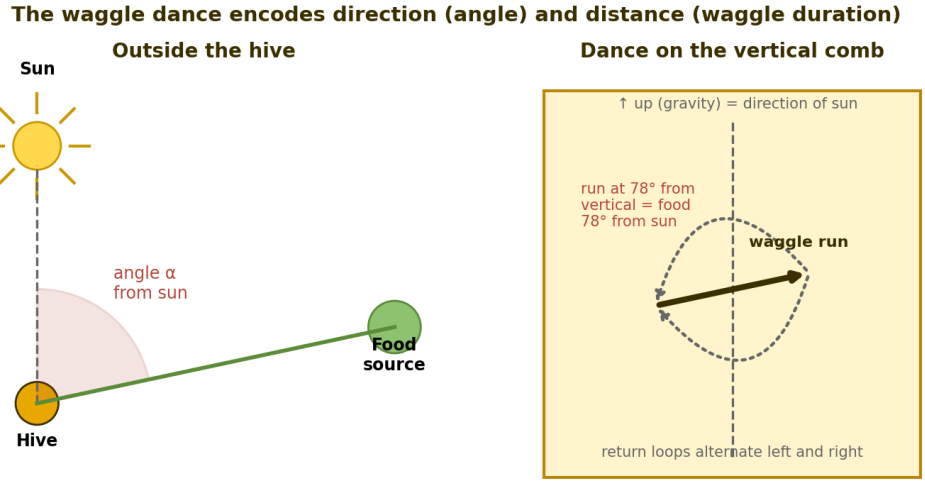


Figure 5. The waggle dance: the direction of the waggle run on the comb relative to vertical corresponds to the angle between the food source and the sun (schematic illustration).

2.4 The annual cycle of the colony

In temperate regions the colony follows a pronounced annual cycle (Figure 6). Colonies overwinter as a tight cluster of workers around the queen, living on stored honey. As days lengthen, the queen increases egg laying, the population expands through spring, and the colony may reproduce by swarming. The peak of colony size coincides with the main nectar flow in early summer, after which brood rearing declines, drones are expelled and the colony prepares for winter by raising long-lived winter bees (Winston, 1987; Seeley, 1995). For economic purposes, this cycle is critical: growers need strong colonies at the time of crop bloom, and the match between colony growth and flowering determines how much pollination the colony can provide.

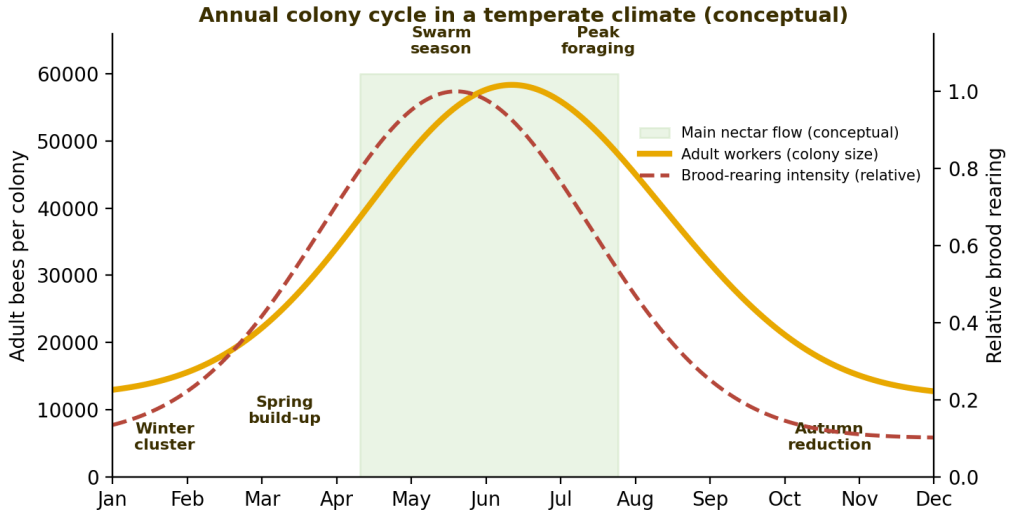


Figure 6. Conceptual annual cycle of a honey bee colony in a temperate climate, showing colony size, brood rearing and the main nectar flow (illustrative, not measured data).

3. Honey Bees as Effective Pollinators: Traits and Ecological Context

3.1 Traits that make honey bees effective managed pollinators

Several biological traits make honey bees uniquely suited to commercial pollination. First, colonies are perennial and typically tens of thousands of workers strong at peak season, so a single hive supplies a very large foraging force at the moment a crop flowers. Second, workers show flower constancy, tending to visit one plant species during a foraging trip, which reduces the transfer of incompatible pollen (Free, 1993). Third, the dance language allows successful foragers to recruit nestmates to profitable patches, concentrating pollinator effort where floral

rewards are highest (Seeley, 1995). Fourth, honey bees are generalists that will forage on hundreds of plant species, which makes them adaptable to varied crops. Finally, because colonies store honey and can be moved on trucks, beekeepers can position them where and when they are needed.

These attributes are complemented by human management. Migratory beekeeping, hive rental contracts and queen breeding have created a commercial pollination industry in many countries. In temperate hill horticulture, including apple production in the Indian Himalaya, growers increasingly place *A. mellifera* colonies in orchards during bloom because natural pollinator populations alone are insufficient at the scale of modern orchards (Abrol, 2012). Honey bees are not equally effective on all crops, however. Some flowers, such as tomato, need buzz pollination, which honey bees cannot perform, and others are better served by specialised solitary bees or bumble bees.

3.2 Complementarity with wild pollinators

A central issue for valuation is the relative contribution of managed honey bees and wild pollinators. Field studies across many crops indicate that wild insects visit flowers in substantial numbers and that their visits are often more effective per visit than those of honey bees (Garibaldi et al., 2013). In a synthesis of 41 crop systems, fruit set increased with visits from wild insects irrespective of honey bee abundance, and honey bee visitation could not substitute for wild insect visitation (Garibaldi et al., 2013). Non-bee insects such as hoverflies also make a significant contribution to crop pollination worldwide (Rader et al., 2016). In some systems, the presence of other bees improves the efficiency of honey bees, as shown for almond, where interactions with wild bees increased the pollination performance of honey bees (Brittain et al., 2013).

Honey bees also interact with wild plant communities. A global analysis of plant–pollinator networks found that honey bees accounted for about 13% of flower visits in natural habitats, and that they were frequent visitors in many networks (Hung et al., 2018). The implication is that honey bees supplement rather than replace wild pollinators, but that in landscapes where wild populations have been reduced, managed colonies may become the dominant, and sometimes the only, source of pollination. This complementary relationship should be kept in mind when interpreting the valuation estimates below, since attributing the entire value of pollinator-dependent crops to honey bees would overstate their role.

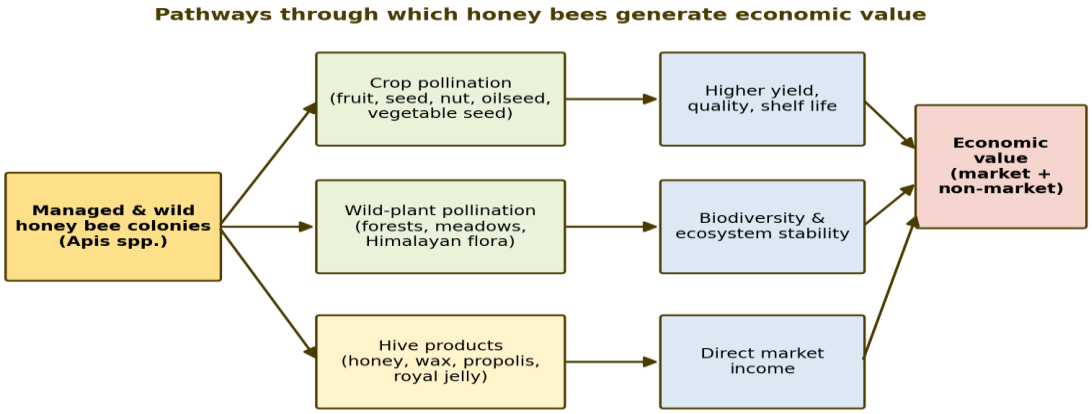


Figure 7. Conceptual framework showing the pathways through which honey bee colonies generate market and non-market economic value.

4. Global Beekeeping and the Market for Hive Products

Beekeeping is practised in almost every country, from backyard hives to migratory operations with thousands of colonies. According to the Food and Agriculture Organization, world honey production has grown steadily over the past six decades, from well under one million tonnes in 1961 to roughly 1.8 million tonnes in the early 2020s (FAO, FAOSTAT). Figure 8 shows this trend and the leading producing countries. China is by far the largest producer and exporter, with a share of the world total several times larger than that of any other country, followed by a group of countries that includes India, Türkiye, Iran, Argentina, Ukraine, the United States and Russia. The global stock of managed colonies grew more slowly than crop demand for pollination over the same period (Aizen & Harder, 2009).

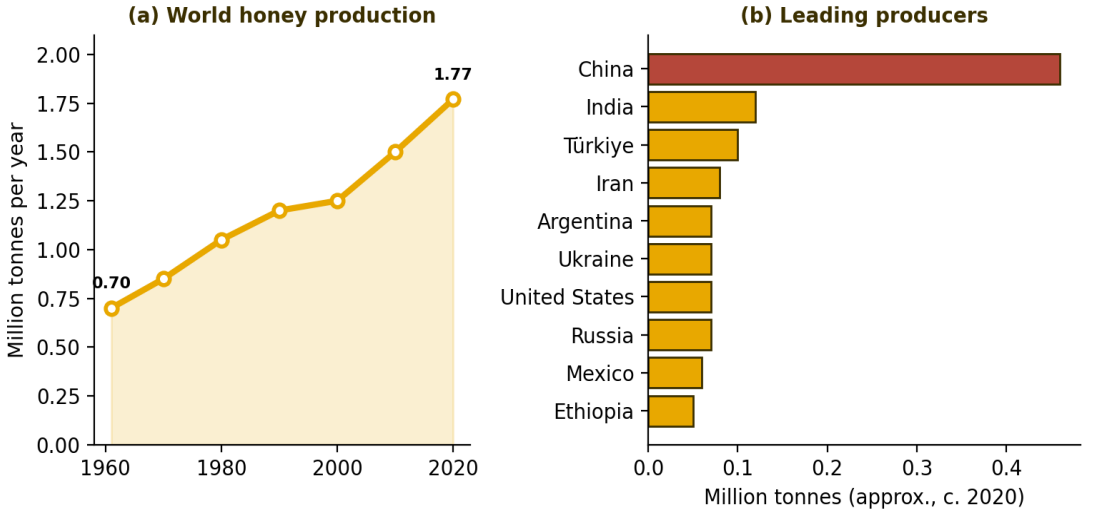


Figure 8. (a) Approximate trend in world honey production, 1961–2020, and (b) approximate leading honey-producing countries around 2020. Values are rounded and compiled from FAOSTAT; check exact figures at source before citing.

Honey is only one of several products of the hive (Table 2). Beeswax is used in cosmetics, candles and pharmaceuticals; propolis, a resinous mixture collected from plants, is used in health products; royal jelly and bee pollen are sold as dietary supplements; and bee venom has research and therapeutic uses. Beekeepers also sell queens, nucleus colonies and package bees. In many beekeeping regions the largest source of income is no longer honey but the rental of colonies to growers, a market that has no equivalent in national statistics on livestock products. The total market value of all hive products, while significant for rural livelihoods, is small compared with the value of the crops that the same colonies pollinate.

Table 2. Products and services of honey bee colonies and the way their value is realised.

Product / service	Main uses	How value is realised
Honey	Food, sweetener, traditional medicine	Sold in local and international markets; prices recorded
Beeswax	Cosmetics, candles, pharmaceuticals, comb foundation	Sold as raw material; often by-product of honey harvest
Propolis	Health and cosmetic products, hive defence in nature	Sold as extract or raw product; niche market
Royal jelly, bee pollen	Dietary supplements and functional foods	Specialised, higher-value markets
Bee venom	Research, therapeutic and cosmetic products	Very small, specialised market
Queens, nuclei, package bees	Colony replacement and expansion	Sold between beekeepers
Pollination service	Crop yield, quality and seed production; wild plant reproduction	Hive-rental fees (managed portion only); most value accrues to growers, consumers and ecosystems and is not priced

5. Dependence of Global Agriculture on Animal Pollination

Quantifying economic value begins with measuring how much production depends on pollinators. In a widely cited assessment of the 115 leading global crops, Klein et al. (2007) found that fruit, vegetable or seed production from 87 of these crops, comprising about 35% of global food production by volume, benefits from animal

pollination. Only 28 crops did not depend on animal pollinators, and these include the major cereals rice, wheat and maize, which are wind pollinated or self pollinated. Because cereals dominate the calories consumed globally, the overall share of production that depends on pollinators is modest by volume. In terms of nutritional quality and diversity, however, the dependence is much greater: many of the foods that supply vitamins, minerals and healthy fats, such as fruits, nuts, oilseeds and vegetables, rely on pollination.

Klein et al. (2007) classified crops by the production loss expected in the absence of animal pollinators. As Figure 9 shows, 13 crops were rated as essential, with losses of more than 90%, and 30 were rated as having a great dependence (40–90% loss). A further 27 crops had modest dependence and 21 showed little dependence, while 7 showed no increase and 17 remained unclassified because of insufficient data. Representative examples from each class are given in Table 3. The dependence ratios used in economic studies are derived largely from compilations such as McGregor (1976) and Delaplane and Mayer (2000), later refined by Klein et al. (2007).

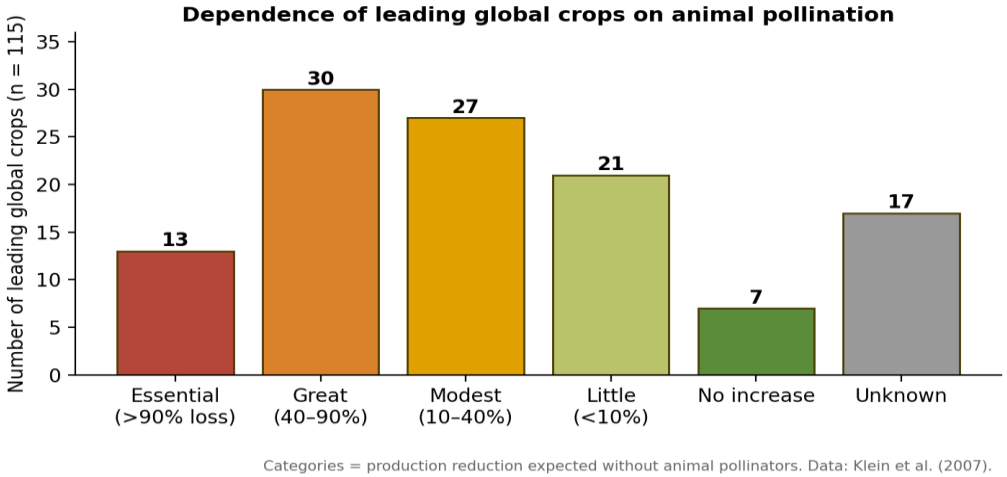


Figure 9. Distribution of the 115 leading global crops across pollinator-dependence classes. Data from Klein et al. (2007).

Table 3. Examples of crops by degree of dependence on animal pollination (after Klein et al., 2007) and their relevance to honey bees.

Dependence class	Example crops	Comment
Essential (>90% loss)	Almond, kiwifruit, cucumber, pumpkin/squash, cocoa, Brazil nut	Honey bees are the principal managed pollinator for almond and several cucurbits; cocoa depends mostly on midges
Great (40–90%)	Apple, pear, cherry, plum, avocado, many berries	Managed honey bees are widely rented for orchard bloom
Modest (10–40%)	Oilseed rape, sunflower, coffee, soybean, cotton	Yield and oil quality benefit; honey bees add significant value in large monocultures
Little (<10%)	Certain legumes and tree crops	Small contribution to yield; other factors dominate
No increase	Rice, wheat, maize, barley, potato (tubers)	Wind or self pollinated, or propagated vegetatively

Note: classification follows the production-reduction categories of Klein et al. (2007); crop assignments are indicative.

The trend in dependence is also important. Between 1961 and 2007, the area under pollinator-dependent crops expanded by around 300% globally, considerably faster than the area of non-dependent crops, while the global stock of managed honey bee colonies increased by only about 45% (Aizen & Harder, 2009). As Figure 10 shows, demand for pollination has therefore outpaced the growth of managed supply, and the pollination deficit has grown in regions where large monocultures of dependent crops have replaced diverse landscapes. Analysis of European data likewise suggests a mismatch between the number of honey bee colonies and the pollination demand of crops in many countries, and points to agricultural policies as a contributing factor (Breeze et al., 2014). Crop production in the United States is also frequently limited by a lack of pollinators (Reilly et al., 2020).

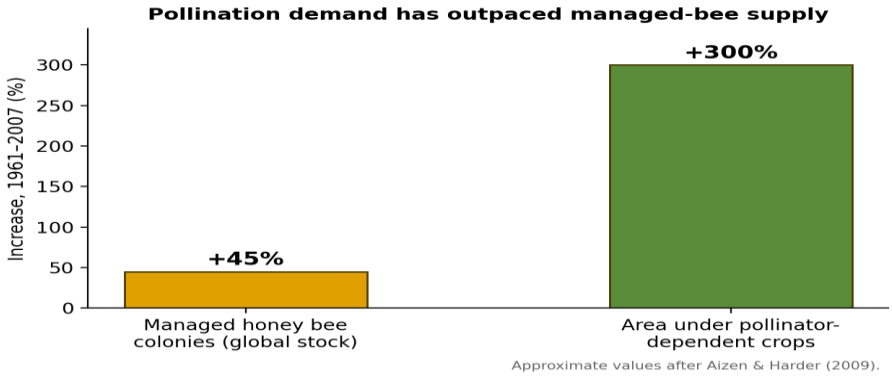


Figure 10. Growth in global pollinator-dependent crop area compared with the global stock of managed honey bee colonies, 1961–2007 (approximate values after Aizen & Harder, 2009).

6. Methods for Valuing Pollination Services

Economists use several approaches to value pollination, and the choice of approach strongly influences the result. The simplest and most common is the dependence-ratio method. This multiplies the market value of each crop by a dependence ratio, which is the fraction of production lost without pollinators, and sums across crops. Where the aim is to attribute value to honey bees specifically, a further factor is applied for the share of pollination performed by honey bees (Morse & Calderone, 2000). This approach is transparent and data-light, but it assumes fixed prices and ignores consumers' and producers' responses to changing scarcity, so it tends to give an upper bound on short-term value.

A second approach is the replacement-cost method, which asks how much it would cost to replace the service, for example by hand pollination. Hand pollination of fruit trees has been practised commercially in parts of China where pollinators have been depleted, and it illustrates how expensive a substitute for natural pollination can be. A third method uses observed market transactions, notably the fees paid by growers to beekeepers for hive rental. These fees give a direct signal of willingness to pay, but they capture only the managed portion of the service and reflect local market conditions (Rucker et al., 2012). A fourth, consumer-surplus approach models the loss in welfare experienced by consumers and producers when reduced supply raises prices (Southwick & Southwick, 1992; Gallai et al., 2009). Finally, general-equilibrium and macroeconomic models trace the effects of pollinator loss through the entire economy, including trade and land use responses (Bauer & Wing, 2016). Table 4 compares these approaches.

Table 4. Main approaches used to value pollination services.

Approach	Principle	Strengths	Limitations
Dependence ratio (production function)	Crop value × fraction lost without pollinators (× honey bee share)	Simple, transparent, widely applicable	Static; ignores price and land-use response; sensitive to ratios
Replacement cost	Cost of substituting hand pollination or other inputs	Intuitive; shows scale of dependence	Substitute rarely practical at scale; data-scarce
Market fees for hive rental	Prices paid by growers to beekeepers	Observed, real transactions	Covers managed service only; local, seasonal, incomplete
Consumer/producer surplus	Welfare change from reduced supply and higher prices	Accounts for market response	Needs demand elasticities; complex data
General equilibrium / macroeconomic	Economy-wide impacts of pollinator loss	Captures trade and cross-sector effects	Model assumptions strongly influence results

The mechanics of the dependence-ratio method can be shown with a hypothetical example. Suppose a crop has an annual farm-gate value of US$100 million, a dependence ratio of 0.65 (65% of production would be lost without animal pollinators), and honey bees perform 60% of pollination. The estimated contribution of honey bees is then 100 × 0.65 × 0.60 = US$39 million. Table 5 shows how strongly this answer varies when the two uncertain parameters are changed, which explains why published estimates can differ widely even when they are based on the same crop statistics.

Table 5. Sensitivity of a hypothetical dependence-ratio estimate (US$ million) to the assumed dependence ratio and honey bee share, for a crop worth US$100 million.

Dependence ratio	Honey bee share 0.30	Honey bee share 0.60	Honey bee share 0.90
0.40	12.0	24.0	36.0
0.65	19.5	39.0	58.5
0.90	27.0	54.0	81.0

Note: illustrative calculation only; values are not real crop data.

7. Published Estimates of Economic Value

7.1 Global estimates

Using the dependence-ratio approach with crop production and price data, Gallai et al. (2009) estimated the total economic value of insect pollination worldwide at about €153 billion in 2005, equal to around 9.5% of the value of world agricultural food production. A later assessment by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services put the annual global output of pollinator-dependent crops at between US$235 billion and US$577 billion (in 2015 prices), noting that this is the market value of crops that depend on pollinators to some degree rather than the value attributable to pollination alone (IPBES, 2016). These figures refer to all insect pollinators. Honey bees account for a large but uncertain fraction, and in many crop systems the managed honey bee is the pollinator that growers can actually purchase or influence.

Global estimates carry important caveats. They are sensitive to the dependence ratios used, and they generally do not net out the contribution of wild pollinators. They also focus on market crops and omit wild plant reproduction, animal feed and the cultural value of pollinated landscapes. Nonetheless, all methods lead to the same qualitative conclusion: the value of pollination greatly exceeds the market value of honey. Global honey production is measured in a few billion US dollars, whereas the value of pollinator-dependent crops is two orders of magnitude higher.

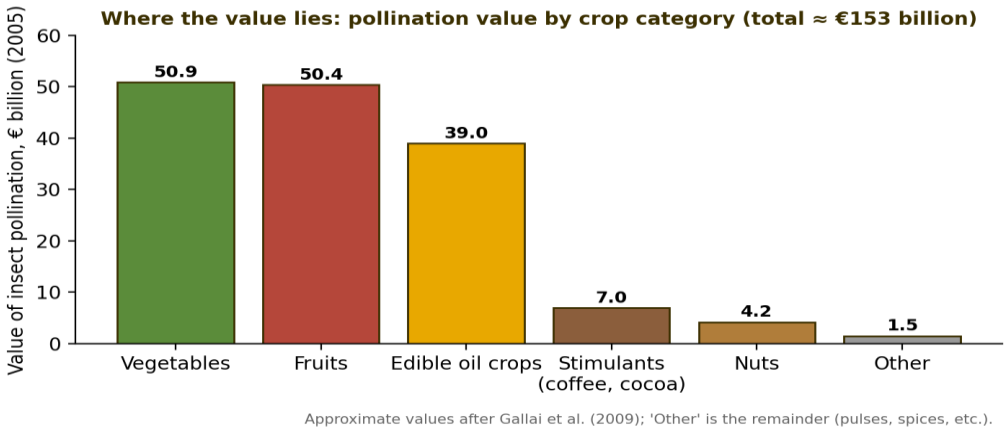


Figure 11. Approximate distribution of the value of insect pollination among crop categories (after Gallai et al., 2009).

7.2 Regional evidence

Regional studies give more concrete estimates. In the United States, Morse and Calderone (2000) calculated that honey bee pollination added about US$14.6 billion to the value of crops in 2000, of which almonds, apples and citrus made up a large share. Almond is the most striking case: the crop is essentially dependent on insect pollination, orchards cover very large areas, and growers rent a large fraction of all colonies in the country each spring. The annual movement of hives to almond orchards is one of the largest managed pollination events in the world, and it has led to a robust pollination-rental market in which fees are influenced by colony supply, honey prices and colony health (Rucker et al., 2012; Rucker et al., 2019).

In Europe, the relationship between colony numbers and crop needs is less well matched. Analysis of national statistics indicates that the supply of honey bee colonies falls short of the demand from pollinator-dependent crops in a number of countries, and that this shortfall has widened as the area of dependent crops such

as oilseed rape has increased (Breeze et al., 2014). In Asia, where both *A. mellifera* and the native Asian honey bee *A. cerana* are managed, pollination is especially relevant to fruit, oilseed and vegetable seed production. In the Indian Himalaya, orchard crops such as apple, plum and pear are grown in areas where the numbers of wild pollinators are limited by terrain, weather at bloom and pesticide exposure, and the use of managed colonies has become a routine part of orchard management (Abrol, 2012). Because comparable price and production data are less consistently available in developing countries, formal valuation studies remain fewer, and this is an important knowledge gap.

Table 6. Selected published estimates of the economic value of pollination services.

Study	Scope	Reference year	Estimate	Notes
Morse & Calderone (2000)	United States; honey bees	2000	≈ US$14.6 billion	Dependence ratios × crop value × honey bee share
Gallai et al. (2009)	World; insect pollinators	2005	≈ €153 billion (≈ 9.5% of food production value)	Dependence-ratio method using FAO data
IPBES (2016)	World; all pollinators	2015	US$235–577 billion per year	Market value of pollinator-dependent crop output
Klatt et al. (2014)	Strawberry; experimental	Field trial	Higher market value from improved quality	Bee pollination improved shape, redness, firmness and shelf life

Note: estimates use different methods, currencies and years and are not directly comparable.

7.3 Crop case studies

Case studies illustrate how the abstract dependence ratios translate into practical reliance on honey bees (Table 7). The almond industry of California is the most prominent example. Almond is essentially dependent on insect pollination, flowering takes place in late winter when few other pollinators are active, and plantings cover an extremely large area. Growers therefore rent a large share of all colonies in the United States each February, and the movement of hives to almond orchards is probably the largest managed pollination event in the world (Rucker et al., 2012). Prices for this service respond to colony health and to alternative returns for beekeepers, which makes the almond market an informative window into the value that growers place on honey bee pollination (Rucker et al., 2019).

In temperate fruit production, apple is the classic honey bee crop. Apple flowers are self-incompatible and require cross-pollination, so orchards rely on a mix of wild insects and managed colonies, with the latter often providing the greater share of visits where orchards are large and natural habitat is scarce. In the western Himalaya, including Himachal Pradesh, apple orchards are concentrated on terraced slopes where bloom is short and often coincides with cold, wet weather that limits flight, and the placement of colonies at bloom is a widely recommended practice (Abrol, 2012). Oilseed rape and sunflower show a different pattern. Both are partly self-fertile, but insect pollination increases seed yield, oil quality and market value, and the large flowering area of these crops can attract and support many managed colonies (Bommarco et al., 2012). Strawberries and other soft fruits benefit mainly in quality (Klatt et al., 2014). Kiwifruit, whose flowers offer little nectar and whose male and female flowers are on separate plants, requires heavy stocking rates of colonies to ensure adequate pollen transfer (Delaplane & Mayer, 2000).

Table 7. Case-study crops and the role of honey bees in their pollination.

Crop	Dependence on pollinators	Role of honey bees	Main benefit
Almond	Essential	Colonies rented in very large numbers at late-winter bloom	Nut yield
Apple	Great (self-incompatible)	Principal managed pollinator; supplemented by wild bees	Fruit set, size and shape
Oilseed rape / sunflower	Modest (partly self-fertile)	Colonies placed at large fields to raise visitation	Seed yield, oil quality, market value
Strawberry	Modest to great (quality)	Supplement to wild bees	Fruit shape, firmness, shelf life
Kiwifruit	Essential	High stocking densities needed	Fruit size and seed number

Note: qualitative summary based on the cited literature.

8. Beyond Yield: Quality, Stability and Non-Market Value

Yield is only part of what pollination provides. Adequate pollination improves the size, shape, sugar content and shelf life of fruit and thus its commercial grade. A field experiment with strawberries showed that bee pollination

improved fruit quality, shelf life and market value, and that quality gains were as important as yield to growers (Klatt et al., 2014). Cross-pollination also raises the seed set and oil content of crops such as oilseed rape and sunflower, and it is essential for producing hybrid seed of many vegetables. The additional income arising from better quality is not always captured by yield-based valuation and suggests that dependence-ratio estimates may in some cases understate value.

Pollination can also reduce the risk associated with crop production. A diversity of pollinators stabilises pollination in variable weather, and managed honey bees provide an insurance layer where wild populations fluctuate. Beyond agriculture, honey bees contribute to reproduction of wild plants and thus indirectly support food webs, carbon storage in forests and cultural landscapes. These non-market values are the hardest to measure, and they are largely absent from the estimates in Table 6. Ecosystem-service assessments emphasise that ignoring them means undervaluing the full contribution of pollinators (Costanza et al., 2014; IPBES, 2016).

Finally, pollination has a nutritional dimension. Because pollinator-dependent crops provide a large share of dietary micronutrients, a reduction in pollination could shift diets and raise health burdens, particularly in low-income regions where food supply is already vulnerable. Although quantifying this effect is difficult, it reinforces the view that the value of pollination goes beyond the arithmetic of crop revenue.

9. Threats to Pollination Services and Economic Consequences

The service that honey bees supply is under pressure from multiple, interacting stressors. Reviews of pollinator declines identify habitat loss, agrochemicals, pathogens and parasites, invasive species and climate change as the main drivers, and emphasise that these factors combine in ways that are more harmful than any single stress alone (Potts et al., 2010; Goulson et al., 2015). For managed honey bees, the ectoparasitic mite *Varroa destructor* is widely regarded as the most damaging problem: it weakens bees directly and vectors viruses, notably deformed wing virus, whose global spread has been closely linked to the mite (Martin et al., 2012). Colony losses, including the phenomenon known as colony collapse disorder in the United States, have raised concern about the security of the managed supply (Neumann & Carreck, 2010; Ellis et al., 2010).

Pesticides and nutrition are further pressures. Field-realistic studies of neonicotinoid insecticides show negative effects on honey bees and wild bees in some countries and not others, indicating that outcomes depend on the environmental context (Woodcock et al., 2017). Loss of floral diversity through intensive agriculture can lead to nutritional stress, which in turn is thought to reduce colony resistance to disease (Naug, 2009; Brodschneider & Crailsheim, 2010). Climate change adds a further layer of risk by altering temperatures, rainfall and the timing of flowering, which can disrupt the match between colony development and forage availability (Le Conte & Navajas, 2008).

Economic models suggest that the consequences of a decline in pollination would be considerable. A macroeconomic analysis found that the loss of pollination would impose substantial welfare costs, distributed unevenly among regions and among consumers and producers, with larger effects on poorer populations (Bauer & Wing, 2016). At the level of farms, shortages of colonies raise rental fees, increase costs for growers and can prompt costly transport of hives across long distances. Studies of the pollination market show that colony health problems are transmitted to prices, and that growers and beekeepers adapt through changes in contract terms and management (Rucker et al., 2019).

10. Why the Value Remains Hidden and Policy Implications

The hidden nature of pollination value is a consequence of market structure. Pollination is a positive externality: much of the benefit accrues to growers of nearby crops, to consumers and to wild plants, while the beekeeper is compensated only where a rental market exists. In many regions, including much of the developing world, such markets are absent or thin, and farmers receive free pollination from hives that they neither own nor pay for. Because beekeepers cannot charge for that service, the incentive to maintain colonies and forage is weaker than the social benefit would justify, and the shortfall is felt only when pollinators decline.

Several policy responses follow from this analysis. First, pollination should be included in agricultural and environmental accounting so that policy makers see its value alongside that of crops and honey. Second, payments or support for beekeepers, such as extension training, disease management support, and rental-market development, can help secure supply. Third, integrated pest management and careful regulation of pesticides

reduce harm to bees and lower the need for replacement colonies. Fourth, habitat measures such as flower strips, hedgerows and preservation of natural vegetation in and around farmland strengthen both managed and wild pollinators and reduce dependence on a single species (Garibaldi et al., 2013). Finally, in countries where beekeeping is expanding, promotion of both *A. mellifera* and native *Apis* species, combined with quality queen breeding and disease surveillance, can build resilient pollination capacity.

11. Conclusion and Future Directions

Honey bees deliver an economic service that greatly exceeds the market value of the hive products they yield. Animal pollination affects a large proportion of crop species and about one third of global food production by volume, and published estimates place the value of pollinator-dependent crops in the hundreds of billions of dollars each year. Honey bees are not solely responsible for this value, but they are the pollinator that can be managed, moved and purchased, and in many production systems they are indispensable. The service is hidden because it is an externality without a price, and it is increasingly at risk because demand is growing faster than supply while colonies face parasites, pesticides, nutritional stress and a changing climate.

Several gaps remain. Valuation studies are concentrated in North America and Europe, and estimates for Asia, Africa and Latin America are scarce. Better data on crop-specific dependence, on the share of pollination performed by honey bees relative to wild species, and on the value of non-market benefits would improve accuracy. Dynamic models that include price responses, land-use change and nutritional outcomes are needed to judge the true cost of decline. Above all, communicating the value of pollination to farmers, policymakers and the public is essential for converting a hidden benefit into an explicit priority for conservation and sustainable agriculture.

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Crop Diversification: The Smart Way to Save Water and Improve Farm Income

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Introduction

Indian agriculture is facing a new challenge: producing more with fewer and increasingly uncertain natural resources. Water scarcity, erratic rainfall, declining groundwater levels, rising input costs and changing market conditions are making traditional crop choices increasingly difficult for farmers. In this situation, crop diversification offers a practical pathway towards sustainable and profitable farming. Crop diversification means moving from dependence on one or a few crops towards a suitable combination of crops, varieties, cropping systems and allied enterprises based on the available resources and market opportunities. It does not simply mean replacing one crop with another. Rather, it involves choosing the right crop for the right soil, water availability, climate and market. Recent ICAR assessments have highlighted a mismatch between water demand from existing cropping patterns and groundwater availability in several states, including Tamil Nadu. Alternative cropping systems have therefore been identified based on agro-climatic conditions, resource availability and market opportunities.

Why Crop Diversification Matters

In many agricultural regions, farmers traditionally depend heavily on crops that provide assured markets or have been cultivated for generations. However, a crop that is profitable in one location may not necessarily be suitable in another. Excessive dependence on water-intensive crops can place pressure on groundwater resources, particularly in drought-prone areas. Diversification provides an opportunity to reduce such pressure. Introducing pulses, millets, oilseeds, vegetables, fruits, fodder crops or other locally suitable crops can help farmers make better use of available soil moisture and irrigation resources. The objective should not be simply to reduce water use, but to increase the productivity of every unit of water used.

From Water-Intensive Crops to Water-Smart Crops

Water availability should become an important factor in crop planning. Farmers can consider short-duration, drought-tolerant and relatively water-efficient crops wherever they are agronomically and economically suitable. For example, pulses and oilseeds can provide alternatives in situations where continuous cultivation of water-demanding crops is difficult. Millets also have considerable importance in dryland agriculture because of their adaptability to relatively harsh growing conditions. Recent field initiatives have demonstrated this approach. In drought-prone areas of Odisha, ICAR-CRIDA promoted non-paddy crops such as pigeonpea, groundnut and maize as alternatives suited to local conditions.

Diversification Can Reduce Farm Risk

A farmer depending entirely on a single crop is exposed to multiple risks. Failure of the crop due to drought, pest attack, disease outbreak or an unexpected fall in market price can seriously affect the household income. Diversification distributes this risk. If one crop performs poorly, another crop or allied enterprise may provide income. A diversified farm can therefore function as a risk-management system. Crop diversification can also be combined with livestock, poultry, goat rearing, beekeeping, agroforestry or horticulture. Such integrated systems can provide multiple sources of income throughout the year.

Diversification and Soil Health

Crop diversification is also important for maintaining soil health. Continuous cultivation of the same crop can contribute to nutrient imbalance and increased pest and disease pressure. Including legumes and crops with different nutrient requirements can improve nutrient cycling and contribute to better soil management. Crop residues can also be incorporated into farming systems rather than being treated as waste. Proper residue

management improves organic matter recycling and reduces environmental problems associated with residue burning.

The Market Must Come Before the Crop

One of the most important principles of successful diversification is "market first, crop next." A farmer should not choose a crop merely because it requires less water. The expected price, local demand, storage facilities, processing opportunities, transportation, availability of quality seed and technical support should also be considered. High-value horticultural crops, pulses, oilseeds, millets and value-added products may provide attractive opportunities in suitable locations. However, market fluctuations can also create risks. Therefore, farmers should preferably diversify gradually rather than shifting the entire farm area to a new crop at once.



Role of Farmer Producer Organisations

Farmer Producer Organisations can make diversification more effective by helping farmers overcome individual marketing constraints. Collective procurement of inputs, aggregation of produce, grading, processing, branding and direct marketing can improve farmers' bargaining power. For crops with limited local markets, collective marketing and value addition can make diversification economically more attractive.

Technology Can Make Diversification Smarter

Modern agricultural technologies can support crop diversification through weather-based advisories, soil testing, satellite-based crop monitoring, precision irrigation and digital market information. Soil Health Cards and location-specific agro-advisories can help farmers select crops according to soil and resource conditions. Precision irrigation technologies such as drip and sprinkler systems can further improve water-use efficiency. The future of diversification therefore lies not simply in growing more crops, but in making scientifically informed decisions about which crops should be grown, where they should be grown and how they should be marketed.

A Sustainable Path for the Future

Crop diversification is not a universal formula in which one crop should be replaced everywhere by another. It is a location-specific strategy. Soil type, rainfall, irrigation availability, climate, farm size, labour, market access and farmer preferences must all be considered. Recent ICAR emphasis on resource-based crop planning highlights the importance of matching cropping patterns with natural-resource availability and local conditions. For Indian agriculture, diversification can therefore become an important bridge between water conservation, climate resilience and improved farm income. The smart farmer of the future may not necessarily be the farmer who produces the maximum quantity of a single crop, but the farmer who uses every drop of water, every piece of land and every available resource more efficiently.

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Climate Change and Its Impact on Honey Bee Health and Productivity

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Abstract

Honey bees (*Apis* spp.) are central to honey production and to the pollination of many crops and wild plants, yet their health and productivity are strongly shaped by climate. This review examines how climate change, including warming, altered precipitation, more frequent extreme events and rising atmospheric CO_2, affects honey bee colonies through four broad pathways: physiology and thermoregulation, foraging behaviour, floral resources and their timing, and the dynamics of pests and pathogens. Warming can extend the foraging season and speed colony build-up in cool regions, but heat, drought and erratic winters can reduce foraging, disrupt brood rearing, deplete food stores and increase overwintering losses. Shifts in flowering time may create mismatches between colony demand and forage supply, and changes in temperature and brood availability can favour the parasitic mite *Varroa destructor* and the microsporidian *Nosema ceranae*. Climate acts together with pesticides, poor nutrition and habitat loss, so that its effects are often multiplied rather than simply added. We compare vulnerabilities across temperate, semi-arid, tropical and mountain regions, summarise adaptation options ranging from apiary management to landscape planning and breeding, and identify research gaps. Evidence for direct effects on managed *A. mellifera* remains less complete than for wild bees, and long-term, region-specific monitoring is needed to guide adaptive beekeeping.

Keywords: climate change; honey bee health; *Apis mellifera*; thermoregulation; phenological mismatch; *Varroa destructor*; colony losses; honey productivity; adaptation

1. Introduction

The honey bee *Apis mellifera* and its Asian relatives, notably *A. cerana*, provide honey and other hive products and contribute to the pollination of many crops and wild plants (Klein et al., 2007; IPBES, 2016). The ability of these insects to keep this role depends on colony health and productivity, which are governed by temperature, moisture, floral resources and the community of parasites and pathogens the colony encounters. All of these are affected by climate.

The scale of climatic change is now well documented. The Intergovernmental Panel on Climate Change reports that global surface temperature in 2011–2020 was about 1.1 °C higher than in 1850–1900, and that heat extremes, heavy precipitation and agricultural and ecological droughts have become more frequent and intense in many regions (IPCC, 2021). Projections indicate further warming and increased variability during this century unless emissions are strongly reduced (IPCC, 2023). Such changes act on organisms directly through physiological tolerances and indirectly through ecological interactions, and pollinators are no exception (Settele et al., 2016).

Research on climate and pollinators has focused heavily on wild bees, especially bumble bees, which show range contractions at warm southern margins and limited expansion at cooler northern margins (Kerr et al., 2015; Soroye et al., 2020). Managed honey bees are often assumed to be buffered because beekeepers can feed, move and treat colonies and because the species occupies an extremely broad climatic range. That assumption deserves scrutiny. Colonies are sensitive to weather at critical times in their annual cycle, their performance depends on the alignment of forage with colony development, and beekeeping practice is itself tuned to the local climate (Le Conte & Navajas, 2008; Vanbergen & the Insect Pollinators Initiative, 2013).

This review synthesises current knowledge on the impact of climate change on honey bee health and productivity, with illustrations of colony biology and global data. Section 2 introduces the climate-sensitive biology of the colony. Section 3 describes the climatic drivers and pathways of effect. Section 4 explains the climatic sensitivity of colony biology, and Section 5 reviews impacts on health, including physiology, nutrition, phenology, disease and stressor interactions. Section 6 considers productivity, Section 7 compares regions, Section 8 outlines adaptation strategies and Section 9 identifies knowledge gaps. Section 10 concludes.

2. Climate-Sensitive Biology of the Honey Bee Colony

To understand how climate affects honey bees, it is necessary to appreciate how closely colony biology is tied to temperature and season. A colony is a eusocial unit made up of a single fertile queen, tens of thousands of sterile workers and, in the breeding season, a few hundred drones (Winston, 1987). The queen lays eggs in wax cells, and each egg passes through larval and pupal stages before emerging as an adult, a process that takes about 21 days for a worker, 16 for a queen and 24 for a drone (Figure 1). The developing brood is the colony's most thermally sensitive component, since it requires a stable temperature of about 34–35 °C. Pupae that develop outside the optimum range emerge as adults with reduced behavioural performance, including poorer dance communication and learning, even if the deviation is only a degree or two (Tautz et al., 2003).

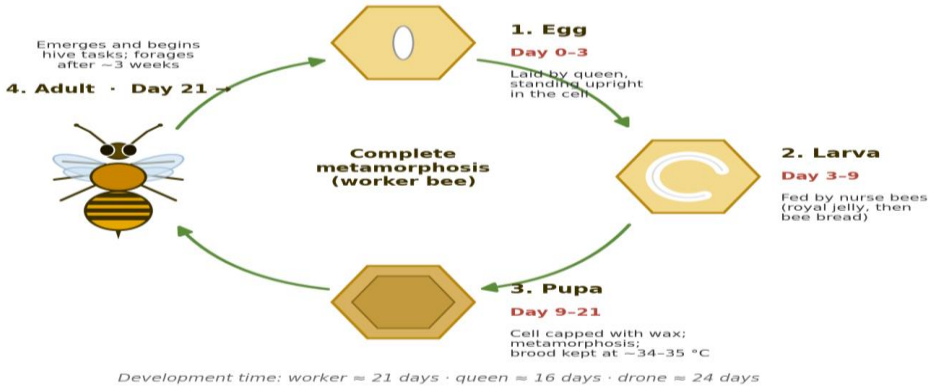


Figure 1. Life cycle of the worker honey bee. The sealed pupal stage is held at about 34–35 °C by the colony, which makes development sensitive to heat and cold (schematic illustration).

Colonies in temperate regions follow an annual cycle that is driven by day length, temperature and forage (Figure 2). In winter the colony shrinks to a cluster of workers that generates heat by muscle activity and consumes stored honey. In spring brood rearing expands, followed by rapid growth of the worker population, swarming, and peak foraging during the main nectar flow. In late summer and autumn the colony raises long-lived winter bees and reduces brood. Each phase depends on weather and on the timing of floral resources, and a disturbance at one stage, such as a warm spell that triggers early brood rearing, can carry over to the next (Winston, 1987; Seeley, 1995).

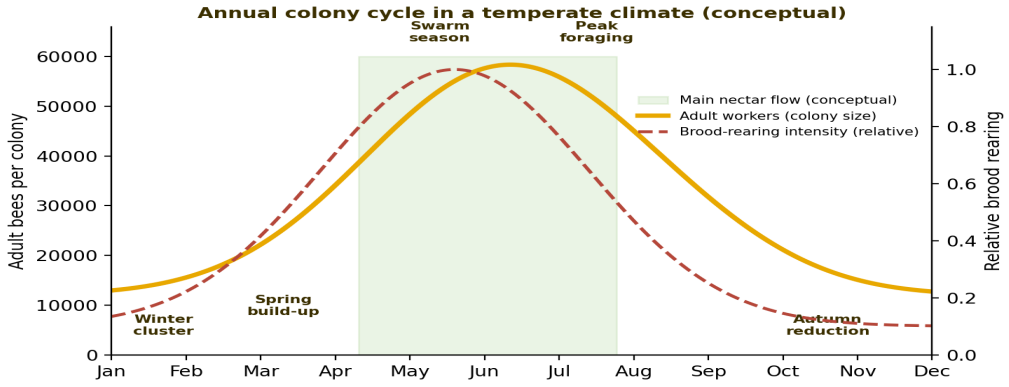


Figure 2. Conceptual annual cycle of a honey bee colony in a temperate climate, indicating the timing of brood rearing, colony growth and the main nectar flow (illustrative, not measured data).

Unlike most insects, the colony does not simply track ambient temperature. Workers regulate nest temperature collectively (Figure 3). In the cold they cluster and generate heat by shivering the flight muscles, and the cluster density adjusts to the temperature outside. In the heat they fan the nest to move air, and they collect water that is spread in thin layers and evaporated to cool the brood area (Kühnholz & Seeley, 1997; Stabentheiner et al., 2010). This social thermoregulation makes colonies far more tolerant of climatic variation than solitary insects, but it also creates costs in terms of food consumption and labour that may be diverted from foraging. As a result, the effects of climate on honey bees are often indirect: they act through the energy and workforce that colonies must spend on maintaining their internal environment.

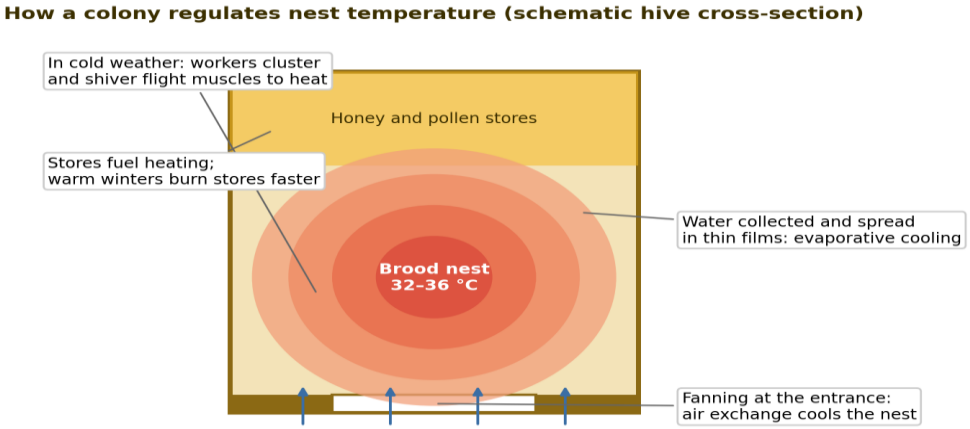


Figure 3. Schematic cross-section of a hive showing the central brood nest and the main behaviours that regulate its temperature (illustrative).

3. Climate Drivers and Pathways of Effect on Honey Bees

Four aspects of climate change are particularly relevant to honey bees. The first is rising mean temperature, which alters the length of the active season, the rate of brood development and the energy cost of maintaining the nest. The second is altered precipitation and increasing drought, which change nectar secretion, pollen availability and water balance. The third is greater frequency of extreme events such as heat waves, cold snaps, storms and floods, which can cause abrupt colony failure. The fourth is elevated atmospheric CO_2, which changes plant chemistry and can reduce the nutritional quality of pollen (Ziska et al., 2016).

Observed and projected warming provide the background for these effects. Figure 4 shows the warming recorded in 2011–2020 relative to the pre-industrial baseline, together with the best-estimate warming projected for the end of the century under five emission scenarios assessed by the IPCC (2021). Only under the very-low-emissions scenario does the end-of-century estimate approach 1.5 °C, and under the high-emission scenarios the best estimates exceed 3–4 °C. Regional changes are often larger than the global mean; land areas, high latitudes and many mountain regions are projected to warm faster than the global average, so that the pace of change experienced by bee colonies in these places may be considerable.

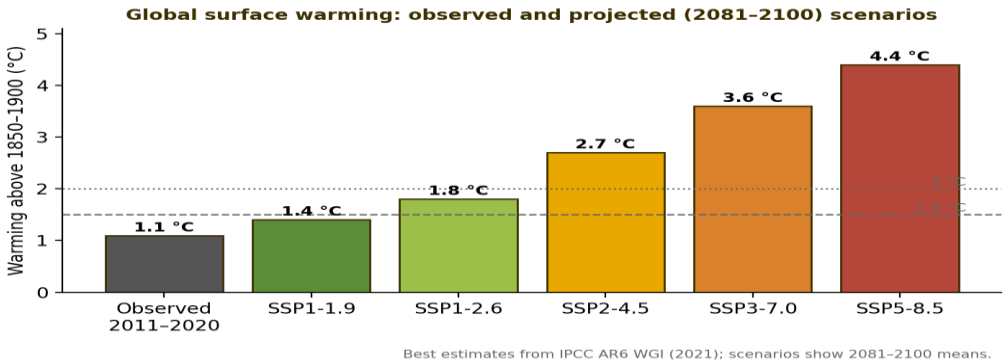


Figure 4. Observed global warming (2011–2020) and best-estimate projected warming for 2081–2100 under five IPCC shared socioeconomic pathways (values from IPCC AR6 WGI, 2021).

These drivers influence colonies through the linked pathways shown in Figure 5: direct effects on colony physiology and thermoregulation; effects on foraging activity and flight range; changes in the quantity, quality and timing of floral resources; and changes in pests, pathogens and natural enemies. The outcomes are brood rearing and overwintering success, nectar and pollen intake, and disease load. Together, these determine colony health, honey productivity and the pollination service that the colony delivers.

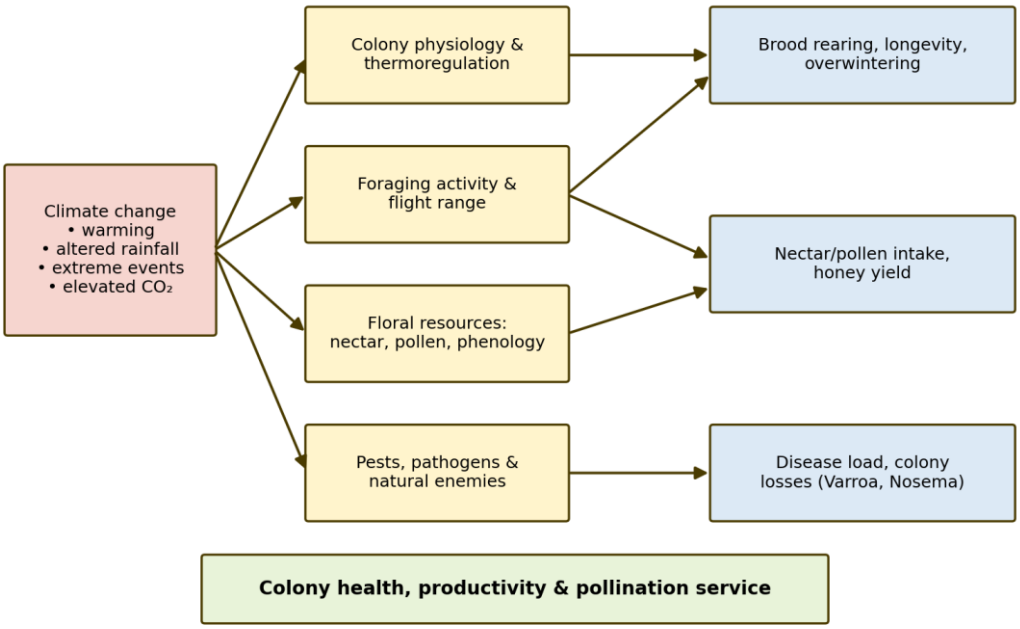


Figure 5. Conceptual pathways through which climate change affects honey bee colonies and the services they provide.

Table 1. Principal climatic drivers, mechanisms and likely effects on honey bee colonies.

Climatic driver	Main mechanism	Likely effects on colonies	Strength of evidence*
Warming (mean)	Longer active season; faster brood development; altered winter cluster energetics	Earlier build-up and longer foraging in cool regions; risk of heat stress and higher stores consumption in warm regions	Moderate
Heat waves	Hive overheating; increased water demand; reduced foraging above thermal limits	Lower forage intake, brood stress, absconding in some situations	Moderate
Drought / reduced rainfall	Lower nectar secretion and flowering; water scarcity	Reduced honey flow, dearth periods, nutritional stress	Moderate
Heavy rain, storms, floods	Foraging days lost; hive damage; forage washed out	Starvation risk during prolonged wet spells; apiary loss	Moderate
Milder, erratic winters	Interrupted cluster; early brood rearing; continuous brood for mites	Faster depletion of stores; higher Varroa build-up; winter losses	Moderate
Shifted flowering time	Change in overlap between forage and colony demand	Phenological mismatch; forage gaps at key growth stages	Low to moderate
Elevated CO_2	Changes in plant chemistry, e.g. lower pollen protein	Possible reduction in nutritional quality of forage	Low

Indicative qualitative assessment by the author based on the literature reviewed; evidence for managed A. mellifera is generally weaker than for wild bees.*

4. Climatic Sensitivity of Honey Bee Colony Biology

4.1 Thermoregulation and the brood nest

Honey bee colonies are unusual among insects in that they regulate the temperature of their nest. The brood area is maintained at approximately 32–36 °C, and deviations outside this range harm larval and pupal development (Seeley, 1995). Bees warm the nest by clustering and by shivering the flight muscles, and they cool it by fanning and by evaporative cooling with water carried into the hive (Kühnholz & Seeley, 1997). This capacity gives colonies considerable resilience but at a cost: as ambient temperatures rise, more workers must be diverted from foraging and brood care to water collection and fanning, and in cold or unstable winters more honey must be burned to maintain the cluster.

Different races and ecotypes of *A. mellifera* differ in their tolerance of temperature and humidity, indicating that local adaptation may govern responses to climate (Abou-Shaara et al., 2012). As a general rule, however, the thermoregulatory system operates within limits, and prolonged heat, unseasonal cold or rapid temperature swings can exceed the compensatory capacity of a colony, particularly when it is small, weak or short of stores.

4.2 Foraging activity

Foraging is strongly constrained by weather. Workers begin to forage when temperatures rise above roughly 10–12 °C, and activity increases with temperature and light before declining under very hot, dry or windy conditions (Abou-Shaara, 2014). Rain and strong wind suppress flight altogether. Climate change can therefore lengthen the foraging window in cool regions, but it may compress foraging into cooler parts of the day, or interrupt it entirely, in hot regions. Figure 6 illustrates this concept: foraging performance follows a humped response to temperature, and brood development is maintained within a narrower optimum. As the temperature range shifts, a colony may gain foraging time at one end of the season and lose it at the other.

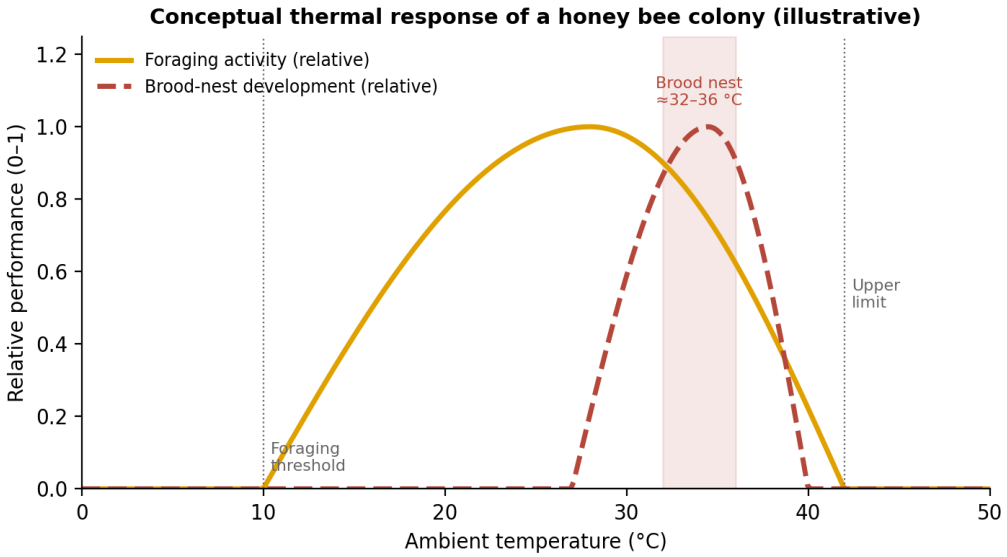


Figure 6. Conceptual (illustrative, not measured) relationship between ambient temperature and relative foraging and brood-development performance of a honey bee colony.

4.3 Reproductive health of queens and drones

Reproduction is a particularly sensitive part of the colony cycle. Queen quality is a major determinant of colony performance, and queens that have been exposed to heat or cold during shipping or in the apiary can suffer a loss of fertility, as shown by a study in which exposure to temperatures outside the normal range reduced sperm viability in the stored semen of queens and was associated with premature queen failure (McAfee et al., 2020). Drones are likewise sensitive to temperature, and the reproductive quality of males can be reduced by heat or poor nutrition, which could limit the successful mating of queens (Rangel & Fisher, 2019). These effects are important for beekeeping, which relies on the regular replacement of queens, and they illustrate how climate can influence colony productivity through mechanisms that are not easily seen in colony counts.

5. Impacts on Colony Health

5.1 Overwintering and colony survival

Winter survival is a bottleneck for colonies in temperate regions, and it depends on the size of the winter bee population, the quantity of stores and the weather. Statistical analysis of winter mortality in Austria showed that seasonal temperature and precipitation contribute to colony loss, which demonstrates that overwintering success is climate-sensitive even in well-managed apiaries (Switanek et al., 2017). Warm spells in winter can lead bees to leave the cluster and resume brood rearing early, consuming stores faster and exposing bees to cold snaps that follow; milder winters also allow continuous brood production, which favours parasites (Le Conte & Navajas, 2008). On the other hand, warmer winters may reduce direct cold mortality in very cold regions, so net effects depend on the baseline climate and on management.

5.2 Floral resources and phenology

Honey bees depend on nectar and pollen from a succession of plants throughout the season. Nutrition affects immunity, longevity and colony growth, and nutritional stress increases vulnerability to disease (Brodschneider & Crailsheim, 2010; Dolezal & Toth, 2018). Climate change can affect forage in several ways. Drought and heat reduce the flowering intensity and nectar secretion of many species. Warming advances the flowering of many plants, and in some cases alters the sequence of flowering, potentially opening gaps in forage between major flows. Increasing CO_2 lowers the protein concentration of pollen in at least some plants, as shown for goldenrod, a key late-season resource for North American bees (Ziska et al., 2016).

The temporal match between plants and pollinators is a central concern. Simulation of phenological shifts in plant–pollinator networks indicated that some pollinator species could lose a significant fraction of their food supply if flowering and pollinator activity move apart (Memmott et al., 2007). Reviews of warming effects on plant–pollinator interactions underline the potential for mismatches but note that outcomes vary among species and systems (Hegland et al., 2009; Gérard et al., 2020). In eastern North America, long-term records showed that spring-flying bees and the plants they visit have advanced their timing at broadly similar rates, suggesting that mismatch is not universal (Bartomeus et al., 2011). For managed honey bees, the situation has an additional complication: colony growth is driven by both temperature and stored resources, so warmth in early spring can prompt brood expansion before forage is available, whereas late-season drought can leave bees under-provisioned before winter (Figure 7).

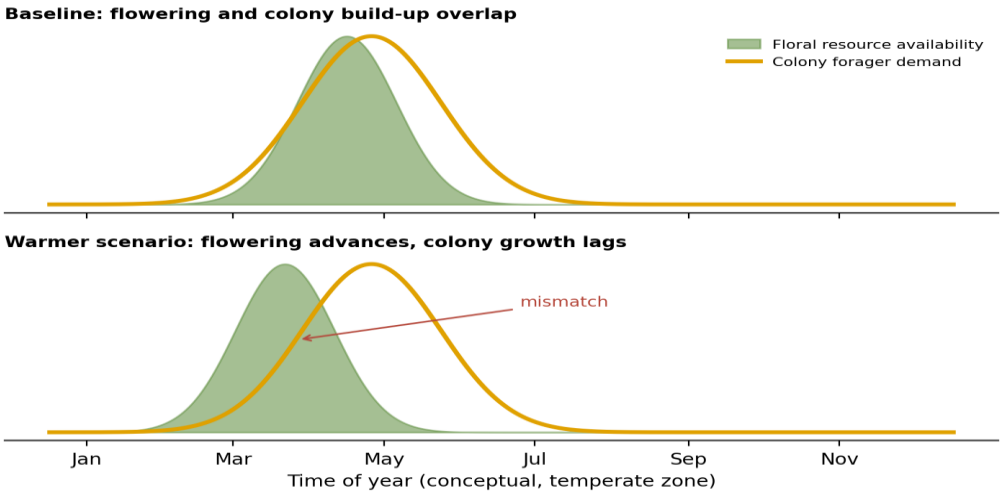


Figure 7. Conceptual illustration of phenological mismatch: advancement of flowering under warming relative to colony demand (schematic, not empirical data).

5.3 Pests and pathogens

Climate can influence the parasites and diseases of honey bees by changing the bees' condition, the pathogen's own biology and the opportunities for transmission. The parasitic mite *Varroa destructor* reproduces inside capped brood, so its population growth is tied to the availability of brood. Regions and seasons with warmer conditions and longer brood-rearing periods can support more mite generations per year, which increases pressure

on colonies and increases the spread of viruses such as deformed wing virus (Le Conte & Navajas, 2008; Martin et al., 2012). This helps explain why colony losses attributed to Varroa and associated viruses are of particular concern in mild climates.

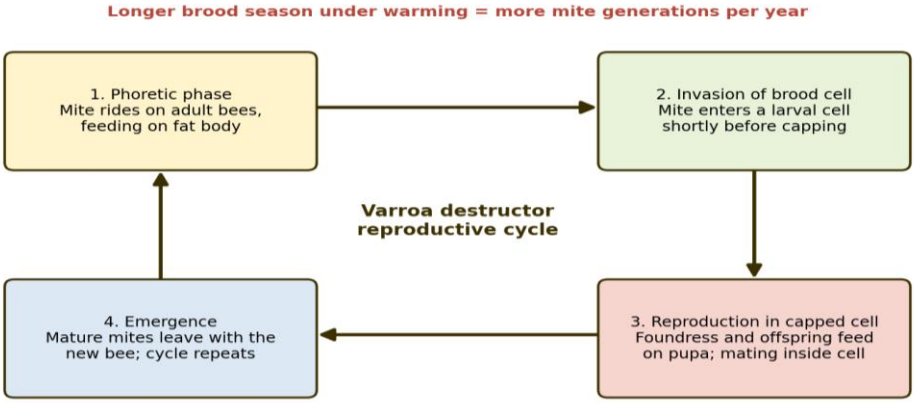


Figure 8. Reproductive cycle of the parasitic mite *Varroa destructor*. Because reproduction occurs in sealed brood, longer brood-rearing seasons favour higher mite populations (schematic illustration).

The reproductive biology of *Varroa* is shown in Figure 8. A foundress mite enters a brood cell shortly before it is sealed, lays eggs on the developing pupa and, together with her offspring, feeds on the bee's fat body and transmits viruses, before emerging with the new adult and moving to other bees (Rosenkranz et al., 2010; Ramsey et al., 2019). Because the number of mite generations that can occur in a year depends on the number of weeks in which brood is present, any climatic change that extends brood rearing can accelerate mite build-up.

Temperature also affects the microsporidian gut parasites *Nosema apis* and *N. ceranae*. Laboratory work indicates that *N. ceranae* tolerates higher temperatures than *N. apis*, which may have contributed to its success in warmer regions (Martín-Hernández et al., 2009). Beyond individual pathogens, climatic stress can weaken immunity and thereby raise susceptibility. Warmer conditions may also facilitate the range expansion of other threats, such as small hive beetle and Asian hornets, although the role of climate in these cases is still being resolved.

5.4 Interactions with other stressors

Climate change rarely acts alone. Honey bees are simultaneously exposed to pesticides, pathogens, habitat loss and management pressures, and these stressors interact (Potts et al., 2010; Goulson et al., 2015). Poor forage, for example, increases sensitivity to pesticides and parasites, while heat and drought both reduce the availability of nutritious pollen and raise the cost of colony maintenance. Because of such interactions, the effect of climate change is often larger than would be predicted from single-factor studies, and separating the climatic contribution from other factors remains a major challenge (Vanbergen & the Insect Pollinators Initiative, 2013).

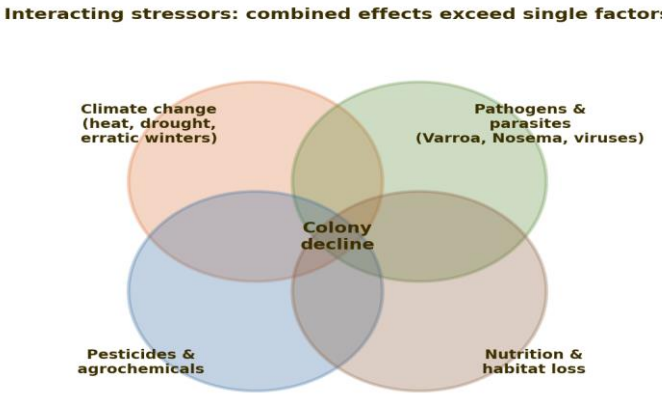


Figure 9. Conceptual overlap of the main stressors affecting honey bee colonies; climate acts alongside, and often magnifies, other pressures (schematic).

6. Impacts on Productivity

Colony productivity is measured in honey yield, colony strength, queen and brood production and, for pollination services, the number and quality of colonies available at crop bloom. Climate affects each of these. Honey yield is determined chiefly by the intensity and duration of nectar flows, which are sensitive to temperature, rainfall and soil moisture. In dry or erratic seasons, flows may be short or fail, leading to low surpluses and requiring supplementary feeding. In contrast, in cool regions where the season has been short, warming may raise the total number of foraging days and improve yields, at least while forage remains adequate. The net response therefore varies between regions and years, and no single direction of change applies everywhere (Le Conte & Navajas, 2008).

Climate also affects beekeeping operations. Earlier springs alter the optimal timing of colony management, splitting and queen rearing. Heat can limit the success of queen mating flights and the storage of hive products. In migratory beekeeping, hive movements are timed to fit flowering calendars, and shifts in bloom time can leave colonies mis-timed for key crops. For the pollination market, colony losses and weak colonies at bloom raise the cost and risk to growers, as outlined in the economic literature on pollination services (Rucker et al., 2019; IPBES, 2016).

The link between climate, honey bee health and agricultural production is especially important for crops that depend on managed pollination. A reduction in the number or vigour of colonies at bloom reduces the pollination available to crops such as almond, apple and oilseeds, and the consequences will be greatest where wild pollinators are also declining (Klein et al., 2007; Settele et al., 2016). Thus, climate impacts on honey bees are not only a beekeeping issue but also a food-production and economic issue.

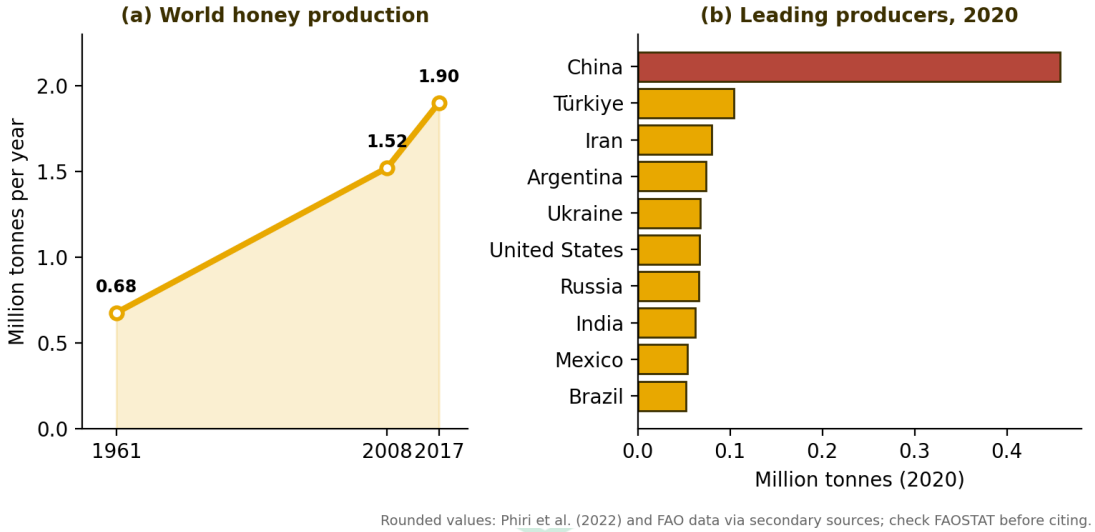


Figure 10. (a) World honey production at three anchor years (1961, 2008, 2017; values after Phiri et al., 2022, and FAO as reported in secondary sources) and (b) leading honey-producing countries in 2020 (FAO data as reported in secondary sources). Values are rounded; check against FAOSTAT before citing.

At the global scale, honey production has increased over the past six decades (Figure 10). An analysis of FAO data for 1961–2017 found that managed colonies increased by about 85%, honey production by about 180%, and honey produced per colony by about 45%, although the number of colonies per head of human population declined (Phiri et al., 2022). The trend shows that beekeeping has so far been resilient in aggregate, but global totals conceal strong regional differences, and year-to-year production in individual countries can fall sharply during drought or unfavourable spring weather. Aggregate statistics also do not capture the effort and cost required to maintain colonies, such as feeding and replacement of lost colonies, which may rise as climatic stress increases.

7. Regional Perspectives

The response of honey bees to climate change differs between regions, because baseline conditions, bee races and beekeeping systems are different. Table 2 and Figure 11 summarise the main risks in four broad regions. In

temperate areas the main concerns are overwintering under variable winters, phenological mismatch and increased parasite pressure. In Mediterranean and semi-arid regions, drought, heat and reduced flowering are dominant threats, and colonies may need supplementary feeding and water. In tropical and subtropical areas, colonies already operate near thermal limits and face intense rainy seasons and dearth periods, where local subspecies and native *Apis* species may be better adapted than introduced stocks.

Mountain regions, including the Himalaya, deserve special attention. Warming shifts the elevation zones of vegetation, and the flowering of temperate fruit and wild plants at a given altitude is changing in timing, so beekeepers, who often move colonies along altitudinal gradients, must adjust their calendars. Orchard crops in hill regions depend heavily on managed colonies for pollination during a short bloom period (Abrol, 2012), and a mismatch between bloom and cold, wet spring weather that limits flight could sharply reduce pollination. Mountains are also expected to warm at rates that vary with elevation, which adds uncertainty to local forecasts (IPCC, 2021). Both *A. mellifera* and the native *A. cerana* are kept in such regions, and their relative resilience to climate change is an important research question.

Table 2. Broad regional vulnerabilities of honey bee colonies to climate change and management implications.

Region type	Key climate risks	Implications for beekeeping
Cool temperate	Variable winters; early spring build-up; phenological mismatch; more brood-season Varroa	Monitor stores and mites; adjust timing of splitting and feeding; ensure diverse forage
Mediterranean / semi-arid	Drought; heat waves; shorter or failed nectar flows	Water sources and shade; supplementary feeding; migratory access to reliable forage
Tropical / subtropical	Intense rainy seasons; dearth periods; thermal stress; pests	Use locally adapted stock; manage absconding; protect hives from flooding and heat
Mountain (e.g. Himalaya)	Shifting elevation zones and bloom timing; erratic spring weather	Altitudinal migration planning; flexible calendars; strengthen colonies before bloom

Note: summary is qualitative and generalises across highly variable local conditions.

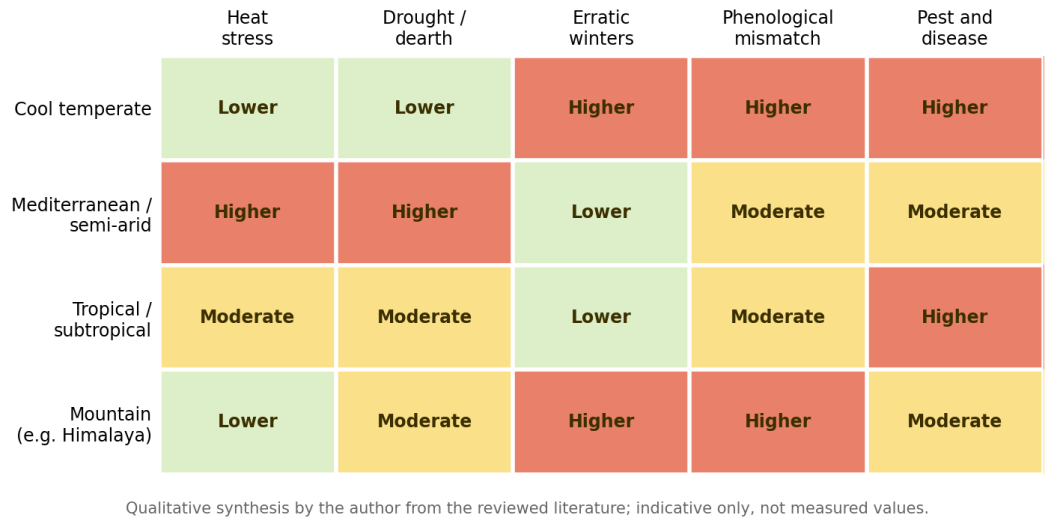


Figure 11. Qualitative comparison of the relative importance of major climate-related risks to honey bee colonies in four broad regional types (indicative synthesis of the reviewed literature).

8. Adaptation Strategies

Because managed colonies can be influenced by beekeepers, adaptation options exist at several levels, summarised in Table 3. At the apiary level, careful monitoring of colony weight, stores and mite levels, timely feeding during dearth, shading and ventilation of hives, and provision of clean water can help colonies cope with heat and drought. Integrated Varroa management is especially important where warming extends the brood

season. At the population level, selection of stock with hygienic behaviour, mite resistance and suitable overwintering ability can improve resilience, and maintaining genetic diversity, including local races, preserves adaptive potential (Abou-Shaara et al., 2012).

At the landscape level, diverse and continuous forage is a fundamental buffer against climate variability. Planting or retaining plant species with different flowering times, drought-tolerant nectar plants, hedgerows and flower strips can reduce dearth gaps and spread risk (Goulson et al., 2015). Policy and institutional measures are equally important: long-term monitoring of colony losses and phenology, extension services that train beekeepers in adaptive management, and integration of pollinators into climate adaptation and agricultural planning (IPBES, 2016; Settele et al., 2016). Adaptation should be region-specific, since the same management practice may help in one climate and not in another.

Table 3. Adaptation options to reduce climate risk to honey bee colonies.

Level	Options	Expected benefit
Apiary management	Colony monitoring; supplementary feeding; shade, ventilation and water; integrated Varroa control; adjusted timing of splitting and queen rearing	Reduces heat, dearth and disease stress; improves overwintering
Breeding and genetics	Select for hygienic behaviour, mite tolerance and local adaptation; conserve local races and native *Apis* species	Improves resilience and adaptive capacity
Landscape and forage	Diverse, sequential flowering plants; drought-tolerant forage; hedgerows and flower strips; protection of natural vegetation	Buffers against forage gaps and mismatch
Policy and knowledge	Long-term monitoring; beekeeper training; climate-informed pollination planning; pesticide regulation	Supports evidence-based, region-specific responses

9. Knowledge Gaps and Research Priorities

Despite growing interest, several gaps limit our ability to predict the effects of climate change on honey bees. First, most evidence on climate effects on pollinators comes from wild bees and from temperate regions of Europe and North America, while data for tropical and Asian systems, and for native *Apis* species, are sparse. Second, field studies that separate climatic effects from management, pesticide exposure and disease are limited, and long-term data linking colony performance to weather remain patchy. Third, mechanistic understanding of how heat and humidity affect brood, queens and drones, and how they interact with pathogens, needs further study. Fourth, models that combine bee biology, forage phenology and beekeeping management are needed to project regional risk and to test adaptation options.

Priority actions therefore include establishing standardised long-term monitoring of colony performance and phenology across climatic zones, experimental studies on interactions between heat, nutrition, pesticides and pathogens, and participatory work with beekeepers to test adaptation practices under local conditions. Improved communication between climate scientists, ecologists and beekeepers would help to translate emerging knowledge into practical guidance.

10. Conclusion

Climate change affects honey bee health and productivity through physiology and thermoregulation, foraging behaviour, floral resources and their timing, and pests and pathogens. The direction of change is not uniform: warming may lengthen the active season in cool regions, but heat, drought, erratic winters and phenological mismatch threaten colonies in many others, and climatic effects interact with pesticides, poor nutrition and disease to amplify risk. Managed honey bees are more resilient than many wild pollinators because beekeepers can intervene, but this resilience has limits and depends on knowledge, resources and forage that climate change itself may erode.

Sustaining honey production and pollination in a changing climate will require adaptive apiary management, stock suited to local conditions, diverse landscapes that supply forage across the season, and supportive policy

and research. Because honey bee pollination underpins crop production and rural livelihoods, safeguarding colonies against climate risk is a matter of food security as well as apiculture.

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Digital Twin of a Watershed: Can We Simulate the Future Before It Happens?

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Introduction:

Can We See Tomorrow's Watershed Today?

Imagine that before constructing a check dam, farm pond or contour bund, we could first test its possible effects on a computer. Imagine being able to ask: *Where will runoff accumulate during an extreme rainfall event? Which parts of the watershed are most vulnerable to soil erosion? How much water may be available during a drought? What could happen if land use changes over the next ten or twenty years?*

These questions are becoming increasingly important as watersheds face changing rainfall patterns, droughts, floods, soil erosion, groundwater stress, land-use changes and increasing agricultural water demand. Watershed management traditionally depends on field surveys, rainfall records, soil information, topographic maps, hydrological analysis and engineering knowledge. These remain essential. However, advances in remote sensing, Geographic Information System (GIS), Internet of Things (IoT), artificial intelligence (AI), cloud computing and hydrological modelling are creating new possibilities for more dynamic watershed management.

One emerging concept is the **Digital Twin of a Watershed**—a virtual representation of a real watershed that combines data, models and observations to understand present conditions and explore possible future scenarios. Research has already demonstrated watershed-oriented Digital Twin platforms capable of integrating geospatial information, real-time observations, simulation models and decision-support functions.

What is a Digital Twin?

A Digital Twin is a dynamic digital representation of a real-world system. It combines information about a physical system with digital models, data and, where available, continuously updated observations. The concept is already being applied or explored in areas such as manufacturing, infrastructure, transportation, water resources and environmental management.

A watershed is a particularly suitable system for this concept because it is made up of interconnected natural and human components. Rainfall interacts with soil, topography, vegetation, agricultural land, streams, groundwater and water-harvesting structures. Therefore, a Watershed Digital Twin can be understood as "A dynamic digital representation of a real watershed that integrates spatial, environmental, hydrological and field data with scientific models and computational tools to monitor, simulate and support watershed-management decisions."

The concept goes beyond simply creating a digital map. Research on Digital Twin watersheds emphasizes the connection between the physical watershed and its virtual representation, including real-time synchronization, simulation, interaction and decision support.

Digital Model vs Digital Twin

The terms *digital model* and *Digital Twin* are closely related but are not exactly the same. A **digital model** can simulate a watershed using available data. For example, a rainfall-runoff model can estimate runoff generated from a particular rainfall event. A **Digital Twin** goes further by establishing a continuing connection between the

real and virtual systems. New information from satellites, weather stations, sensors and field observations can be incorporated to update the virtual watershed.

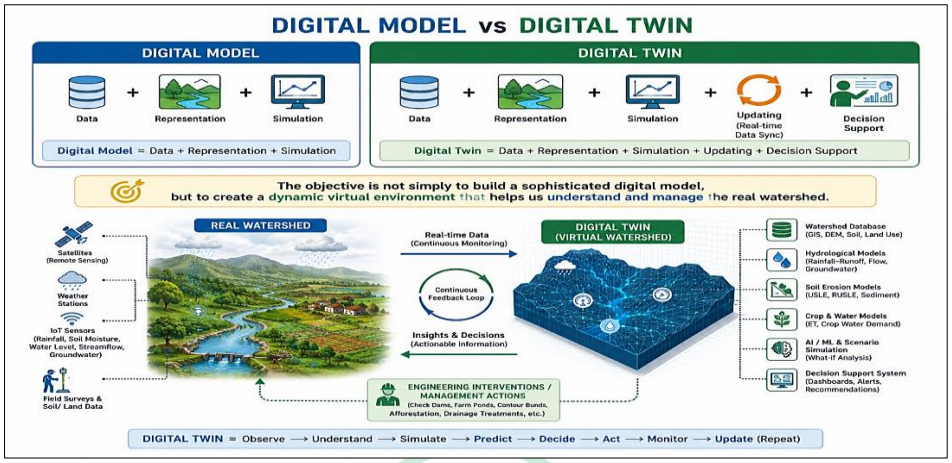


Fig. 1. Conceptual comparison of a digital model and a Digital Twin for watershed management.

Building Blocks of a Watershed Digital Twin

A Watershed Digital Twin requires several technologies and datasets working together.

1. Geographic Information System (GIS)

GIS provides the spatial foundation of the Digital Twin. It can integrate:

- watershed and sub-watershed boundaries
- drainage networks
- soil types
- land use and land cover
- elevation and slope
- agricultural areas
- roads and settlements
- water-harvesting structures

2. Remote Sensing and Satellites

Satellite observations allow large watersheds to be monitored repeatedly without requiring field measurements at every location.

Remote sensing can support assessment of:

- land use and land-cover changes
- vegetation condition
- agricultural areas
- surface water
- drought and vegetation stress
- changes in watershed condition

3. Digital Elevation Models

Topography controls how water moves across a landscape. Digital Elevation Models (DEMs) help derive:

- elevation
- slope
- flow direction
- flow accumulation
- drainage networks
- sub-watersheds

Since water generally flows from higher to lower elevations, terrain information is fundamental to watershed simulation.

4. Weather and Hydrological Data

Rainfall, temperature, humidity, wind speed, solar radiation and evapotranspiration provide information about atmospheric conditions.

Additional observations such as:

- streamflow
- groundwater level
- soil moisture
- reservoir storage
- farm pond water level

can improve the representation of water movement and storage.

5. IoT and Field Sensors

IoT sensors can provide near-real-time information about the watershed.

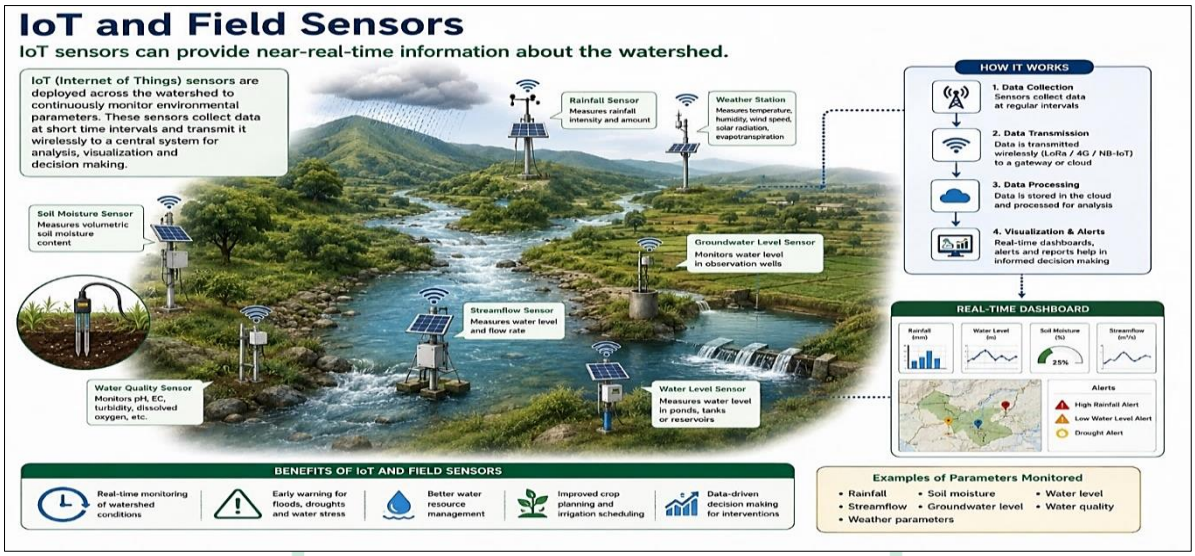


Fig. 2. Role of IoT and field sensors in providing near-real-time watershed information.

These observations can be transmitted to a digital platform and used to update the virtual watershed.

6. Hydrological and Soil-Water Models

Scientific models provide the computational intelligence needed to simulate watershed processes.

They can represent:

- rainfall-runoff
- infiltration
- evapotranspiration
- groundwater recharge
- streamflow
- soil erosion
- sediment transport
- crop water requirements

Thus, a Digital Twin combines **observations with scientific models** to understand watershed behaviour.

Where Does Artificial Intelligence Fit?

Modern watersheds generate enormous amounts of data from satellites, sensors, weather stations and field observations. Artificial Intelligence and Machine Learning can help identify patterns and relationships within these datasets.

Potential applications include:

- Flood prediction: Identifying areas that may experience flooding following intense rainfall.
- Drought assessment: Identifying developing water stress and declining water availability.

- Soil-erosion prediction: Identifying areas that are vulnerable to soil loss based on terrain, rainfall, soil and land use.
- Groundwater prediction: Analysing groundwater-level trends and identifying areas of potential stress.
- Crop-water management: Estimating crop water requirements and supporting irrigation decisions.
- Land-use prediction: Exploring how future changes in agriculture, forest and built-up areas could influence watershed behaviour.

AI can also support **optimization** by comparing different intervention options and helping identify locations where conservation measures may provide greater benefits.

The Real Power: Asking "What If?"

Perhaps the most exciting feature of a Watershed Digital Twin is the ability to conduct what-if scenario simulations. Instead of waiting for an event to occur, planners can explore possible situations virtually.

1) What if there is extreme rainfall?

The Digital Twin can help assess potential runoff, flow concentration and flood-prone areas.

2) What if the watershed experiences drought?

It can help explore possible changes in soil moisture, groundwater stress, irrigation demand and water availability.

3) What if a check dam is constructed?

Different locations can be evaluated to understand potential effects on water storage, runoff and downstream flow.

4) What if a farm pond is constructed?

The system can help assess potential runoff capture, storage and water availability under different rainfall conditions.

5) What if land use changes?

Conversion of agricultural or vegetated land to built-up areas can alter runoff and infiltration. Scenario modelling can help planners understand potential consequences.

6) What if climate conditions change?

Different future climate scenarios can be tested to explore potential changes in rainfall, temperature, evapotranspiration and agricultural water demand.

This capability allows watershed managers to test possible interventions before implementing them in the field.

Digital Twin for Soil and Water Conservation Engineering:

For Soil and Water Conservation Engineering, Digital Twins have considerable potential. Soil erosion is influenced by rainfall, soil properties, slope, land use, vegetation and management practices. By integrating these factors, a Digital Twin can help identify potential erosion hotspots.

This information can support prioritization of:

- contour bunds
- graded bunds
- farm ponds
- check dams
- vegetative barriers
- gully-control structures
- drainage-line treatments
- groundwater-recharge measures

Instead of treating every part of a watershed equally, planners can potentially identify where intervention is most necessary and where it may provide the greatest benefit. The approach can also support water budgeting by considering rainfall, runoff, infiltration, storage, groundwater and agricultural demand as interconnected components.

Benefits for Agriculture and Farmers:

Although Digital Twins involve advanced technology, their ultimate purpose should be to improve real-world decisions.

At the farm level, Digital Twin-based systems could potentially support:

- improved irrigation scheduling

- soil-moisture monitoring
- drought advisories
- flood warnings
- better water-use efficiency
- crop planning
- farm-pond management
- water-resource planning

Farmers do not necessarily need to interact with complex hydrological models. The technical system can operate in the background while farmers receive simple recommendations through mobile applications, dashboards, advisories or agricultural extension services. This is important because the success of digital agriculture should ultimately be measured by whether it provides useful and understandable information to farmers.

Applications for Government and Watershed Agencies:

A Watershed Digital Twin can also become a useful planning and monitoring platform for government departments and watershed-development agencies.

Potential applications include:

- watershed prioritization
- drought preparedness
- flood-risk assessment
- groundwater management
- water budgeting
- monitoring conservation structures
- evaluating watershed-development programmes
- prioritizing investments
- climate-adaptation planning
- long-term watershed performance assessment

A Digital Twin platform developed for a dam and watershed system in South Korea, for example, integrates GIS-based geospatial information, rainfall, water levels, flow data and hydrological/hydraulic simulation models, with AI-supported prediction and operational decision support.

Digital Twin and Climate-Resilient Watersheds:

Climate change makes watershed management increasingly complex.

Future rainfall may not always resemble historical rainfall. Watersheds may experience combinations of extreme rainfall, prolonged dry periods, increasing temperature and changing water demand. Digital Twins can support climate-resilience planning by allowing different scenarios to be tested before decisions are implemented.

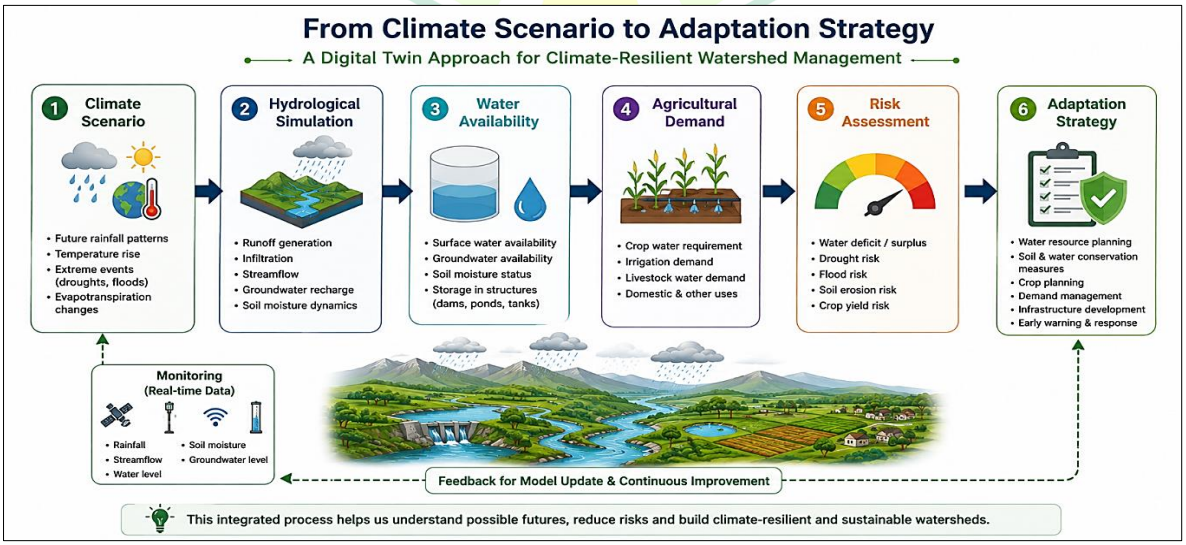


Fig. 3. From Climate Scenarios to Adaptation Strategies for Climate-Resilient Watershed Management

This supports a shift from simply responding to disasters toward anticipating and preparing for potential risks. The FAO emphasizes resilient watershed management that integrates climate and disaster-risk considerations into watershed planning while considering landscape-scale risks and community resilience.

Can Digital Twins Also Track Carbon?

A watershed is not only a water system; it is also a soil, vegetation and carbon system.

Future Digital Twins could integrate:

- soil organic carbon
- vegetation biomass
- land-use change
- soil-management practices
- carbon stocks
- ecosystem services

This could help explore whether watershed interventions can simultaneously improve "Water security + Soil health + Carbon storage + Agricultural productivity + Climate resilience". Such integration is particularly relevant as agriculture moves toward climate-smart and carbon-smart management.

From Observation to Action: The Digital Twin Cycle:

The complete functioning of a Watershed Digital Twin can be understood through a simple cycle:

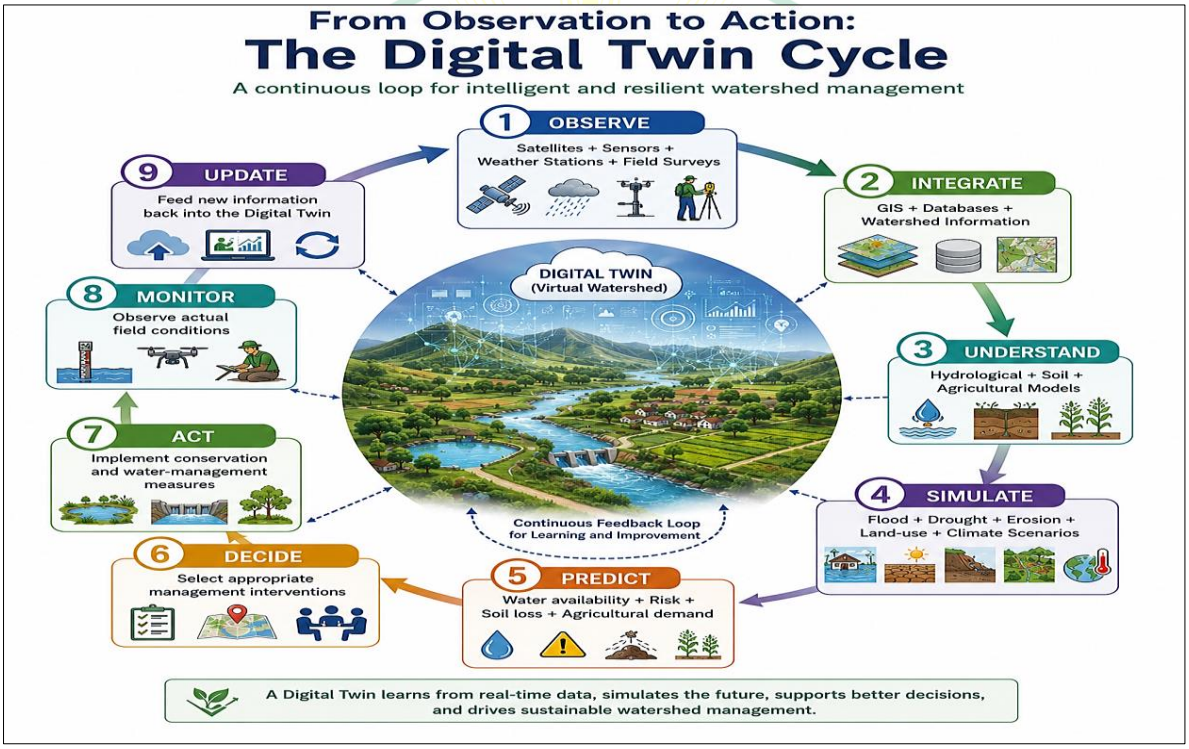


Fig. 4. The Digital Twin Cycle for Integrated Watershed Management

This closed-loop interaction is one of the defining ideas behind advanced watershed Digital Twins.

Challenges and Limitations:

Digital Twin technology is promising, but it is not a magic solution.

Data availability

Reliable and frequent observations are required.

Data quality

Incorrect rainfall, sensor or spatial data can affect model outputs.

Interoperability

Data from different departments, sensors and platforms must be able to communicate with one another. Recent research specifically identifies interoperability as an important challenge in Digital Twin watershed systems.

Cost and infrastructure

Sensors, communication systems, computing infrastructure and technical development require investment.

Technical expertise

Successful implementation requires knowledge of hydrology, soil and water conservation, GIS, remote sensing, modelling, AI and data management.

Model uncertainty

A simulation is not reality. Predictions contain uncertainty because models simplify complex natural processes. Recent basin-scale Digital Twin research highlights challenges related to data, model integration, policy, infrastructure and equitable access. Therefore, Digital Twins should support engineering judgement and local knowledge rather than replace them.

The Indian Opportunity:

India has many of the building blocks required for advanced watershed Digital Twins, including Earth observation technologies, GIS, weather observations, hydrological models, digital connectivity, cloud computing, AI and IoT. The major opportunity is to integrate these technologies into interoperable, decision-oriented systems.

This could be particularly valuable for:

- rainfed agricultural regions
- drought-prone areas
- groundwater-stressed regions
- flood-prone watersheds
- areas affected by soil erosion
- climate-sensitive agricultural landscapes

Indian watershed management also needs to consider the realities of small and marginal farmers, fragmented land holdings and local institutional capacity. Technology should therefore be designed around simple outputs and practical decisions, rather than complexity for its own sake. Most importantly, Digital Twins should complement community participation and local knowledge. Watershed management is ultimately a social, ecological and engineering process, not merely a digital exercise. FAO emphasizes integrated watershed management involving land, water, livelihoods, upstream-downstream relationships and community-based planning.

The Future: From Smart Watersheds to Intelligent Watersheds:

The future of watershed management will not require choosing between traditional engineering and advanced digital technologies. A check dam will still be a physical structure. A farm pond will still store water. A contour bund will still reduce runoff and erosion. However, digital technologies can help answer four important questions:

1) **Where should the intervention be implemented?**
2) **When should it be implemented?**
3) **How should it be designed?**
4) **What impact could it have under different future conditions?**

The next generation of watershed management may therefore combine:

This represents a shift from reactive watershed management to predictive, preventive and adaptive watershed management.

Conclusion: Simulating Tomorrow, Managing Today

A Digital Twin cannot predict the future with absolute certainty. Instead, it provides a scientific framework for exploring possible futures using available data, models and observations. For watershed management, this means moving beyond simply recording what happened toward understanding what is happening now and what could happen next. The integration of remote sensing, GIS, field sensors, hydrological models and artificial intelligence can potentially transform watershed management into a more predictive, adaptive and climate-resilient discipline. The greatest value of a Watershed Digital Twin is therefore not the digital technology itself. Its value lies in helping engineers, farmers, researchers and policymakers make better decisions for the real watershed. The watershed of the future may not simply be mapped. It may be continuously observed, digitally represented, virtually tested and intelligently managed.

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The Art and Science of Dol Net Fishing: Exploring a Traditional Fishing Method on the Maharashtra Coast

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Abstract

Dol net fishing is a traditional fishing practice along the Maharashtra coast, supporting coastal livelihoods and contributing to local fish production. This article explores the working principles, design, fabrication and catch composition of dol nets, with particular reference to the Uran-Karanja coastal region. It examines the influence of tidal dynamics, seasonal variations, fishing locations and gear characteristics on catch composition and fishing efficiency. The article also highlights challenges associated with juvenile fish capture, bycatch and environmental sustainability. Integrating traditional fishing knowledge with scientific assessment and selective gear modifications can help improve fishing practices while promoting responsible resource utilisation and sustainable coastal fisheries.

Keywords: Dol net fishing; Uran-Karanja coast; Fishing gear design; Catch composition; Gear selectivity; Sustainable fisheries.

1. Introduction

The Maharashtra coastline, extending along the eastern Arabian Sea, supports a diverse range of marine and estuarine fisheries that contribute substantially to food security, employment, and the livelihoods of coastal communities. Traditional fishing practices remain an integral component of this sector, reflecting generations of accumulated knowledge regarding tides, currents, fishing grounds, gear construction, and seasonal fish availability. Among these practices, dol net fishing, also known as bag-net fishing, occupies a distinctive position in the traditional fisheries of northern Maharashtra. This stationary fishing gear is generally deployed in tidal waters, where the movement of water carries aquatic organisms into a tapering, bag-shaped net. Its operational efficiency depends on gear configuration, mesh dimensions, deployment conditions, and local hydrodynamic characteristics.

The Uran-Karanja coastal region, particularly the Karanja estuary in Raigad district, provides an important setting for understanding this fishing tradition. Research conducted in the Karanja estuary documented a diverse dol-net catch comprising finfish, crustaceans, cephalopods, and other aquatic organisms, demonstrating the ecological diversity associated with this fishery. Beyond its economic contribution, dol net fishing represents a practical expression of indigenous fishing knowledge, adapted to local environmental conditions and transmitted through generations of fishers. However, the sustainability of dol net fisheries requires careful consideration of catch selectivity, juvenile fish capture, bycatch, and fishing pressure. Studies along the Maharashtra coast have highlighted the importance of improving gear selectivity and strengthening fisheries management to support responsible exploitation of marine resources. These concerns underscore the need to integrate traditional knowledge with systematic scientific assessment. In this context, understanding the design and fabrication of dol nets, together with their catch composition, is essential for evaluating the performance and ecological implications of this traditional fishing method. Documenting gear characteristics and identifying the organisms captured can provide valuable insights for improving fishing efficiency, reducing unwanted catches, and promoting sustainable livelihoods. Exploring dol net fishing along the Uran-Karanja coast therefore offers an opportunity to appreciate a longstanding coastal tradition while examining its relevance to contemporary fisheries science and resource conservation.

2. Understanding Dol Net Fishing

Dol net fishing is a traditional fishing method widely practised along the Maharashtra coast, particularly in tidal creeks, estuaries and nearshore waters. The dol net is a stationary, funnel-shaped bag net that captures aquatic

organisms transported by tidal currents. Unlike active fishing gears, which are dragged or towed through the water, dol nets generally remain fixed at designated fishing stations, allowing water movement to guide fish and other organisms towards the collecting portion of the net. This method is therefore dependent on tidal conditions, current velocity, fishing-ground characteristics and the structural configuration of the gear.

The net typically comprises a broad entrance, an elongated tapering body and a terminal collecting section, commonly referred to as the cod-end. The mouth intercepts organisms carried by the current, while the progressively narrowing netting directs them towards the cod-end, where they accumulate for subsequent retrieval. The gear is secured using suitable anchoring arrangements and ropes to maintain its position against hydrodynamic forces. Its operation requires knowledge of tidal cycles, water depth, current direction and the timing of setting and hauling. As a passive fishing gear, the dol net combines a relatively simple operating principle with specialised construction adapted to local environmental conditions. Research on dol nets operated in the Bhayander Estuary, Maharashtra, documented variation in overall net dimensions and mesh sizes across different sections, demonstrating the importance of regional adaptations in gear design. These characteristics distinguish dol net fishing from other net-based fishing methods and illustrate the relationship between traditional fishing knowledge and practical gear engineering.

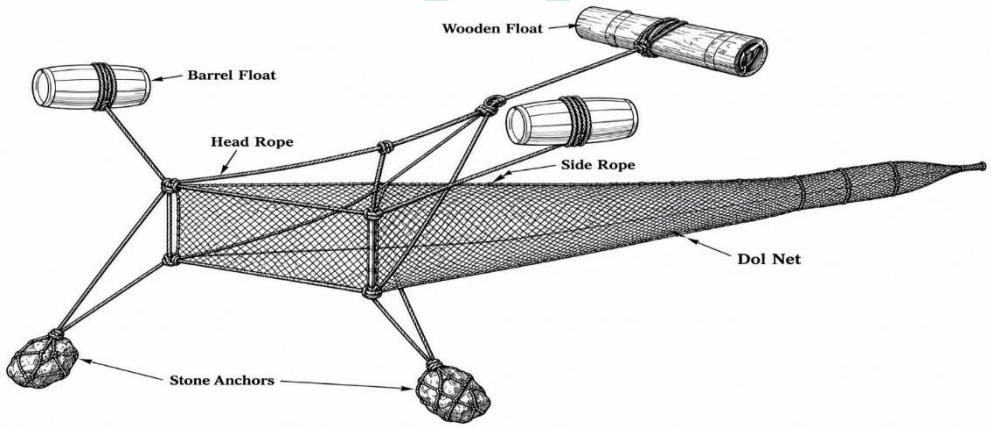


Fig. 1: Dol Net

3. The Art of Net Design and Fabrication

The design and fabrication of a dol net require careful selection of netting materials, mesh dimensions, twine characteristics, net geometry and supporting components. Synthetic fibres, particularly nylon or polyamide, are widely used in modern fishing nets because of their favourable strength-to-weight ratio and resistance to repeated handling. The selection of netting material should consider tensile strength, abrasion resistance, knot security, durability in seawater and ease of repair. Ropes, attachment points and anchoring components must also withstand the combined forces generated by tidal currents, the weight of the catch and environmental exposure. A characteristic feature of dol net construction is the variation in mesh size along its length. Larger meshes are generally used towards the mouth, whereas progressively smaller meshes are incorporated towards the cod-end. In the Bhayander Estuary, Pradhan et al. (2019) reported mesh sizes ranging from approximately 8 to 160 mm across different sections of the net. These measurements illustrate regional design practices and should not be treated as universal specifications for dol nets operating along the Uran–Karanja coast. Mesh selection must be evaluated in relation to the target species, body dimensions, desired catch, and applicable fisheries regulations.

During fabrication, netting panels are assembled and joined to produce a symmetrical, tapering structure. The number of meshes, panel dimensions, joining technique and rate of taper influence the final shape and opening of the net. Accurate measurement of stretched mesh size is particularly important because mesh dimensions can be reported using different conventions. The entrance, supporting ropes, anchoring system and cod-end must be assembled to maintain structural integrity during operation. Operational performance is also influenced by fishing depth, tidal flow, net orientation, deployment duration and the accumulation of debris. Regular inspection, repair of damaged meshes and secure anchoring are essential for maintaining gear efficiency and operational safety. Moreover, appropriate cod-end mesh dimensions and selective modifications deserve

particular attention because very small meshes may retain juvenile fish and unwanted organisms. Recent research on dol net modifications along the Mumbai coast has investigated square-mesh panels as a potential means of improving selectivity and reducing juvenile capture.

4. Exploring the Catch

Dol net fisheries along the Maharashtra coast exploit a diverse assemblage of aquatic organisms transported by tidal currents through estuarine and coastal waters. The catch composition reflects the ecological characteristics of the fishing ground, the availability of different species and the operational features of the gear. A field study conducted in the Karanja Estuary, Raigad district, between September 2016 and May 2017 documented 50 species of finfish, three species of elasmobranchs, 13 species of shrimps, 10 species of crabs, five species of cephalopods, and several other groups, including jellyfish, sea snakes, lobsters and stomatopods. Among the commercially important organisms reported from Karanja were Bombay duck (*Harpadon nehereus*), grenadier anchovy (*Coilia dussumieri*), spotted catfish (*Arius maculatus*), tengra (*Mystus gulio*), ribbonfish (*Lepturacanthus savala*), jawala paste shrimp (*Acetes indicus*), rainbow shrimp (*Parapenaeopsis sculptilis*) and crabs such as *Charybdis callianassa*. These findings demonstrate that dol nets capture a mixture of commercially valuable species and non-target organisms rather than a single uniform fishery resource. The study also documented unwanted catches, including jellyfish, juvenile fishes and plastic debris, highlighting the importance of examining both the economic value and ecological implications of the catch.

Research in the Bhayander Estuary similarly recorded a diverse catch, with Bombay duck, grenadier anchovy, smallhead hairtail, croakers, catfish, shrimps and crabs among the major groups. Although these studies provide a useful regional baseline, their species lists and relative abundances should not automatically be attributed to every fishing station along the Uran-Karanja coast. The actual composition varies with location, season and fishing conditions. Consequently, systematic identification and quantification of the catch are essential for understanding local fishery patterns, assessing commercially important resources and identifying opportunities to reduce unwanted catches.

5. What Influences the Catch?

The catch composition and fishing efficiency of dol nets are influenced by a combination of environmental conditions, biological processes and gear-related characteristics. Among these, tidal dynamics are particularly important because the gear depends on water movement to transport aquatic organisms into the net. Changes in tidal amplitude, current velocity and current direction can influence the volume of water passing through the net and the movement of fish and crustaceans within the fishing ground. Research on dol net fisheries along the Mumbai coast identified current speed as an important factor associated with catch variation. Seasonal changes also influence catch composition through variations in species distribution, recruitment, feeding behaviour and migration. Monsoon conditions may alter salinity, turbidity, freshwater discharge and fishing accessibility, while post-monsoon conditions may favour the occurrence of particular species. Studies in Karanja and Bhayander have documented temporal variation in dol net catches, supporting the importance of season-specific assessments.

Location is another important determinant. Differences in depth, substrate, estuarine connectivity, water circulation and habitat characteristics influence the availability of organisms at individual fishing stations. Furthermore, gear characteristics including mesh size, net length, mouth dimensions, taper, cod-end configuration and anchoring arrangements may affect the retention of organisms and the efficiency with which the net intercepts them. Fine meshes can retain smaller individuals, while differences in net configuration may alter water flow and the escape opportunities available to organisms. These factors interact rather than operate independently. For example, a change in tidal current may influence both the movement of fish and the hydrodynamic loading on the net. Similarly, seasonal recruitment may increase the presence of juvenile fish in fishing grounds, potentially increasing their representation in the catch. Therefore, understanding dol net performance requires observations that integrate catch composition with environmental conditions and gear specifications. For the Uran-Karanja coast, recording species-wise catch, individual or total weight, mesh dimensions, fishing duration, tidal conditions and seasonal variation would provide a sound basis for evaluating these relationships. Such information can support practical recommendations for improved gear selectivity, responsible harvesting and the long-term sustainability of traditional coastal fisheries.

6. Traditional Knowledge Meets Fisheries Science

Traditional fishing knowledge represents an important resource for understanding coastal ecosystems and developing locally appropriate fisheries management strategies. Dol net fishers possess practical knowledge of tidal cycles, current direction, fishing-ground characteristics, gear maintenance and seasonal changes in catch availability. This knowledge, acquired through repeated observations and experience, can complement scientific investigations by helping researchers identify relevant environmental variables, select sampling locations and interpret variations in catch composition. Scientific assessment can strengthen this traditional knowledge through systematic documentation of gear dimensions, mesh sizes, materials, deployment practices and species-specific catches. Recording the number, length and weight of organisms captured during individual fishing operations enables researchers to distinguish changes in catch quantity from changes in species composition and size structure. When these observations are linked with tidal conditions, season and fishing duration, they can help identify the environmental and operational factors associated with fishing performance.

Experimental evaluation of alternative gear designs is particularly valuable. For example, Abass et al. investigated a 35 mm square-mesh panel incorporated into the cod-end of dol nets off Madh Island, Mumbai, to improve size selectivity and reduce juvenile retention. Their findings demonstrate the potential of modifying traditional fishing gear through evidence-based design. However, such modifications require testing under the specific conditions of the Uran-Karanja fishery before their effectiveness can be assumed locally. Participatory research involving fishers, fisheries scientists and management authorities can facilitate this process. Combining fishers' practical experience with standardised catch monitoring and controlled gear trials can help develop improvements that are ecologically beneficial, technically feasible and economically acceptable. This collaborative approach recognises traditional knowledge not as a substitute for scientific assessment, but as a complementary source of information for adaptive and sustainable fisheries management.

7. Challenges and Sustainable Solutions

Despite its socioeconomic importance, dol net fishing presents several challenges associated with catch selectivity, juvenile exploitation, non-target organisms and environmental waste. The small mesh sizes used in certain sections of dol nets may retain immature fish and small-bodied species alongside commercially marketable organisms. When juvenile fish are harvested before reaching maturity, their contribution to future spawning stocks may be reduced, potentially affecting recruitment and the long-term productivity of fish populations. Research on dol net fisheries along the Mumbai coast has documented substantial juvenile representation in catches of commercially important species, including *Lepturacanthus savala* and *Coilia dussumieri*.

A major priority is therefore to improve gear selectivity without unnecessarily compromising the livelihoods of traditional fishers. Potential interventions include testing alternative mesh dimensions, incorporating appropriately positioned square-mesh escape panels, and modifying cod-end configurations. These measures should be evaluated against species-specific retention, juvenile escape, total commercial catch and economic returns. The appropriate design must be determined through controlled trials because the effectiveness of a modification depends on the species assemblage, fish morphology, current conditions and configuration of the net. Other measures include identifying seasons or fishing locations associated with high juvenile abundance, improving catch handling and sorting practices, and documenting unwanted catches. Where live organisms can be released safely, prompt and careful release may improve their survival; however, survival depends on the species, duration of confinement and physical condition of the organisms. Lost or damaged netting should also be retrieved or repaired promptly to minimise plastic pollution and the risk of continued capture by abandoned gear.

These interventions are consistent with the Food and Agriculture Organization's Code of Conduct for Responsible Fisheries, which emphasises selective fishing practices, the reduction of discards and the conservation of aquatic biodiversity. Importantly, gear improvements should be developed in consultation with fishing communities and assessed for affordability, durability, operational safety and economic viability. A combination of scientific monitoring, fisher participation and appropriate management measures offers a practical pathway towards more responsible dol net fisheries.

8. Conclusion

Dol net fishing represents an important intersection of traditional craftsmanship, ecological knowledge and coastal livelihoods along the Maharashtra coast. Its continued significance reflects the adaptability of fishing communities and their accumulated understanding of tidal environments and fishing operations. At the same time, changes in fishing pressure, catch composition and the potential capture of juvenile and non-target organisms highlight the need to strengthen the scientific basis of traditional fishing practices. For the Uran-Karanja coast, systematic documentation of dol net design, fabrication characteristics, operational conditions and catch composition can provide a valuable foundation for assessing fishing performance and identifying opportunities for improvement. Integrating these observations with experimental gear modifications, environmental monitoring and participatory research would help determine practical approaches to reducing unwanted catches while maintaining the economic viability of the fishery.

Sustainable development of dol net fisheries does not require the abandonment of traditional methods. Rather, it requires their continued evolution through collaboration between fishing communities, fisheries scientists and management institutions. By combining local experience with scientific evidence, it is possible to preserve valuable fishing traditions while encouraging responsible harvesting, conserving aquatic biodiversity and supporting the long-term resilience of coastal livelihoods. Ultimately, the future of dol net fishing depends on maintaining a balance between the needs of fishing communities and the ecological sustainability of the resources on which they depend.

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Morphometric Analysis is Key Way to Analyze Watershed

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Abstract

Morphometric analysis is a quantitative approach used to evaluate watershed by its geometry, drainage characteristics, and relief conditions. It provides information about runoff behaviour, groundwater potential, erosion susceptibility, and watershed prioritization. The method is based on measurement of linear, areal, and relief parameters derived from topographic maps, remote sensing, and GIS. Horton (1945) introduced quantitative drainage basin analysis, while Strahler (1957) improvise the stream order and watershed characterization methods. Morphometric analysis has become an essential tool for sustainable watershed planning and natural resource management.

Keywords: Morphometric; Watershed; Drainage Network; GIS; Stream Order; Hydrology

1. Introduction

A watershed represents a natural hydrological unit where precipitation is collected and drained through a network of streams in single outlet. The known of watershed characteristics are necessary for flood assessment, groundwater exploration, erosion control, and water resource planning. Morphometric analysis provides numerical descriptions of basin shape, drainage arrangement, and terrain characteristics (Horton, 1945; Strahler, 1957). It explains how watershed structure influences hydrological processes such as runoff generation, infiltration, erosion, and sediment transport.

2. Watershed Characteristics

Size:

It is nothing but an area demarcated by the divide. Measured in hector, Sq. km., Sq. m., etc

Drainage Divide:

Also known as watershed boundary. Which divides the water flow from the area, which means whether water flowing towards or away from the area within watershed.

Topography:

It refers to the terrain of the land within watershed boundary.

Watershed Delineation:

Shape:

Square, Rectangular and Triangular are common shape of watershed and it is determined by “shape index”, as given below,

$$S_w = \frac{L}{W} or \frac{L^2}{A}$$

Where, Sw – Shape Index, L – Length of watershed along the main stream from the outer to the most distant ridge of the watershed (km), W – Average width of watershed (km), ($\frac{A}{L}$), A – Area of Watershed (Sq. km)

Slope:

Slope is nothing but degree of inclination or steepness of the land surface relative to the horizontal plane. Can be defined as rate of change in elevation over a given horizontal distance. The average slope of watershed is determined from the topographic map of the watershed by using following formula,

$$S = \frac{M \times N}{A} \times 100$$

Where, S – Percent watershed slope, M – Total length of contour lines within the watershed (m)
N – Contour interval (m), A – Area of watershed (m^2)

3. Types of Morphometric Parameters

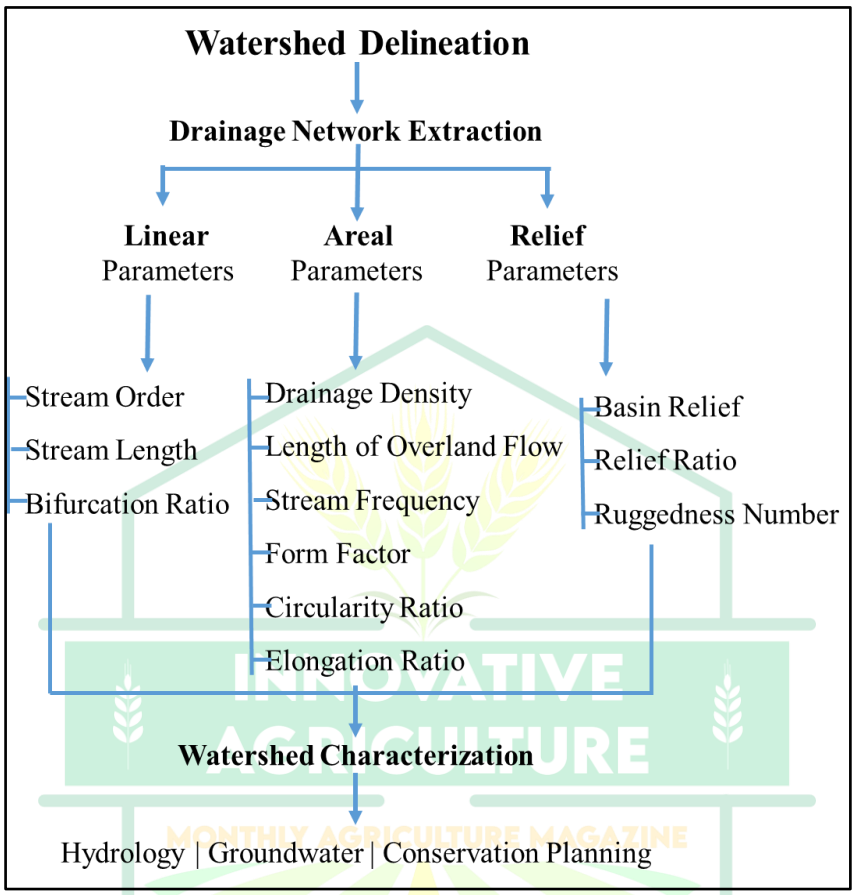


Fig. 1. Classification of Morphometric Parameters

3.1 Linear Morphometric Parameters

Linear parameters describe the characteristics of drainage channels as given below,

Stream Order: the stream is the water flow path over the earth surface. The stream order provides a kind of stream classification, e.g. the smallest stream in the watershed has lower order and the largest stream include highest order. The lowest stream order may be the tributaries or rivulets, while highest order stream is the outlet of watershed. The designation of stream order of drainage basin is the first step in analysis of drainage basin. They are designated in terms of Ist, IInd, IIIrd order and so on.

Stream Number: Total number of streams of each order. It is related to the size of watershed, channel dimension and to the stream discharge. Higher values indicate dense drainage and greater runoff potential and vice-versa.

Stream Length: Total length of streams belonging to each order. Denotes the characteristics size of different components of drainage system and its contributing area. Longer channels generally indicate gentler slopes and permeable terrain.

Bifurcation Ratio: Defined as the ratio of number of stream segments of a given order u to the number of stream segment of next higher order. Usually ranges from about 3–5 for those watersheds in which geological formation do not distorted the drainage pattern of watershed. Higher the value more it is elongated, lower the value more it circular.

$$\boldsymbol{R_b = \frac{N_u}{N_{u+1}}}$$

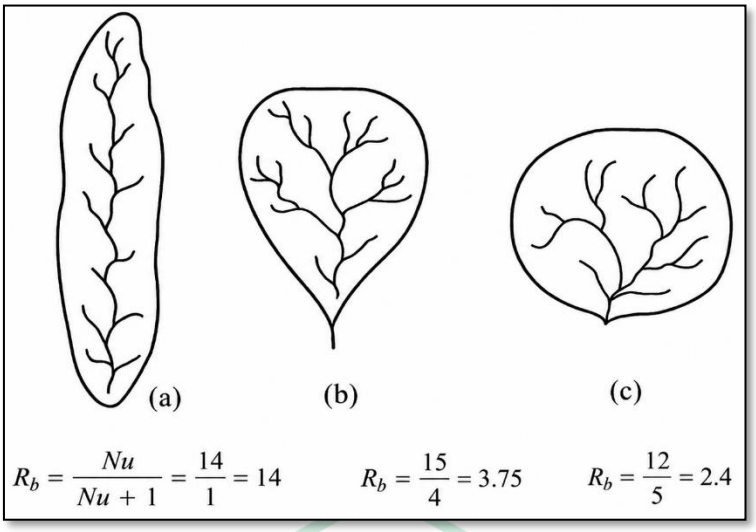


Fig. 2. Variation in bifurcation ratio with their shapes.

3.2 Areal Morphometric Parameters

Areal parameters represent basin geometry and drainage texture as given below,

Drainage Density: Drainage density of a watershed is the ratio of cumulative length of streams of all orders existing in the watershed to the total area of watershed projected on horizontal plane. Low values indicate high resistant sub-soil strata, dense vegetation and low relief and high values indicate weak sub-surface strata, sparse vegetation's and strong relief.

$$Drainage\ Density = \frac{Total\ Stream\ Length}{Basin\ Area}$$

Stream Frequency (F_s): It is defined as the ratio of cumulative number of streams of all order existing in a watershed to the total area of watershed. i.e. Number of streams per unit area. High frequency indicates impermeable surface conditions.

$$F = \frac{\sum_{i=1}^{k} N_u}{A_k}$$

Where, Nu – Number of streams of all order, A – Area of the watershed, m^2.

Form Factor (R_f): it defined as the ratio of basin area to the square of the basin length and given as under. Lower values indicate elongated basins, whereas higher values indicate more circular basins. It is used for flood response estimation.

$$R_f = \frac{A_u}{{L_b}^2}$$

Where, R_f – Form factor, dimensionless, A_u – Basin Area, Sq. km, L_b – Basin Length, km

Circularity Ratio (R_c): defined as the ratio of basin area (A_u) to the area of a circle (A_C) which has same perimeter as drainage basin. It is given as below. Values closer to 1 indicate circular basins and shorter concentration of time.

$$R_C = \frac{A_u}{A_c}$$

Elongation Ratio:

It is an index to mark the shape of drainage basin. Defined as the ratio of diameter of circle which has the area same to the basin, to the maximum basin length, expressed as,

$$R_l = \frac{D_C}{L_{bm}}$$

Where, R_l – elongation ratio, dimensionless, D_C – Diameter of circle which has same area as drainage basin, m, L_{bm} – Maximum basin length, m.

3.3 Relief Morphometric Parameters

Relief parameters explain elevation variation and terrain characteristics.

Basin Relief: It is defined as the elevation difference between the reference points located in the damage basin i.e. difference between maximum and minimum elevation (Rokade et al., 2026). High relief indicates steep terrain and greater erosion potential.

Relief Ratio: It is the ratio of relief to the horizontal distance on which relief is measured. Higher values indicate steep slopes and rapid runoff.

Maximum Basin Relief:

It is the elevation difference between basin outlet and the highest point located at the perimeter of the basin.

Relative Relief:

It is the ratio of maximum basin relief to the basin perimeter, expressed as under,

$$R_{hp} = \frac{H}{P} \times 100$$

Where, Rhp – Relative relief (%), H – Maximum basin relief (m) and P – Basin Perimeter (m)

Ruggedness Number: Combination of drainage density and basin relief. Higher values represent rugged terrain and erosion-prone areas.

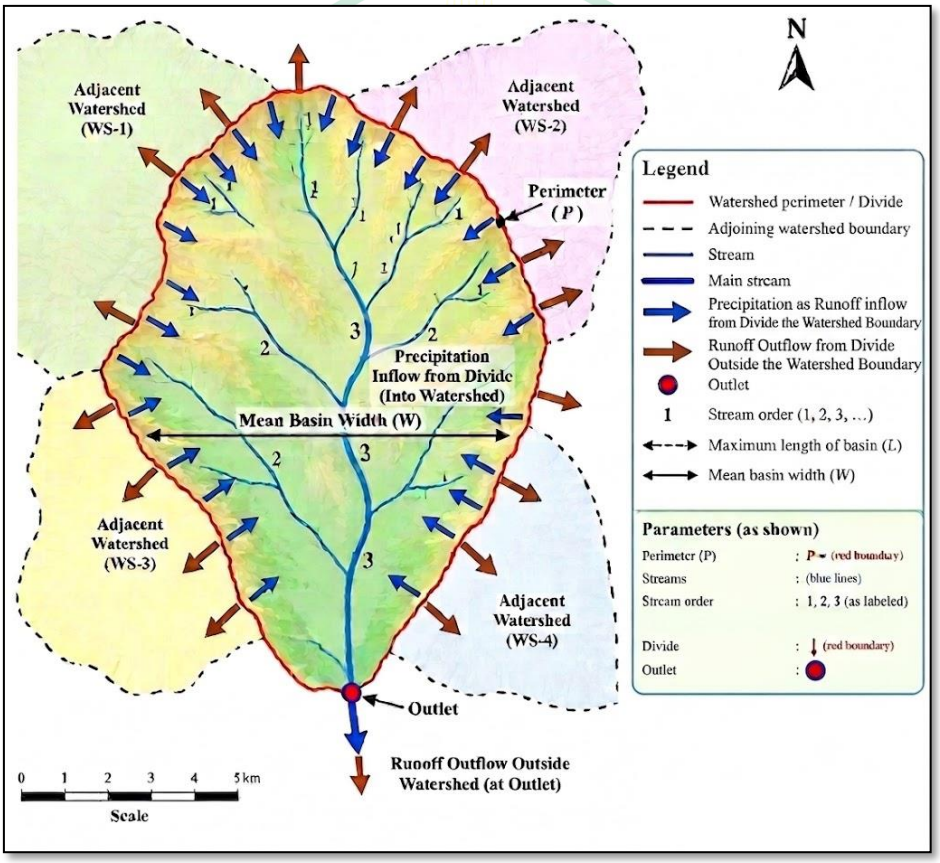


Fig. 3. Watershed Characteristics

4. Applications of Morphometric Analysis in Watershed Studies

1. Rainfall-runoff relationship estimation.
2. Flood hazard and watershed vulnerability assessment.
3. Groundwater potential zone identification.
4. Erosion and sediment yield evaluation.
5. Watershed prioritization and conservation planning.
6. Land and water resource management.

5. Conclusion

Morphometric analysis provides a scientific framework for understanding watershed behaviour. Evaluation of linear, areal, and relief parameters helps identify hydrological response, erosion risk, groundwater potential, and suitable management strategies. Therefore, morphometric analysis is a key approach for effective watershed planning.

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Watershed Development for Climate-Resilient Agriculture: Building Farms That Can Withstand Drought, Floods and Climate Uncertainty

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Introduction:

Can Agriculture Become Climate-Resilient Without Managing Water and Soil?

Agriculture depends on two resources that are increasingly under pressure: soil and water. Changing rainfall patterns, prolonged dry periods, intense rainfall events, floods, rising temperatures, soil erosion and declining groundwater availability are creating new challenges for farmers. These challenges are particularly important in rainfed and drought-prone agricultural regions, where crop production depends heavily on the timing, amount and distribution of rainfall.

Climate change does not affect agriculture only through temperature. Changes in rainfall intensity, dry spells, floods, droughts and other extreme events can directly influence soil moisture, runoff, erosion, groundwater recharge and crop productivity. FAO identifies climate and disaster risks as major factors affecting food systems and emphasizes the need for climate-resilient land and water management.

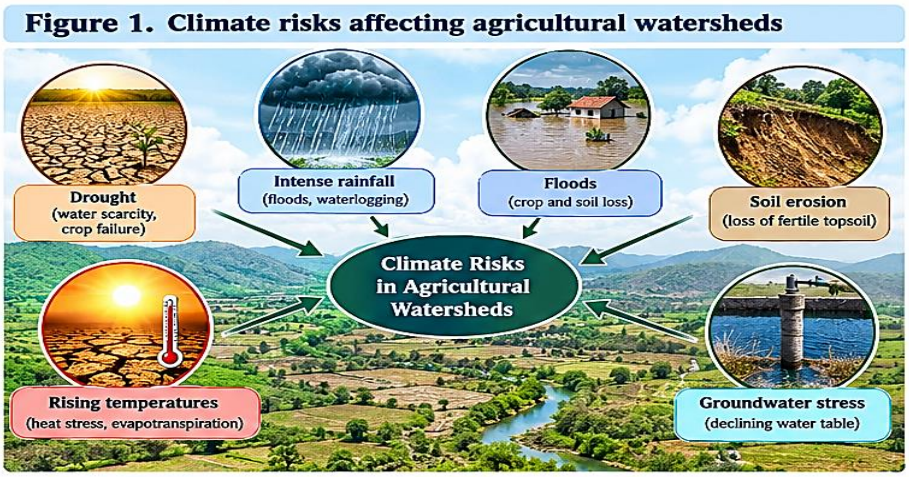
What is Climate-Resilient Agriculture?

Climate-resilient agriculture refers to agricultural systems that can withstand, adapt to and recover from climate-related stresses while maintaining productivity and conserving natural resources. Climate resilience therefore cannot be achieved only through changing crop varieties or irrigation methods. It requires management of the entire soil–water–crop system. This is where watershed development becomes important.

Why Does the Watershed Matter?

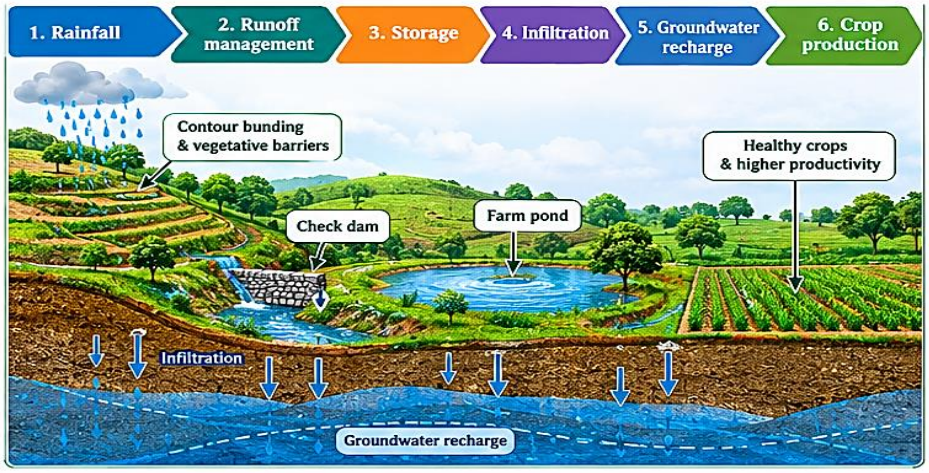
Rainfall falling on a watershed follows several pathways. Some water becomes runoff, some infiltrates into the soil, some is stored in surface structures and some contributes to groundwater recharge.

Figure 1. Climate risks affecting agricultural watersheds



If rainfall is not properly managed, intense rainfall can result in rapid runoff, soil erosion, flooding and loss of valuable nutrients. At the same time, insufficient infiltration and storage can leave farmers with inadequate water during subsequent dry periods. FAO notes that degradation of watershed functions can increase erosion and runoff, reduce infiltration and groundwater recharge, increase flood risks and reduce soil productivity. Therefore, watershed development aims to convert rainfall from a short-duration hazard into a useful resource. Every drop of rainwater conserved within a watershed is an investment in future agricultural resilience.

Figure 2. Watershed development pathway



How Watershed Development Builds Climate Resilience:

Watershed development combines structural, biological and management interventions according to local soil, slope, rainfall, drainage and land-use conditions.

1. Rainwater Harvesting and Storage

Rainwater harvesting is one of the most important components of watershed development.

Structures such as:

- farm ponds
- check dams
- percolation tanks
- nala bunds
- water-harvesting structures
- recharge structures

can help slow down runoff and increase opportunities for water storage and infiltration.

The objective is not simply to store more water. The larger objective is to improve the seasonal availability of water. Stored or infiltrated water can potentially support crops during dry spells, livestock requirements and groundwater recharge.

2. Soil and Moisture Conservation

Soil is the foundation of agricultural production, but intense rainfall can remove fertile topsoil through erosion.

Measures such as:

- contour bunding
- graded bunding
- terracing
- vegetative barriers
- mulching
- conservation tillage
- residue management

can help reduce runoff velocity and soil loss while improving soil moisture conservation.

Research from semi-arid agricultural systems has shown that integrated soil and water conservation practices can support productivity while maintaining soil quality. The objective is therefore not merely to prevent soil from leaving the field but to retain water, nutrients and productive soil within the farming system.

3. Drainage-Line Treatment

During intense rainfall, water becomes concentrated in natural drainage lines. If flow velocity becomes high, it can produce gullies, sediment transport and downstream damage.

Appropriate measures may include:

- gully plugs
- loose-boulder structures
- check dams
- vegetative stabilization
- drainage-line treatment

These measures can help reduce flow velocity and sediment movement while providing opportunities for water retention and infiltration.

Figure 3. Integrated watershed management interventions



4. Groundwater Recharge

Groundwater is an important source of irrigation in many agricultural regions.

Watershed development can improve opportunities for groundwater recharge by slowing runoff and allowing more water to infiltrate where conditions are suitable.

Measures may include:

- percolation tanks
- recharge structures
- check dams
- farm ponds
- infiltration measures
- appropriate land and drainage-line treatments

However, recharge alone is not sufficient. Groundwater withdrawal must also remain within sustainable limits. Therefore, groundwater management should combine recharge with water budgeting and efficient irrigation.

From "More Water" to "Better Water Management"

A common misconception is that watershed development simply means creating more water.

In reality:

Watershed development means better capture, storage, infiltration, distribution and efficient use of available water.

This requires preparing a **water budget**.

Available water

Rainfall + Surface storage + Groundwater

↓

Water demand

Crops + Livestock + Domestic requirements

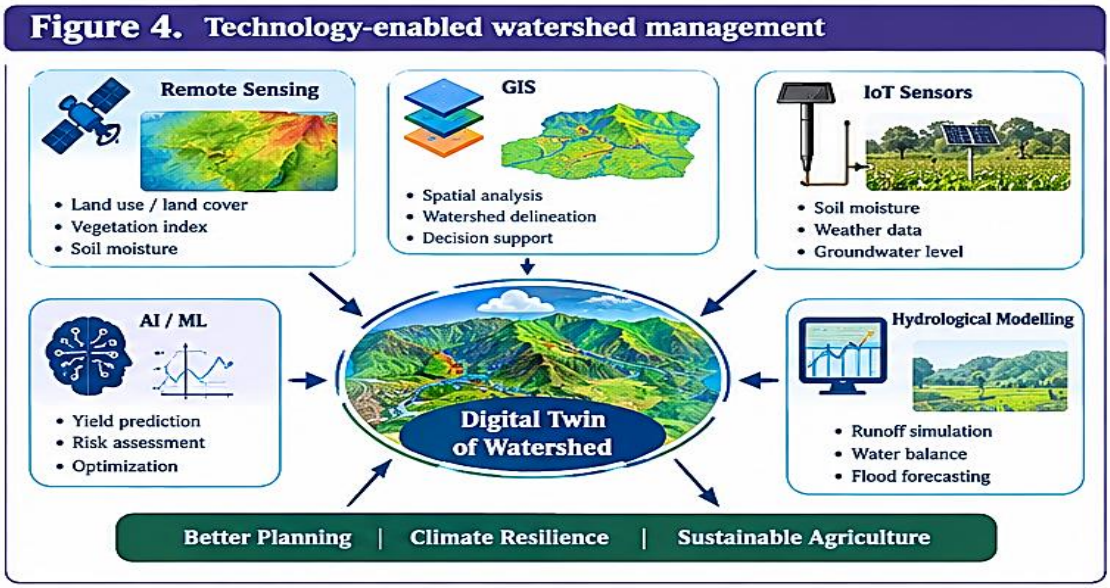
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Water balance

↓

Crop and irrigation planning

Such planning can help farmers select crops and irrigation strategies that are compatible with available water resources.



Watershed Development and Climate-Smart Crop Planning

Watershed development should not stop at constructing structures. The water and soil conserved within the watershed should be efficiently utilized through appropriate agricultural practices.

Climate-resilient agriculture can include:

- drought-tolerant crop varieties
- crop diversification
- intercropping
- crop rotation
- appropriate sowing dates
- conservation agriculture
- micro-irrigation
- efficient fertilizer management
- residue management
- agroforestry
- integrated farming systems

The selection of crops should consider **soil type, rainfall, available water, climate risk and market opportunities**.

For example, a water-intensive crop may not be suitable in a water-stressed watershed even if irrigation is temporarily available.

Therefore, the question should not simply be:

"How much water can we obtain?"

It should also be:

"Which crops can we sustainably grow with the water available?"

Vegetation: The Green Infrastructure of a Watershed

Vegetation plays an important role in improving watershed resilience.

Trees, grasses and other vegetation can:

- protect soil from raindrop impact
- reduce surface runoff
- improve infiltration
- reduce erosion
- support soil organic matter
- provide biomass
- contribute to carbon storage
- support biodiversity

Suitable interventions may include:

- agroforestry
- afforestation
- pasture development
- grass strips
- vegetative barriers
- riparian vegetation
- restoration of degraded land

FAO recognizes watershed management as a framework that integrates agriculture, forestry, pasture and other land-use systems while maintaining ecosystem services and local livelihoods.

Role of Remote Sensing and GIS

Modern watershed development can be strengthened by digital technologies.

Remote sensing can provide repeated information about:

- land-use and land-cover change
- vegetation condition
- surface water
- crop condition
- drought indicators
- watershed degradation

GIS can help analyse:

- slope
- drainage
- soil
- runoff pathways
- erosion-prone areas
- land use
- potential locations for water-harvesting structures
- watershed priority areas

These technologies allow watershed planners to move from generalized planning toward **spatially targeted interventions**.

Role of IoT, AI and Emerging Technologies

The next generation of watershed management can go beyond maps.

IoT sensors

Field sensors can monitor:

- rainfall
- soil moisture

- groundwater levels
- streamflow
- water levels
- temperature

This information can provide near-real-time knowledge of watershed conditions.

Artificial Intelligence and Machine Learning

AI/ML can potentially support:

- runoff prediction
- flood forecasting
- drought assessment
- groundwater-level prediction
- soil-erosion risk mapping
- crop-water demand estimation
- optimization of watershed interventions

Digital Twins

An advanced watershed system could eventually integrate satellite observations, field sensors, GIS, hydrological models and AI into a **Digital Twin**.

Such a system could allow planners to ask:

What could happen if rainfall becomes more intense?
What if groundwater levels decline?
What if a new water-harvesting structure is constructed?
What if land use changes?

This moves watershed development toward **predictive and adaptive management**.

Watershed Development and Carbon Management

Climate resilience should not focus only on water.

Soil and vegetation are also important components of the carbon cycle.

Practices such as:

- agroforestry
- residue management
- reduced soil disturbance
- improved soil organic matter
- vegetation restoration
- sustainable land management

can support soil health and carbon storage while also providing other environmental benefits.

FAO highlights soil-carbon management as a pathway that can simultaneously support agricultural production, soil health and reduction of soil and water losses.

Thus, the future watershed should be viewed as a:

Water-smart + Soil-smart + Carbon-smart + Climate-smart system.

Benefits at Different Levels

Level	Major benefits
Farm	Better soil moisture, reduced erosion, improved water availability and crop stability
Village	Improved groundwater conditions, reduced runoff and stronger livelihood resilience
Watershed	Improved water balance, soil conservation and ecosystem restoration
Regional	Better drought and flood resilience and reduced land degradation
Environment	Improved soil health, vegetation, carbon storage and ecosystem services

Recent research on integrated watershed management in Indian drylands reports improvements in soil moisture, agricultural productivity, water-use efficiency and ecosystem services when soil and water conservation, soil-health management and climate-resilient farming are integrated at watershed scale.

The Community at the Centre

Watershed development is not only an engineering exercise.

A check dam can be constructed by an engineer, but its long-term success depends on how the community uses and maintains the available resources.

Farmers possess valuable local knowledge about:

- rainfall patterns
- soil behaviour
- drainage
- groundwater
- crop performance
- historical droughts and floods

Therefore, scientific knowledge and local knowledge should work together.

FAO emphasizes community-based planning, implementation and monitoring as important components of watershed management, along with balancing economic, social and environmental objectives.

Technology should strengthen community decision-making, not replace it.

Challenges in Building Climate-Resilient Watersheds

Watershed development is not a one-time construction activity. Several challenges need continuous attention.

1. Changing climate conditions

Past rainfall patterns may not represent future conditions.

2. Fragmented landholdings

Coordinating interventions across many farms can be difficult.

3. Maintenance

Water-harvesting and soil-conservation structures require regular inspection and maintenance.

4. Groundwater over-extraction

Increasing recharge without managing extraction may not produce long-term sustainability.

5. Limited monitoring

Without long-term data, it is difficult to evaluate the actual performance of watershed interventions.

6. Community participation

Successful watershed development requires participation beyond the construction stage.

7. Data and technology gaps

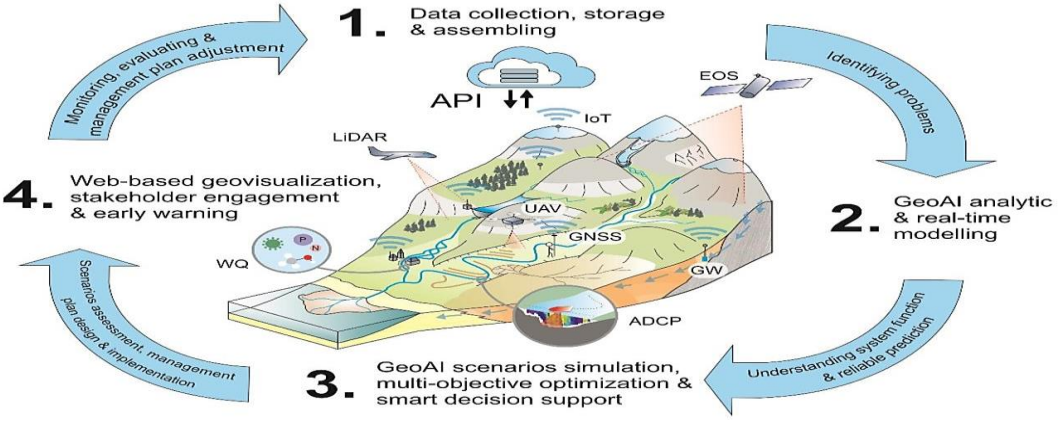
Advanced GIS, sensors and modelling systems require reliable data, technical expertise and institutional capacity.

Therefore, watershed development should be approached as a **long-term adaptive process** rather than a collection of isolated structures.

The Future: From Watershed Development to Watershed Intelligence

The future of climate-resilient agriculture will require the integration of traditional engineering knowledge with emerging technologies.

The framework can be represented as:



This represents a shift from:
Crisis response → Risk anticipation
Rainfall management → Rainwater management
Individual farm planning → Watershed-scale planning
Conventional watershed development → Climate-smart watershed development

Conclusion: A Resilient Farm Needs a Resilient Watershed

Climate change is making agricultural production increasingly uncertain. However, uncertainty does not mean that farmers are without options. A well-managed watershed can help conserve rainfall, reduce runoff and soil erosion, improve soil moisture, support groundwater recharge, strengthen agricultural water availability and restore ecosystem functions.

The solution is not one structure, one technology or one crop. It is an integrated approach to soil, water, vegetation, agriculture and people. Watershed development should therefore move beyond simply constructing physical structures toward climate-risk assessment, water budgeting, soil-health management, ecosystem restoration, appropriate crop planning and continuous monitoring. Emerging technologies such as remote sensing, GIS, IoT, AI and Digital Twins can further strengthen this approach by helping us observe, analyse, predict and manage watershed conditions. Ultimately, A climate-resilient farm begins with a climate-resilient watershed. And a climate-resilient watershed is built not only with structures, but with science, soil, water, vegetation, technology and community participation working together.

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Beyond MSP: From Farm Price to Food Choice What Odisha's Millet Revolution Can Teach India about Agricultural Incentives, Nutrition and Public Health

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Abstract

Minimum Support Price (MSP) is generally viewed as an instrument for protecting farm income. Yet agricultural incentives can have consequences far beyond the farm gate: they influence crop choice, market development, food availability and, indirectly, what reaches the household plate. Odisha's millet experience offers an important case for examining this wider relationship. Between 2018-19 and 2022-23, ragi procurement under the state's millet programme increased from about 18,000 quintals to more than 6 lakh quintals, while farmer participation rose more than tenfold. The transformation, however, cannot be explained by MSP alone. Odisha progressively connected farmers with FPOs, PACS/LAMPCS, TDCCOL, women's SHGs, processing facilities and institutional consumers through PDS and nutrition programmes. This article argues that India should distinguish between an MSP that merely announces a price and an MSP ecosystem capable of creating a dependable market. It proposes a **nutrition-sensitive procurement framework** in which price support, value-chain finance, agro-ecological suitability and institutional food demand are evaluated together. Such an approach could help agricultural diversification contribute simultaneously to farmer prosperity, dietary diversity and long-term public-health objectives.

Introduction

India's agricultural policy once faced an overriding question: How can the country produce enough food? The answer transformed Indian agriculture. Improved seeds, irrigation, fertiliser, Minimum Support Prices, large-scale procurement and the Public Distribution System created an extraordinarily effective rice-wheat food-security architecture. The system provided farmers with greater market certainty while enabling the State to maintain food stocks and supply subsidised grain to millions of households. That achievement should not be understated. But India's food challenge has evolved.

The country must continue ensuring adequate food and remunerative farm incomes while confronting nutritional imbalance, pressure on natural resources and a growing burden of non-communicable diseases. The ICMR-INDIAB national study estimated diabetes prevalence at 11.4% and prediabetes at 15.3%, corresponding at the time of the study to roughly 101 million people with diabetes and 136 million with prediabetes.

This raises a question that belongs as much to agricultural policy as to health policy:

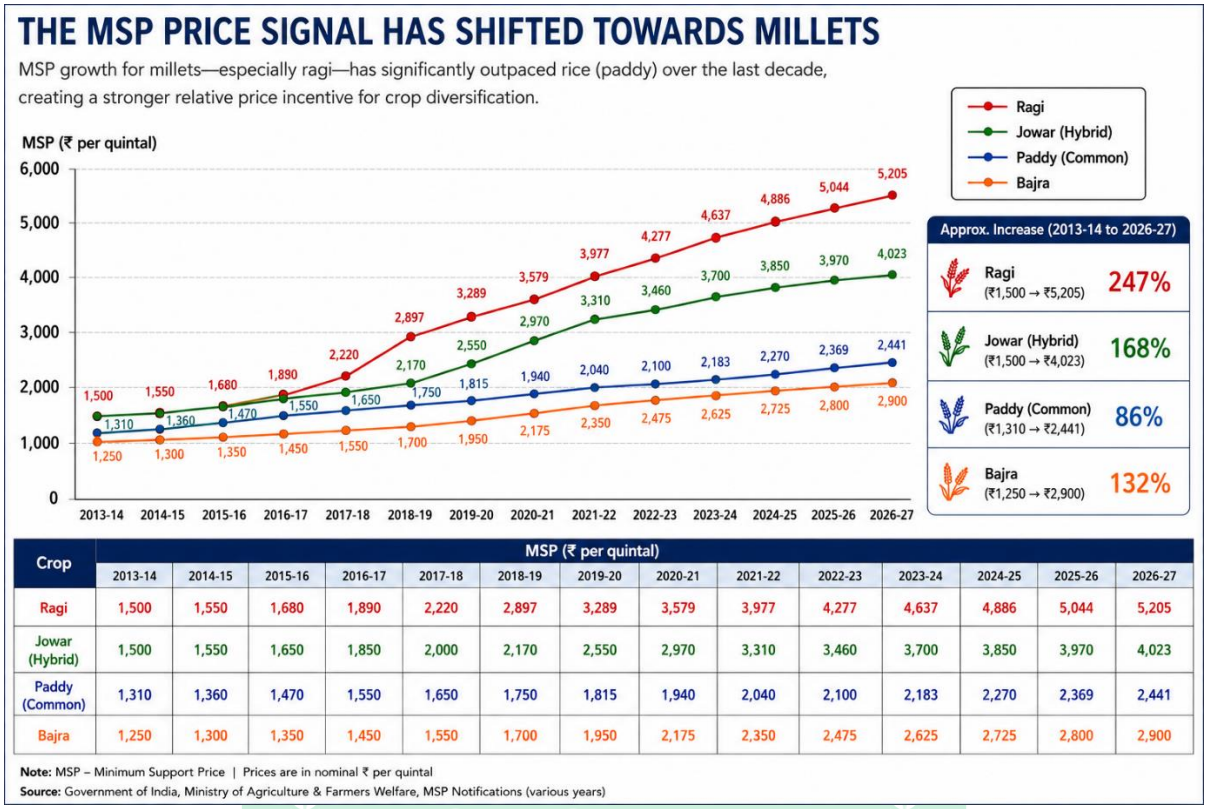
If public policy can influence what farmers find economically attractive to grow, can it also help create a more diverse and nutritionally desirable food environment? Odisha's millet experience provides a useful place to search for the answer.

The MSP Paradox

India has already created a substantial price incentive for millets. For Kharif Marketing Season 2026-27, the MSP for common paddy is **₹2,441 per quintal**. For ragi it is **₹5,205**. Jowar hybrid carries an MSP of ₹4,023 and bajra ₹2,900 per quintal. The long-term comparison is even more revealing. The ragi MSP has therefore risen much faster than the MSP for common paddy. Yet India has not witnessed a millet transition comparable to the earlier expansion of rice and wheat. Why? Because the farmer does not cultivate an **MSP notification**. The farmer cultivates for an **expected market**.

Imagine the decision from the perspective of a small rainfed farmer. ₹5,205 per quintal may appear attractive, but several other questions arise immediately. Where is the procurement centre? Will a few bags be

accepted? What moisture level is permissible? Who will transport the produce? Is a local processor available? How quickly will payment arrive? And perhaps most importantly: **will the same buyer be there next year?**



Crop	MSP (₹ per quintal)													
	2013-14	2014-15	2015-16	2016-17	2017-18	2018-19	2019-20	2020-21	2021-22	2022-23	2023-24	2024-25	2025-26	2026-27
Ragi	1,500	1,550	1,680	1,890	2,220	2,897	3,289	3,579	3,977	4,277	4,637	4,886	5,044	5,205
Jowar (Hybrid)	1,500	1,550	1,650	1,850	2,000	2,170	2,550	2,970	3,310	3,460	3,700	3,850	3,970	4,023
Paddy (Common)	1,310	1,360	1,470	1,550	1,650	1,750	1,815	1,940	2,040	2,100	2,183	2,270	2,369	2,441
Bajra	1,250	1,300	1,350	1,450	1,550	1,700	1,950	2,175	2,350	2,475	2,625	2,725	2,800	2,900

These questions reveal the difference between a price announcement and an economic incentive. I would describe the first as **Nominal MSP** - the officially announced price. The second is **Accessible MSP** - a support price that an ordinary eligible farmer has a realistic opportunity to realise. But agricultural transformation requires something more : **Transformative MSP** - price support connected to procurement, aggregation, processing and sustainable demand. Odisha's experience demonstrates the difference.

Odisha Did Not Build an MSP Programme. It Built a Chain.

The Odisha Millets Mission was launched in 2017 and has subsequently evolved into **Shree Anna Abhiyan**. Its original ambition was broader than increasing millet acreage. Production, productivity, mechanisation, processing, community institutions, household consumption and urban demand were treated as connected components. The programme documentation supplied for this article captures its objective as bringing millets back into both farms and plates. The procurement numbers show how rapidly this ecosystem expanded.

Within four years, procurement quantity expanded approximately **33.5 times**, while the number of participating farmers increased more than **tenfold**. The interesting question is not simply how much Odisha procured. It is who made that procurement possible. Who Actually Carries MSP from the Government to the Farmer?

At the centre of Odisha's ragi procurement system is the Tribal Development Co-operative Corporation of Odisha Ltd. (TDCCOL), functioning as the State Procurement Agency. But TDCCOL does not stand alone.

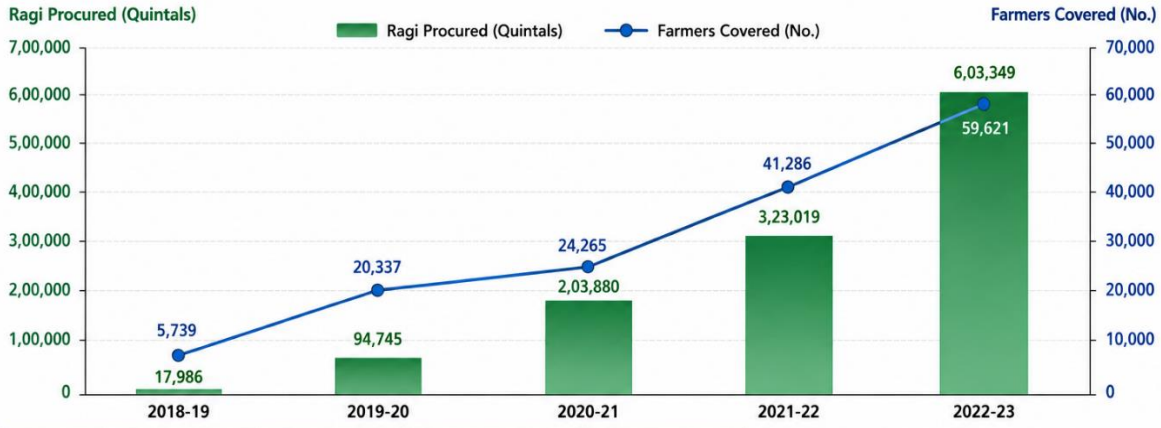
The operational architecture brings together PACS, LAMPCS, Farmer Producer Organisations and women's SHG federations as local procurement institutions. Odisha's procurement guidelines assign them practical functions such as farmer mobilisation, registration support, procurement-centre operation and awareness regarding Fair Average Quality requirements. Procurement agencies need basic infrastructure including weighing equipment, moisture meters, stitching facilities, internet connectivity, working capital and access to storage.

This apparently administrative detail is fundamental to understanding why MSP succeeds or fails. A moisture meter can matter almost as much as the MSP announcement. A farmer whose grain fails quality

specifications cannot realise the support price merely because government has declared one. Similarly, transporting a small quantity over a long distance can substantially reduce the effective value of procurement. Odisha therefore attempted to bring the market closer to the producer rather than expecting every small farmer to independently navigate it.

Odisha's Ragi Procurement Transformation Under the Millet Mission

Between 2018-19 and 2022-23, ragi procurement increased 33.5 times and the number of participating farmers rose 10.4 times.



Year	Ragi Procured (Quintals)	Farmers Covered (No.)	Increase in Procurement (Compared to 2018-19)	Increase in Farmers (Compared to 2018-19)
2018-19	17,986	5,739	–	–
2019-20	94,745	20,337	5.3 times	3.5 times
2020-21	2,03,880	24,265	11.4 times	4.2 times
2021-22	3,23,019	41,286	18.0 times	7.2 times
2022-23	6,03,349	59,621	33.5 times	10.4 times

Key Takeaways

- Ragi procurement grew from 17,986 quintals in 2018-19 to 6,03,349 quintals in 2022-23 (33.5 times increase).
- Farmer participation increased from 5,739 to 59,621 during the same period (10.4 times increase).
- The expansion was driven by assured procurement, decentralised collection centres, FPO/SHG engagement and linkage with public distribution and nutrition programmes.

Note: Data pertains to procurement under the Odisha Millets Mission.
Source: Government of Odisha (Millet Mission data as reported in "Millet Revolution in Odisha" - Mohapatra & Sendhil, 2024)

An FPO Shows What the "Missing Middle" Looks Like

NITI Aayog's field documentation provides a useful example from Bijepur in Bargarh district. Chirasabuja Producer Company Limited, supported locally through Mahashakti Foundation, participated in the millet programme as a farmer institution. At the stage documented by NITI Aayog, it had 209 shareholder farmers ,124 men and 85 women and five Community Resource Persons associated with programme implementation. The FPO participated in procurement and marketing rather than limiting itself to production support.

More interestingly, it experimented with value addition. NITI's field account records ragi being purchased, processed and packaged, with ragi powder marketed at a higher price than the unprocessed grain. The economics behind this small example are important. A farmer selling grain captures the value of the commodity.

An FPO that cleans, processes, packages and markets the same grain begins capturing part of the **consumer value** as well. The question for agricultural policy therefore changes from: "What price did the farmer receive?" to: "How much of the value created after harvest remained in the rural economy?" This is where agricultural finance also enters the discussion.

The Value Chain Needs a Credit Chain

A procurement ecosystem cannot run on policy announcements alone. An FPO needs working capital before it can aggregate produce. It may need storage, weighing equipment, moisture testing, cleaning and grading machinery. A processor needs fixed investment as well as inventory finance. A women's SHG producing millet snacks requires machinery, packaging, working capital and a market. A warehouse needs infrastructure finance. Odisha's own procurement criteria recognise this reality by requiring participating FPOs and SHG federations to demonstrate minimum operational and financial capacity. This leads to an overlooked implication for banks and policymakers: Crop diversification requires credit diversification.



Financing cultivation while leaving aggregation, storage and processing undercapitalised merely moves the bottleneck from before harvest to immediately after it. The required chain is broader:

Crop finance → FPO working capital → storage → primary processing → enterprise finance → market receivables.

If government wants MSP-induced diversification to become commercially sustainable, financial institutions must increasingly assess the commodity **as a value chain rather than only as a crop loan**.

Women's SHGs: Where a Commodity Becomes Food

Another important feature of the Odisha model is the role of women's collectives. The programme did not assume that consumers would automatically start purchasing whole ragi merely because farmers produced more of it. SHGs were encouraged to move millet into forms that people could actually buy and eat flour, snacks, cooked foods and other value-added products.

NITI Aayog's field documentation includes the experience of Maa Thakurani SHG, supported through an institutional network involving JanaSahajya, Mission Shakti and the Kutia Kondh Development Agency. A loan of about ₹3 lakh supported the transition of a tiffin-centre activity towards a small restaurant enterprise.

This may appear small compared with lakh-quintal procurement statistics, but it represents the other end of the agricultural transformation. A procurement agency can create offtake. A processing enterprise creates **usability**. A food entrepreneur creates **consumer experience**. Without the last two, a farmer may produce more millet while household food habits remain unchanged.

Government Became an Anchor Consumer

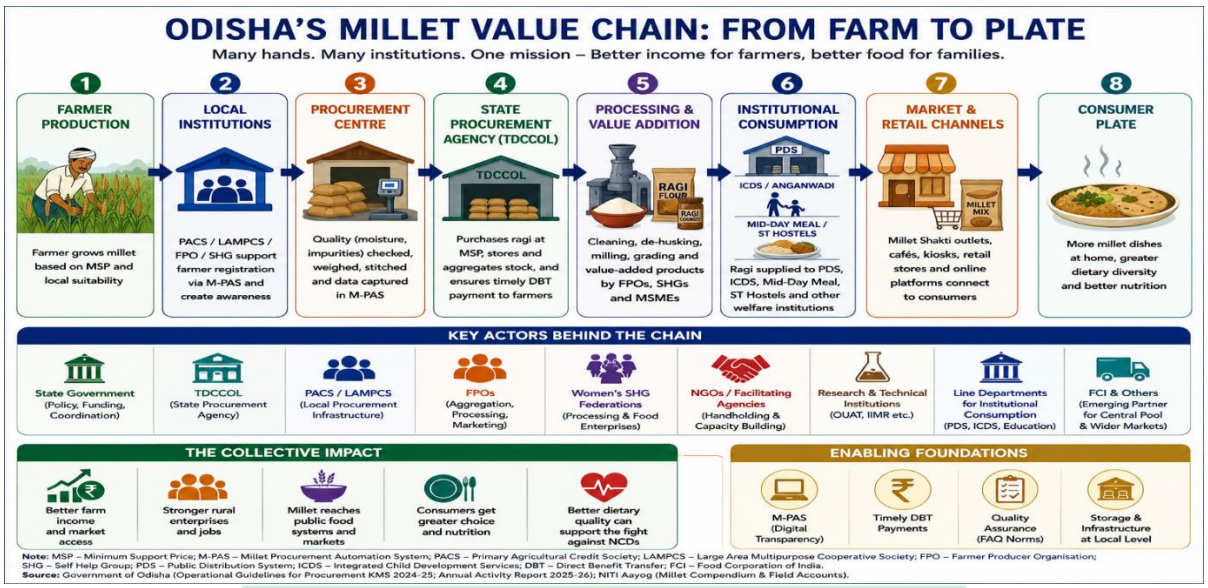
Odisha's most consequential intervention may therefore have occurred after procurement.

Ragi was progressively linked with **PDS and nutrition programmes**, creating institutional demand rather than waiting entirely for an immature commercial market to absorb additional production. The uploaded programme study documents this movement from procurement into PDS and ICDS. The approach can be visualised as a circular system.

The latest scale is significant. Odisha's Annual Activity Report 2025-26 reports Shree Anna Abhiyan operating in 177 blocks across all 30 districts, with millet demonstrations covering about 1.42 lakh hectares and

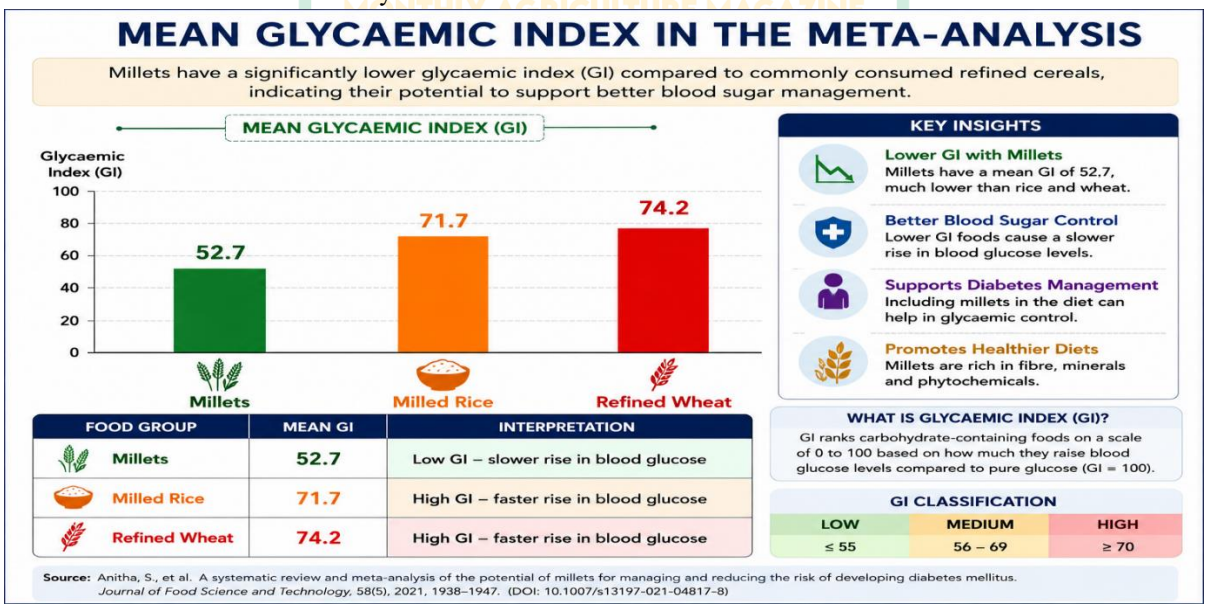
2.39 lakh farmers during Kharif 2025-26. It reports 7.5 lakh quintals of ragi procurement in KMS 2024-25 and an 8-lakh-quintal procurement programme for KMS 2025-26.

More importantly for the farm-to-plate argument, 5.93 lakh quintals were approved for PDS distribution, while 4 lakh quintals of surplus ragi were approved for supply to FCI's Central Pool. That final development potentially changes the scale of the experiment. A crop once supported through a state millet mission can begin moving into the national food-distribution architecture.



The Health Dividend: Evidence, Not Exaggeration

This brings us to the most sensitive part of the argument. Can such agricultural policy help India address diabetes? Not directly. No credible evidence allows us to say that increasing millet procurement will by itself reduce diabetes prevalence. Diabetes is influenced by total diet, body weight, physical activity, genetics, age, socioeconomic conditions and many other factors.



Nevertheless, food composition matters. A systematic review and meta-analysis covering multiple millet types reported a mean glycaemic index of **52.7**, compared with **71.7 for milled rice and 74.2 for refined wheat**.

Processing and preparation substantially influence these values, and individual millet varieties differ. The finding should therefore support dietary diversification - not a simplistic claim that millet is medicine.

The appropriate public-policy proposition is: Agricultural policy cannot treat diabetes, but it can influence the food environment within which diabetes prevention must operate. That distinction becomes especially relevant when India has an estimated 101 million people with diabetes and another 136 million with prediabetes.

Health policy usually begins after food has already reached the consumer. Agricultural policy begins much earlier. It influences what is profitable to cultivate, what government buys, what processors can access and, through public food programmes, what millions of households regularly encounter.

From MSP 1.0 to MSP 2.0

Odisha's experience suggests that the next evolution of MSP need not be another across-the-board increase in prices.

It could instead be an evolution in policy architecture.

MSP 1.0

Cost → MSP → Procurement

MSP 2.0

Agro-climatic suitability
↓
Remunerative MSP
↓
Accessible procurement
↓
FPO/SHG aggregation
↓
Value-chain finance
↓
Processing and private enterprise
↓
PDS / ICDS / PM-POSHAN / market demand
↓
Dietary diversification
↓
Measurable social return

Such a framework should not promote ragi everywhere. Koraput need not grow what Punjab grows, and Punjab need not imitate Koraput. The appropriate crop portfolio must reflect rainfall, irrigation, soil, existing dietary preferences, farmer economics and market possibilities. Nor should the objective be to replace one monoculture with another.

The Economic Survey 2025-26 itself points towards calibrated diversification, recognising the need to align farmer incentives with changing consumption requirements, environmental sustainability and national priorities. The deeper reform would therefore be to measure more than tonnes procured. For selected diversification programmes, government could develop a **Social Return on Procurement** framework asking:

How much farmer income was generated?

How many small producers actually accessed MSP?

How much processing capacity emerged?

How many viable rural enterprises were created?

How much nutritionally useful food reached households?

How much demand survived outside government procurement?

These questions would reveal whether public expenditure created merely a stock of grain or a functioning food economy.

Conclusion: Complete the MSP

Odisha's millet experience does not demonstrate that MSP can cure diabetes. Nor does it suggest that rice and wheat crop central to India's food security should simply be displaced. Its lesson is more fundamental. A remunerative MSP can encourage a farmer to reconsider what to grow. But price alone cannot aggregate the crop,

test its moisture, finance an FPO, operate a processing unit, create a millet entrepreneur or persuade a family to change what it eats. Institutions must perform those functions.

Odisha connected the farmer with the FPO, the FPO with procurement, procurement with processing, women's enterprises with consumers, and public food programmes with sustained demand. That institutional chain helps explain why its millet experience matters far beyond Odisha. India therefore does not necessarily need to abandon MSP or even simply raise it further. It needs to complete it.

The Green Revolution showed that agricultural policy could transform what India produces. The next transformation should ask whether farmer prosperity, resource resilience, dietary diversity and public health can increasingly be designed as parts of the same food system. Perhaps the MSP of the future should be judged not only by the price it promises at the mandi, but by how much social value that promise creates before the food finally reaches the plate.

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Atmanirbhar in Fertilizer-Feeding the Soil Without Feeding Our Imports

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A sack of white granules



It is 5 a.m. in a cooperative society yard in rural Punjab, and the queue is already long. Farmers have come with their Aadhaar cards and their patience, waiting for the truck that will bring the season's urea. Each 45 kg bag will cost them Rs 242. Very few in that line know that the same bag costs the government roughly ten times more. Further few know that the gas used to make it probably crossed the Arabian Sea in a tanker from Qatar, or that half the nitrogen inside it may never reach the paddy it is meant to feed.

In the 1960s, India faced a food crisis. A national campaign called "Miss a Meal" ran full-page ads in the country's major newspapers asking people to skip dinner. Indian policymakers scrambled to find a sustainable, long-term solution to hunger. New, high-yielding varieties of grain were introduced in India that needed high performing chemical fertilizer to maximize their potential. Then entered "The sack of white granules: Urea". Urea provided a concentrated and affordable source of nitrogen that fueled high-yielding crop varieties, driving massive food grain production and helping India escape chronic food shortages.

Total nitrogen fertilizer production, which once approximately 0.1 million tons of fertilizer increased to 225 lakh metric tonnes in 2015 and to 314 lakh metric tonnes in 2025. Import dependance on Urea remains at reasonable scale of 25%. However, even in 2026, India's dinner plate is still tied to gas prices in the Gulf, phosphate mines in Morocco and potash fields in Russia and Canada.

By attaining Atmanirbharta in Fertilizer and Agriculture, India can turn the vision of Atmanirbhar Bharat into reality.

From Bag to Plant: How Much Fertilizer Is Really Used?

Of every 100 kg of urea, an Indian farmer applies, the crop typically takes up only 30 to 35 kg. The rest is lost. Researchers measure this as Nitrogen Use Efficiency (NUE), the share of applied nitrogen that ends up in the crop. India's national NUE in 2015 at just 21%, against 30% in China, 41% in the United States and 35% worldwide.

Where does the rest go?

Pathway	What happens	Typical share of applied N lost
Ammonia volatilization	Urea turns to ammonia gas at the soil surface, worst in hot, alkaline soils	Up to 30%
Denitrification	Nitrate converted to N2 and nitrous oxide in waterlogged soils and gets wasted.	5-35%
Leaching	Nitrate washed below the root zone into groundwater	0-20%
Runoff and erosion	Nitrogen carried off the field with water and topsoil	Variable

The economics are startling. If India uses roughly 35-38 million tonnes of urea a year and two-thirds of its nitrogen is lost, the equivalent of more than 20 million tonnes of urea is effectively thrown away annually. That is roughly

double what the country imports. Lifting national NUE to about 30% to 45% would, in principle, eliminate the need for imported urea altogether, without a single new plant.

The Hidden Cost of Lost Nitrogen

Lost nitrogen does not disappear. It pollutes water, warms the climate, degrades soil and drains the public purse.

Groundwater and Human Health: 20.71% of groundwater samples tested exceeded the nitrate limit of 45 mg per liter, with contamination seen in parts of 502 districts across 26 states and UTs. Drinking water high in nitrate can cause methemoglobinemia, thyroid disorders and cancers. Ammonia escaping from fields reacts in the air to form fine particulate matter, adding to the winter smog of the Indo-Gangetic plain.

Climate: Nitrous oxide from fertilized soils is a greenhouse gas roughly 270 to 300 times more potent than carbon dioxide over a century, and it also depletes the ozone layer.

Water bodies: Nitrogen and phosphorus running into lakes and rivers feed algal blooms. When the algae die and decompose, oxygen collapses and fish die, disturbing the ecology.

Soil: Decades of urea-heavy use have acidified soils in many regions, depleted organic carbon and created hidden hunger for Sulphur, zinc and boron. Applying nitrogen alone, without balancing nutrients, eventually lowers yields.

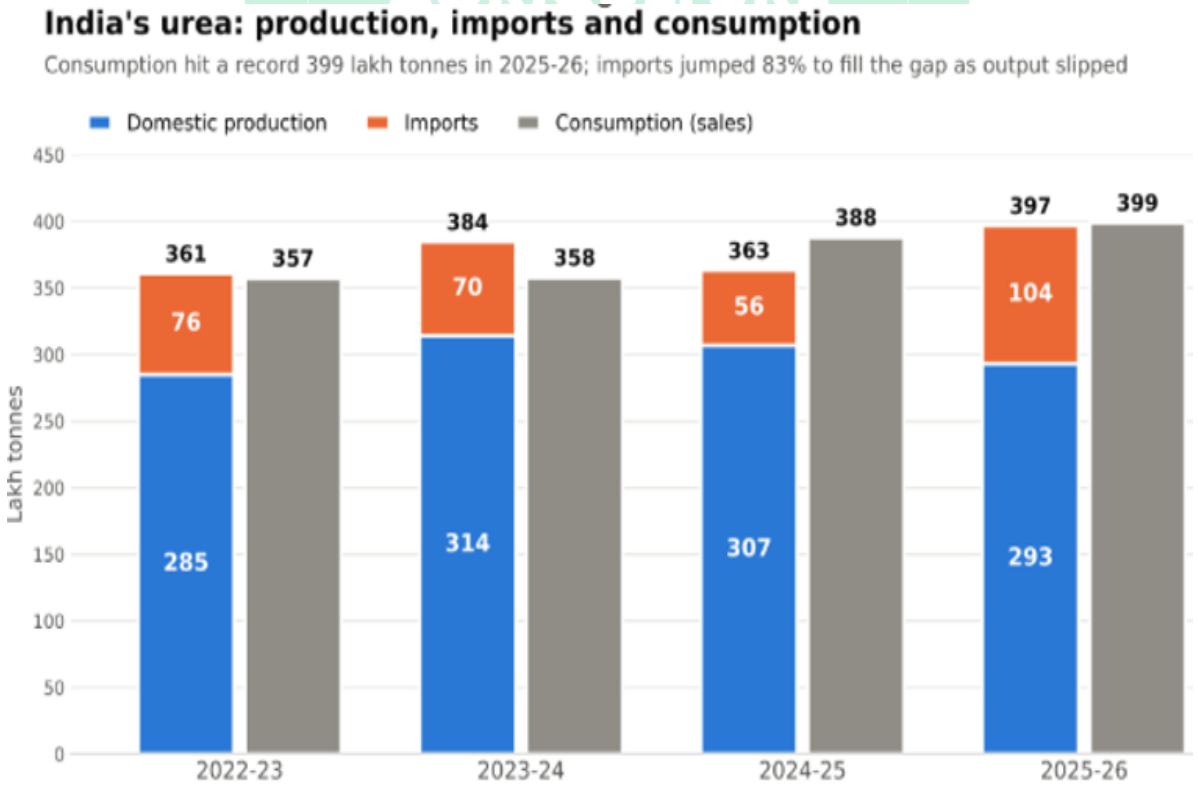
Treasury: Because farmers pay a fixed, heavily subsidized price for urea (Rs 242 for a 45 kg bag), the government absorbs the gap. India's Union Budget 2026–27 allocates ₹1.71 lakh crore for fertilizer subsidies, though the total subsidy burden is projected to reach approximately ₹3.4 lakh crore**, making it one of the largest subsidies after food.**

India's Urea Story in Numbers

Urea consumption rose from 357 lakh tonnes in 2022-23 to a record 399 lakh tonnes in 2025-26, an increase of about 12% in just three years.

However domestic production tells a different story. It rose from 285 lakh tonnes in 2022-23 to a peak of 314 lakh tonnes in 2023-24 and then lowered to 293 lakh tonnes by 2025-26. Imports filled the gap. Imports came down from 76 lakh tonnes in 2022-23 to 56 lakh tonnes in 2024-25 and jumped back to 104 lakh tonnes.

India's demand for urea keeps rising, but domestic production has not kept pace.



Where does Indias fertilizer (N-Nitrogen, P-Phosphorous, K- Potassium) come from?

Each of the three main nutrients rests on a different raw material, and India is short of all three.

Nutrient	Key product	Raw material	India's import share (approximate)	Countries imported from
Nitrogen	Urea, ammonia	Nitrogen from Air and hydrogen from Natural Gas	70-80% of hydrogen required for production of urea is imported.	Qatar, UAE, USA, others.
Phosphorus	DAP, SSP, NPK	Rock phosphate, sulphur	90%	Morocco's OCP is the dominant source.
Potassium	MOP	Potash ore (sylvinite)	100%	Russia, Belarus, Canada, Israel, Jordan, Germany, Turkmenistan.

Nitrogen is the most strategic of the three. The nitrogen itself is free, taken from air. The bottleneck is hydrogen, which today comes from natural gas. India's domestic gas output is limited, so urea plants depend on LNG shipped from Qatar, the UAE, the US and others.

Path to Atmanirbharta 1: Produce More

1. **Coal gasification: India's own hydrogen from its own coal**
   India has the world's fifth-largest coal reserves. Gasification turns coal into syngas (hydrogen and carbon monoxide), which can replace imported LNG as the hydrogen source for ammonia. The National Coal Gasification Mission targets 100 million tonnes of coal gasification capacity by 2030.
2. **Green Urea Mission**
   The Indian government unveiled a roadmap for the Green Urea Mission in June 2026. Green ammonia uses renewable electricity to split water into hydrogen through electrolysis, then combines it with nitrogen from air. No gas, no coal, no imports beyond the equipment. The shift could save an estimated $2.5 billion in foreign exchange over ten years
3. **Nano fertilizers: less volume, more precision, mixed evidence**
   IFFCO's nano urea and nano DAP are liquid formulations sprayed on leaves, delivering nutrients as nanoparticles that plants can absorb directly, in theory replacing part of a bag of granular fertilizer with a 500 ml bottle.

Path to Atmanirbharta 2: Reduce

The cheapest tonne of fertilizer is the one a farmer never has to apply. Three levers, soil testing, natural farming and crop diversification, cut demand at the root.

1. **Soil testing and soil health**
   Most Indian farmers apply fertilizer by habit, the same bags every season, without knowing what their soil already holds. A soil test changes that by showing which nutrients are deficient and which are in surplus. There are over 8,272 soil testing laboratories. It is better to integrate the readings of soil testing to a QR-coded recommendation linked to the farmer's land record and the dealer's point-of-sale machine to issue him adequate quantity of fertilizer for his fields.
2. **Natural farming**
   Natural farming replaces purchased chemicals with on-farm inputs: cow dung and urine preparations such as jeevamrit and beejamrit, mulching, mixed cropping and minimal tillage. Natural farming cuts input costs sharply and restores soil biology, but its yield effects vary by crop and region, and the transition years can be lean.
3. **Crop diversification**
   The rice-wheat system of Punjab, Haryana and western Uttar Pradesh is among the most fertilizer and water-hungry in the world. Replacing part of it with pulses, oilseeds and millets saves nitrogen twice. Pulses such as moong, arhar, chana and soybean fix their own nitrogen through Rhizobium and leave some for the next crop, often 20-40 kg N per hectare. Millets need far less nitrogen than rice. A summer moong crop between wheat and rice, for example, fixes nitrogen, earns income and reduces the urea needed by the following paddy.

4. **The Framework for Fertilizer Sale (FFS)**
   It is a digital pilot launched by the Ministry of Chemicals and Fertilizers and the Ministry of Agriculture and Farmers Welfare to make the distribution of subsidized fertilizer transparent and based on real need. It is running in 56 districts across 23 states. Farmers register on a mobile app using Aadhaar, linked to their AgriStack/Farmer Registry profile, and confirm their land and crop details. The system then works out how much fertilizer they need. Farmers pre-book this quantity and get a QR code, valid for about two days, which the retailer scans on a PoS device and confirms with Aadhaar biometrics. The scheme has helped the government save about ₹1,470 crore, because of better control over diversion and partly because of low rainfall and sowing. Diversion happens towards industries such as plywood, resin, textiles, plastics, cattle feed and explosives. India should look at moving subsidy to account via Direct Cash Transfers, wherein farmers can buy fertilizer at market price and the subsidy will be credited to farmers' accounts, which would remove the incentive for diversion altogether.

Path to Atmanirbharta, part 3: Innovate

1. **Crops that stop nitrogen from leaking**
   Some crops have the ability to reduce the amount of nitrogen that gets wasted in the soil. Their roots can slow down the soil bacteria that convert nitrogen into forms that can easily be lost. This helps keep nitrogen available to the crop for a longer time.
2. **Biofertilizers and microbial nitrogen**
   Biofertilizers, made of live micro-organisms. They can meet a substantial part of a crop's nutrient needs at much lower cost than chemical inputs.
3. **Precision farming: putting the right dose in the right place**
   Precision fertilizer application means applying the right amount of fertilizer, at the right place and at the right time, based on the actual needs of the crop.

Opportunities for Banks: Financing the Shift to Smarter Fertilizer

1. **Finance to fertilizer industry**
   Banks can finance working capital their subsidy receivables for which fertilizer companies wait months from the government.
2. **Organic and waste-to-fertilizer businesses-**
   Compressed biogas (CBG) plants under SATAT and GOBARdhan produce both gas and fermented organic manure (FOM). Banks can finance plant setup. In coastal Andhra Pradesh and Odisha. banks can finance units converting aquaculture sludge and sewage into fertilizer.
3. **Precision farming and service businesses**
   - **Agri-drones:** SHGs get drones with 80% central assistance under Namo Didi. Banks can finance the remaining cost, as well as drones owned by FPOs and rural entrepreneurs.
   - **Soil testing labs, sensor and advisory services, and custom hiring centres** can be financed under Agriculture Infrastructure Fund (AIF) scheme . AIF loans up to ₹2 crore get 3% interest subvention and a credit guarantee, which lowers risk for the bank.
4. **Farmers and FPOs**
   - KCC loans can be linked to Soil Health Card recommendations, so credit supports balanced fertilizer use rather than overuse.
   - Transition finance for natural farming: In the first one or two seasons, farmers may see lower yields. Banks could offer moratorium periods, flexible repayment or crop-insurance-linked loans to help them through this phase.

5.Green and sustainable finance-Projects that reduce fertilizer use, nitrous oxide emissions or LNG imports qualify as green lending. Banks can fund them through green bonds and climate finance lines, and they can count towards ESG targets. In future, an additional repayment source for farmer loans can be from carbon credits from lower nitrogen use and natural farming.

Way forward

India should set one headline target, raising national nitrogen use efficiency from roughly 30% to 45% by 2035, and organize every policy around it, because efficiency alone could erase urea imports.

- Farmer to be sold only what his land requires by linking soil test-based recommendations to the Farmer ID.
- Results of trials of nano fertilizers and biofertilizers to be published for raising awareness and better adoption by farmers.
- Tighten quality control for biofertilizers and crack down on urea diversion.
- Begin phased reform of urea pricing within a nutrient-based framework, with direct benefit transfer protecting small farmers.
- Grow drone and sensor service businesses through FPOs, with credit lines from banks.
- Raise green ammonia blending in fertilizer plants step by step, backed by domestic electrolyser manufacturing.
- Nitrogen efficient varieties of sorghum, pearl millet, wheat and rice to be released.

Conclusion

Now let us return to that co-operative yard in Telangana and imagine it ten years from now. The farmers are still coming for fertilizer, but they carry a single bottle of nano urea home. Their phone, drawing on a soil test linked to land records, tells that their field needs less urea and a little zinc. A drone operator from the village self-help group will spray a top-up dose only where the leaves turn pale. The fertilizer in their bag may be made might have originated from Coal Mines of Odisha. Their new sorghum variety holds on to nitrogen for longer periods and leaves the soil richer than they found it.

The Green Revolution taught India to feed itself by producing more. The next agricultural revolution must teach India to waste less, use resources more efficiently, and build greater self-reliance by producing more at home and reducing dependence on other countries. Atmanirbharta in fertilizer, in the end, is not just about producing more. It is about making every kilogram count, so that the nitrogen that feeds the nation is grown, made and kept closer to home.

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Rice Consumption and Blood Glucose Management: Insights into Glycemic Index, Glycemic Load, and Resistant Starch

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Abstract

Rice is a staple food for more than half of the global population and an important source of dietary carbohydrate. With the increasing prevalence of type 2 diabetes, considerable attention has been directed toward the relationship between rice consumption and postprandial glycemic responses. This review provides the information on factors influencing the glycemic response to rice, with emphasis on glycemic index (GI), glycemic load (GL), resistant starch (RS), amylose–amylopectin composition, milling, cooking, and storage practices. The glycemic response to rice varies substantially according to grain characteristics, processing methods, portion size, preparation techniques, and meal composition. Rice with higher amylose and resistant starch contents generally undergoes slower starch digestion and glucose release, resulting in a lower glycemic response. Cooling cooked rice promotes starch retrogradation and resistant starch formation, which may further reduce postprandial glycemic excursions. Selection of traditional or indigenous low-to-moderate GI rice varieties, eating appropriate portions, avoidance of excessive cooking, and consumption of rice with protein, fiber, and healthy fat rich foods may contribute to improved glycemic control. Importantly, rice consumption alone should not be considered a direct cause of diabetes. Glycemic outcomes are influenced by the interaction of rice characteristics, quantity consumed, preparation and storage practices, and overall dietary pattern. Thus, selection of appropriate rice quantity and preparation within a balanced diet may support glycemic management in diabetic and non-diabetic populations.

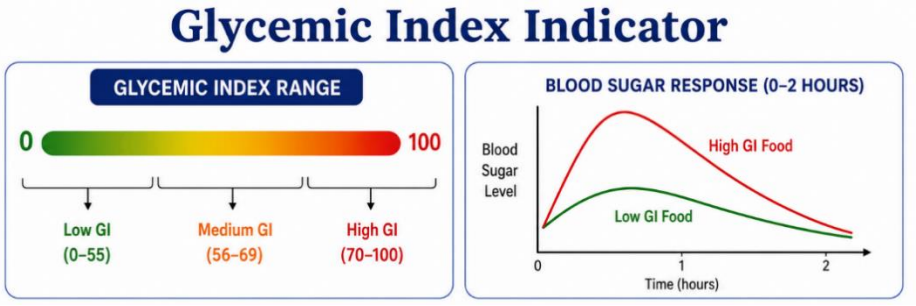
Keywords: Rice; Glycemic index; Glycemic load; Resistant starch; Amylose; Diabetes; Postprandial glycemia; Nutrition.

Introduction:

More than half of the world's population relies on rice as their staple food, and it provides a significant portion of the daily calorie intake. In recent times, the number of people with diabetes has increased considerably. After China, India has the highest number of people with diabetes in the world. According to the ICMR (2023) survey, 101 million people in the country are suffering from diabetes. Of these, 90 to 95 percent have type 2 diabetes. Many among them are under the misconception that eating more rice increases blood sugar. The following points briefly described how to control blood sugar levels in the body and what dietary habits should be adopted.

Glycemic index indicator:

The glycemic index is an indicator that measures how quickly blood sugar levels rise after consuming food. It assigns a numerical value to foods based on how rapidly the carbohydrates present in them are digested and absorbed by the body. Foods with a high glycemic index raise blood sugar levels quickly, while foods with a low glycemic index increase sugar levels gradually and slowly. The glycemic index ranges from 0 to 100. The glycemic index is determined by comparing the glucose response over a two-



hour period (0–2 h) after consuming 50 g of available carbohydrates in the test food with the glucose response from the same amount of carbohydrates from a standard food (Jenkins *et al.,* 1981).

When it comes to rice, the glycemic index value can vary depending on the type of rice and the milling process used to obtain the rice from the grain. For example, white rice has a higher glycemic index value than raw rice because the outer bran layer is removed during milling and polishing. Other varieties of rice, such as traditional (desi) rice and red rice, have lower glycemic index values due to their higher fiber and nutrient content (Frei *et al*., 2003; Sagum & Arcot, 2000).

How does the glycemic index work?

When starchy foods are consumed, they are converted to glucose in the small intestine and enter the bloodstream. As a result, when blood glucose levels rise, insulin is released from the pancreas. Insulin helps store glucose in cells or convert it into fat. This process varies depending on the starchy food consumed.

What is glycemic load?

Although the glycemic index score is a useful tool, it only considers the amount of starch in a food and not the portion size. By contrast, glycemic load takes into account both the glycemic index score and the amount of carbohydrates in the food. Foods with a low glycemic load are especially helpful for those who want to control their blood sugar levels. Eating more rice with a low glycemic index can still result in a higher glycemic load and increase in blood sugar. Glycemic load levels: Low: 0–10; Medium: 11–19; High: 20 or more.

Relationship between glycemic load and resistant starch:

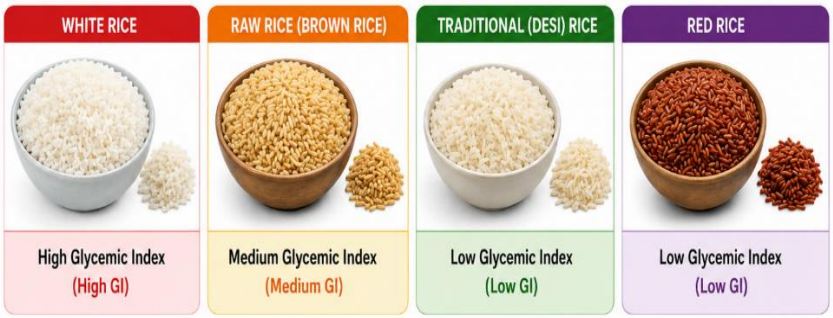
As resistant starch increases, the glycemic index decreases. By knowing the resistant starch content in rice, its glycemic index value can be estimated. The percentage of amylose, resistant starch percentage, and other starches in the food play an important role in affecting digestibility. These help in reducing glycemic response by controlling glucose release in the small intestine. Resistant starch plays a key role in lowering the glycemic index of rice, because it reduces the digestibility of starches and the absorption rate of glucose (Englyst *et al.,* 1992; Sagum & Arcot, 2000; Frei *et al.,* 2003).

Resistant starch is a special type of starch that reaches the colon undigested by the small intestine. It behaves like fiber in the diet. Resistant starch is classified into five types (R.S. 1,2,3,4,5), of which R.S. 3 (retrograded starch) is most relevant to rice. By increasing resistant starch in the diet, a feeling of fullness is reached more quickly, which may limit food intake. Regular consumption of resistant starch may improve the body's response to insulin (Englyst *et al.,* 1992).

The role of resistant starch in lowering the glycemic index

- Resistant starch causes glucose to be released into the bloodstream slowly by not being completely broken down into glucose in the small intestine (Englyst *et al.,* 1992).
- Because starch is converted into simple sugars at a lower rate, postprandial blood sugar levels do not rise significantly (Englyst *et al.,* 1992; Frei *et al.,* 2003).

Tips to lower the glycemic index:



- Parboiled rice and raw rice: These naturally contain more resistant starch than white rice (Sagum & Arcot, 2000).
- Adding coconut oil or vinegar while cooking rice may further increase the resistant starch level.
- Rice varieties with a low glycemic index: Raw rice (50–68%), black rice (42–45%), red rice (55%) and indigenous rice (45–57%) have low to moderate glycemic index levels (Frei *et al*., 2003).
- Consuming a balanced diet can lower the glycemic index. Eating rice together with protein, fiber, and healthy fats (e.g.vegetables, pulses, nuts, coconut oil) slows the release of glucose into the bloodstream.

- ❖ Cooling cooked rice in the refrigerator for more than 12 hours increases resistant starch, thereby reducing the glycemic index.

Conclusion:

The belief that eating rice causes sugar is a misconception. There is no such thing as rice without sugar; rice with a low glycemic index will vary by one or two points depending on the testing method. So far, rice varieties said to have a low glycemic index possess only up to 53 to 55 percent glycemic index. However, varieties with a medium glycemic index have a glycemic index ranging from 55 to 69 percent.

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Where Do Microplastics Enter Aquaculture Systems?

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Abstract

Aquaculture has become a major source of aquatic food worldwide, with farmed aquatic animals now accounting for more than half of global production. According to FAO's 2026 report, aquaculture delivered around 103 million tonnes in 2024, or 53% of the global total. Getting there took a lot of plastic. Pipes, tanks, liners, nets, ropes, feed bags and containers are part of nearly every farm's daily routine, and they make the work cheaper and easier. But plastic does not last forever. As it ages, wears thin or gets rough handling, it sheds tiny pieces known as microplastics into the water. These particles, smaller than 5 mm, can arrive on a farm from many directions: the incoming water, the land around it, the air, the feed and the farm's own equipment. Once they are in, they can drift in the water, settle into the sediment and be taken up by the animals. Studies on shrimp farms point to incoming water and feed as major sources, with equipment and packaging adding to the total. In one Indian study of 12 shrimp ponds, microplastics turned up in 93.7% of the shrimp samples and in every sample of feed, water and sediment. Finding microplastics in farmed animals does not mean the people who eat them are harmed, but it does raise fair questions about animal health, water quality and seafood safety. The answer is not to take plastic out of aquaculture altogether. It is to find the sources that can be avoided, waste less plastic, check farms regularly and adopt practical, plastic-smart habits.

Keywords: Microplastics, shrimp farming, aquafeed, plastic pollution, plastic-smart aquaculture

1. Introduction:

Aquaculture is now one of the main sources of the world's aquatic food. FAO's 2026 report shows that farms produced 103 million tonnes of aquatic animals in 2024, passing 100 million tonnes for the first time and supplying 53% of all aquatic-animal production (FAO, 2026). This growth has gone hand in hand with a rising use of plastic, from hatcheries and nurseries to grow-out ponds, cages and harvesting gear. Farmers rely on plastic for good reasons. It is light, inexpensive, resistant to water and chemicals, and easy to move and clean. The trouble starts as it ages. Sunlight, heat, friction, rough handling and poor waste disposal slowly wear it down. A frayed net or a cracked liner does not simply disappear. It breaks into ever smaller pieces, and some of them end up as microplastics in the water and sediment of the farm. Others arrive from outside, carried in by rivers, coastal water, runoff, wastewater and even the air. A farm is therefore both a source and a recipient of microplastics. This double role makes the problem harder to manage, because the particles do not come from one place. Knowing where they enter is the first step towards reducing them. This article traces that path: what microplastics are, why farms are so exposed, the main routes by which they get in, what happens to them once inside, and what this may mean for farmed animals and seafood safety. It ends with practical steps towards plastic-smart aquaculture.

2. What Are Microplastics?

Microplastics are very small plastic particles, usually **less than 5 mm in size**. Some are produced intentionally in small sizes, while others are created when larger plastic materials gradually break apart through **sunlight, weathering, physical wear and other environmental processes**. Their small size allows them to spread easily through aquatic environments and become distributed in water, sediment and other parts of the ecosystem.

In aquaculture, microplastics can enter through commonly used materials such as **nets, ropes, pipes, tanks and liners**, as well as through water and other materials brought into the farm. Once they enter the system, their movement depends partly on their **size, shape, density and type of plastic**. Some particles may remain floating

or suspended in the water, while others settle into the sediment or become accessible to cultured animals (Su *et al.,* 2024a). As plastic has become an essential part of modern aquaculture, understanding **where microplastics come from, how they move within farms and where they may accumulate** is an important step towards managing their presence in aquaculture systems.

3. Why Are Farms So Vulnerable?

A farm is a small, busy world where water, feed, sediment, animals and equipment are constantly mixing. That makes it easy for tiny particles to build up and pass from one part of the system to another. Three features stand out.

3.1 Water is always moving.

Water flowing into ponds, tanks, cages or raceways can carry microplastics already present in the surrounding environment. **Páez-Osuna et al. (2024) reported that incoming water was an important pathway for microplastic entry in shrimp farming systems, based on their review and mass-balance assessment.** This shows why the quality of water entering a farm is an important part of managing microplastic contamination.

3.2 Plastic is everywhere.

Plastic is used throughout aquaculture, from equipment and mesh to containers and packaging. Many of these materials are repeatedly exposed to water, sunlight, friction and routine farm activities, which can cause them to wear down over time. **Su et al. (2024a) reported that plastic equipment, mesh and packaging are among the potential sources of microplastics in aquaculture environments.** This makes the condition and handling of plastic materials an important consideration in reducing microplastic entry into farms.

3.3 Water, sediment and animals are linked.

Particles that enter a farm do not always stay afloat. Depending on their properties, they can drift, sink into sediment or be taken up by animals, which opens many routes for exposure.

4. Where Do Microplastics Enter Aquaculture Systems?

Microplastics reach a farm from eight main directions, some from outside and some from the farm's own materials and activities. Figure: 1 shows where each one enters.

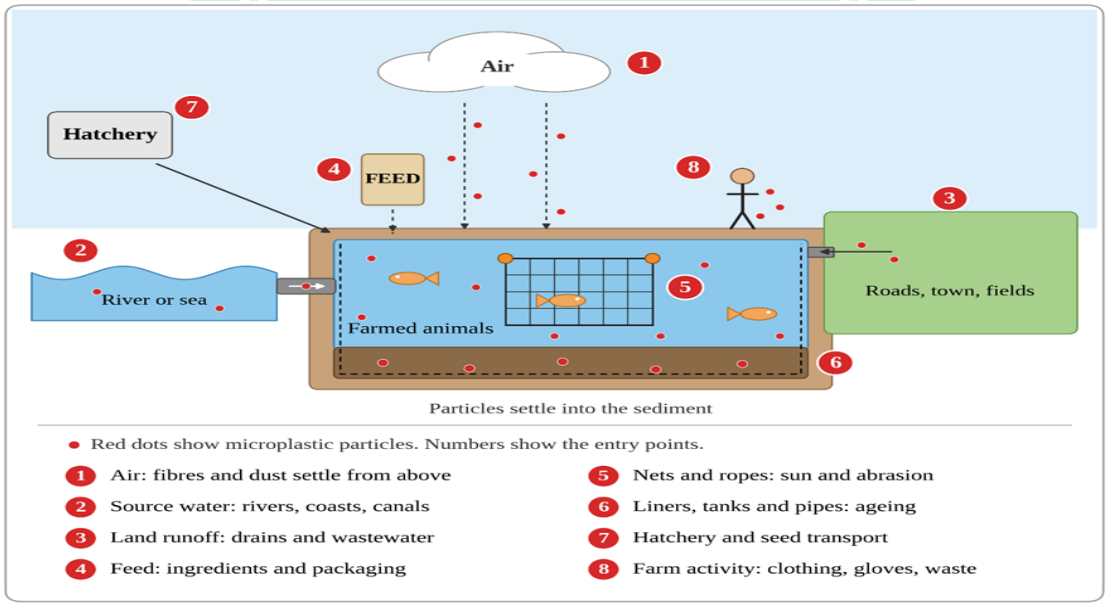


Figure 1. Entry points of microplastics into an aquaculture farm: (1) air, (2) source water, (3) land runoff, (4) feed and packaging, (5) nets and ropes, (6) liners, tanks and pipes, (7) hatchery and seed transport, and (8) farm activity. Red dots show microplastic particles, which spread through the water and settle into the sediment.

4.1 Source Water

Water can be an important route through which microplastics enter aquaculture farms. Rivers, estuaries, groundwater and coastal waters may already contain these particles, allowing them to enter ponds, tanks and other culture systems along with the incoming water. This pathway can be particularly relevant in coastal and shrimp

farming systems where water exchange is frequent. In shrimp ponds, water inputs have been identified as an important component of the estimated microplastic balance (Páez-Osuna et al., 2024). Therefore, managing microplastics cannot focus only on materials used within the farm; **the quality of the water entering the farm also deserves attention.**

4.2 Feed and Feed Ingredients

Feed is another pathway that deserves attention because it is introduced into the culture system in large quantities and comes directly into contact with farmed animals. Microplastics have been reported in aquafeeds and may enter through raw ingredients, processing, transportation or packaging (Su et al., 2024b). In Indian shrimp ponds, microplastics have also been detected in feed along with water, sediment and shrimp samples (Naidu et al., 2025). Once contaminated feed enters a pond, particles may be consumed by animals or become dispersed in the culture environment. Good feed storage, careful handling and reducing unnecessary contact with plastic materials can help minimize this pathway.

4.3 Nets, Ropes, Cages and Other Farm Equipment

Nets, ropes, cages, floats and screens are continuously exposed to **sunlight, water movement, friction and handling**. Over time, this wear can cause plastic surfaces to deteriorate and release small particles into the surrounding environment. Farm equipment and plastic structures are recognized as potential sources of microplastics in aquaculture (Su et al., 2024a). The problem can become more noticeable when equipment is old, damaged or subjected to rough cleaning and handling. Regular inspection and timely replacement of badly worn materials can therefore be a simple but useful part of routine farm management.

4.4 Liners, Tarpaulins, Tanks and Pipes

Plastic liners and tarpaulins are widely used in intensive culture systems, nurseries and temporary farm structures. Tanks, storage units, pipes and pumping systems also contain a variety of plastic components. Because water continuously passes through pipes and pumps, ageing, friction and physical wear may contribute to particle release. This does not mean that all plastic materials need to be removed or replaced immediately. A more practical approach is to **identify materials showing visible ageing or damage and repair or replace them when necessary.**

4.5 Hatcheries, Seed Transport and Routine Farm Activities

Microplastic contamination may begin even before animals reach the grow-out stage. Hatcheries and nurseries commonly use plastic tanks, pipes, filters, bags and containers, while seed may be transported in plastic bags or boxes. Routine farm activities can add further sources, including damaged packaging, plastic containers, synthetic fibres from clothing and poorly managed waste. Although each source may contribute only a small amount, repeated inputs throughout a production cycle can gradually increase the overall load within the farming environment.

4.6 Air and the Surrounding Environment

Microplastics are not restricted to water and sediment; they can also be transported through the air. Small particles and fibres may settle on **pond surfaces, feed storage areas and farm equipment**. Farms located close to roads, urban areas or industrial activities may also be exposed to additional sources through atmospheric deposition, runoff and wastewater. However, farm-level information on airborne microplastic deposition remains limited. This pathway therefore needs further investigation. It also highlights an important point: **microplastic contamination in aquaculture cannot always be separated from the wider environment in which a farm operates.**

5. What Happens After Microplastics Enter the Farm?

What a particle does next depends on its size, density, shape, polymer type and the conditions in the farm. Some particles stay suspended in the water, while others sink into the sediment. Fibres tend to stay mobile longer, and denser particles settle more easily on the bottom. Microbes can also form a living film on the surface of a particle. This community, called the "plastisphere," gives microorganisms a place to live and may affect processes such as nitrogen cycling (Su et al., 2024a). Scientists are still working out how much this matters. It is also worth remembering that particles in the sediment are not automatically eaten by the animals. Exposure depends on how a species feeds, what the particles are like and the conditions in the farm.

6. How Do Microplastics Affect Farmed Animals?

Microplastics can reach farmed fish and shrimp through **water, feed and sediment**. How much is taken up can depend on the species, its feeding habits, and the size and characteristics of the particles (Nabi et al., 2024). Research has linked microplastic exposure with responses such as **oxidative stress, tissue injury and changes in normal biological functions,** although these effects are not the same for every species or farming condition. In shrimp culture, microplastics have been found in **water, feed, sediment and shrimp,** suggesting that these particles can move through different stages of the farming environment before reaching the cultured animals (Naidu et al., 2025; Páez-Osuna et al., 2024). However, simply detecting microplastics in shrimp or fish does not necessarily mean that they are producing harmful effects. Much of the existing evidence comes from laboratory experiments, and more studies under actual farm conditions are needed to understand the long-term implications. From a farmer's perspective, the focus should therefore be on **reducing exposure at the source.** Good water and feed management, regular inspection of plastic equipment, timely replacement of damaged materials and proper handling of plastic waste can help limit the entry and breakdown of plastics within farm systems. Taking these preventive steps can support healthier culture environments while reducing the potential movement of microplastics into farmed animals.

7. Building Plastic-Smart Aquaculture

The goal is not to remove plastic completely from aquaculture. Plastic materials are useful for many farm operations and can contribute to efficient and safe production. The better approach is to use plastic more carefully, prevent unnecessary losses and manage plastic waste before it reaches the aquatic environment. This can be achieved through a simple **six-step plastic-smart approach**.

Six Steps Towards Plastic-Smart Aquaculture

Steps	Action	What it means on the farm
1.	Prevent	Reduce unnecessary single-use plastics and, wherever possible, select durable materials that can withstand regular farm use for longer periods.
2.	Control	Regularly inspect nets, ropes, liners, pipes and tanks for cracks, abrasion and other signs of wear. Store feed properly, minimize unnecessary plastic contact during handling and prevent plastic waste from entering ponds, canals and drains.
3.	Filter	Where practical, use screening, settling or suitable filtration systems to reduce the entry of particles through incoming water.
4.	Monitor	Regular monitoring helps identify where microplastics are entering the farm. Where facilities are available, samples of water, feed, sediment and cultured animals can be examined to trace important contamination pathways.
5.	Manage	Collect damaged equipment and other plastic waste separately and send it for appropriate reuse, recycling or disposal. Plastic waste should never be burned, buried or left near water bodies.
6.	Verify	Monitoring should be repeated after management measures are introduced. This helps determine whether the actions are actually reducing plastic entry rather than simply assuming that they are effective.

Who Should Do What?

Reducing microplastic contamination is not the responsibility of farmers alone. Different parts of the aquaculture sector have a role to play.

Stakeholder	Practical actions
Farmers	Keep intake water as clean as possible; regularly inspect and replace worn nets, ropes and liners; store feed in clean, intact and covered containers; collect used bags, gloves and bottles; and avoid burning plastic waste.
Hatcheries and nurseries	Use durable tanks, pipes and containers; maintain suitable filtration of incoming water; inspect tanks and equipment regularly; and reduce single-use plastics wherever practical alternatives are available.
Feed manufacturers	Maintain good control of raw materials and processing, improve packaging and storage practices, and provide appropriate information on contamination control and testing.
Equipment suppliers	Develop durable, UV-resistant and low-shedding nets, ropes, liners and pipes, while exploring recyclable materials and take-back programmes for used equipment.
Researchers	Develop consistent methods for detecting and reporting microplastics, conduct long-term studies under real farm conditions, and investigate individual pathways to identify the most important sources.
Regulators	Develop practical monitoring guidelines, establish appropriate standards for plastic materials used in aquaculture, and support systems for collection and responsible management of farm plastic waste.

8. Conclusion:

Microplastics are emerging as an important environmental challenge for modern aquaculture. Their presence is closely linked to the extensive use of plastic materials on farms and to the quality of the surrounding aquatic environment. Particles can enter aquaculture systems through source water, feed, equipment, packaging materials, atmospheric deposition, farm activities and nearby land-based sources. Once introduced, they may be transported between water and sediment and can eventually become available to cultured fish and shellfish. Research conducted so far provides sufficient evidence to recognize microplastics as a concern that deserves greater attention, monitoring and preventive action. At the same time, important knowledge gaps remain. We still need a clearer understanding of the relative contribution of different sources and the consequences of long-term, low-level exposure under realistic farming conditions. However, the answer is not to eliminate plastic from aquaculture. Plastic materials play an important role in farm infrastructure, water management, culture systems, packaging and day-to-day operations. The focus should instead be on using plastics more responsibly and managing them throughout their working life. This is where the concept of **plastic-smart aquaculture** becomes relevant. It involves selecting appropriate and durable plastic materials, maintaining farm equipment regularly, reducing unnecessary plastic use, preventing damaged materials from breaking down into smaller particles, and ensuring the proper collection and disposal of plastic waste. Ultimately, controlling microplastics should begin **before they become microplastics.** Preventing unnecessary plastic degradation and limiting the entry of plastic waste into farm systems can be far more effective than trying to remove microscopic particles after they have dispersed through water, sediment and cultured animals. Building plastic-smart practices into everyday aquaculture management can therefore help farms reduce their environmental footprint while maintaining the practical benefits that plastic materials provide.

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India's Silk Economy at a Crossroads: Production Growth, Export Expansion, Import Dependence, and Value-Chain Transformation (2020–21 to 2025–26)

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Abstract

India occupies a highly distinctive position within the global silk economy because it produces all four commercially important varieties of silk—namely mulberry, tasar, eri, and muga—and successfully combines a vast rural production base with substantial domestic consumption and an established export industry. This comprehensive review examines the changing structure of India's silk economy during the period from 2020–21 to 2025–26, with particular attention directed toward raw-silk production dynamics, export performance, persistent import dependencies, and the shifting composition of traded silk products. The analysis demonstrates that total raw-silk production increased significantly from 33,770 MT in 2020–21 to 41,121 MT in 2024–25, representing an expansion of approximately 21.77%. Concurrently, nominal silk export earnings grew from ₹1,466.60 crore to ₹2,361.75 crore, with the latest available trade data indicating a further surge to ₹3,578.76 crore in 2025–26. The composition of exports has increasingly shifted toward downstream high-value products, where fabrics and made-ups maintain the largest export segment while readymade garments recorded an exceptionally strong growth trajectory. Crucially, this export expansion has coexisted with a persistent dependence on foreign raw material, as raw-silk imports rose from 1,804 MT in 2020–21 to 2,627 MT in 2025–26. This review argues that the coexistence of surging domestic production and continuous high-grade raw silk imports highlights a structural quality, productivity, and processing challenge rather than a simple supply deficit. To ensure long-term global competitiveness, India must transition from a traditional production-oriented approach toward an integrated farm-to-fashion and fibre-to-market value-chain strategy.

1. Introduction

Silk occupies an exceptionally prestigious position within the global textile economy due to its unique combination of natural origin, luxurious aesthetic appeal, deep cultural heritage, and high market value. Unlike most natural or synthetic textile fibres, the structural workflow of silk production bridges a diverse array of sectors including agriculture, forestry, animal husbandry, rural cottage industries, reeling, spinning, weaving, advanced wet processing, and international fashion trade. Consequently, the macroeconomic significance of sericulture extends far beyond the mere production tonnage of raw silk, serving as a powerful engine for rural employment generation and structural value creation.

In this global context, the Indian silk sector presents an important and highly instructive paradox. India stands as the world's second-largest producer of raw silk after China and holds the unique biological distinction of commercially farming all four major silk varieties: mulberry, tasar, eri, and muga. While official data from the Central Silk Board confirms a long-term upward trajectory in total raw silk output, the domestic weaving and manufacturing sectors remain heavily dependent on imported high-grade raw silk to satisfy the technical requirements of automated power looms. This operational reality suggests that the central challenge facing the sector is no longer simply whether India can increase its absolute volumetric output, but whether it can produce the requisite international standard quality at a competitive cost, while successfully converting its fiber assets into downstream value-added products demanded by global markets.

2. Objectives and Methodology

This review paper operates under a structured framework designed to achieve multiple primary research goals. First, it examines the recent growth and variety-wise trajectories of raw-silk production in India. Second, it systematically analyzes the performance, structural shifts, and item-wise composition of Indian silk exports over the past six years. Third, it diagnoses the changing structure and absolute value of silk imports to identify the core

drivers of foreign dependency. Fourth, it isolates the underlying technical and supply-chain constraints that limit the trade competitiveness of the industry. Finally, it puts forward actionable policy recommendations and strategic interventions aimed at strengthening the domestic value chain.

The data and insights presented in this study are compiled entirely from secondary datasets sourced from authoritative national and international entities. The primary quantitative series were extracted from the statistical databases of the Central Silk Board, the Ministry of Textiles, the Department of Commerce, and the International Sericultural Commission. These datasets were further supplemented by international trade records from the World Bank World Integrated Trade Solution database and recent peer-reviewed academic literature focusing on textile trade competitiveness. The core analytical horizon spans the financial years from 2020–21 to 2025–26, utilizing nominal trade values reported in current Indian Rupees and US Dollars to construct a comprehensive image of the industry's contemporary transition.

3. Trends in Raw-Silk Production

The domestic silk sector has exhibited a generally strong and positive production trajectory over the reviewed period. Total raw-silk output expanded by approximately 21.77%, climbing from 33,770 Metric Tonnes in 2020–21 to a substantial 41,121 Metric Tonnes in 2024–25. This expansion highlights the successful deployment of field-level interventions and improved rearing methodologies across major sericultural clusters. Mulberry silk continues to serve as the dominant backbone of the national output, growing steadily from 23,896 MT to 31,119 MT, thereby commanding an overwhelming 76.82% share of total production by the conclusion of 2023–24.

In contrast, the non-mulberry or vanya silk segments present a more varied and complex trend. Tasar silk production, which is heavily integrated with forest economies and tribal communities, witnessed a sharp cyclical contraction from 2,689 MT in 2020–21 down to 1,318 MT in 2022–23 due to climatic anomalies and seed supply bottlenecks, before mounting a robust recovery to 1,884 MT in 2024–25. Meanwhile, Eri silk production has emerged as a remarkably stable and growing component, reaching 7,886 MT to represent 18.46% of the total output mix, while the ultra-premium Muga silk remains localized and structurally constrained at 232 MT, contributing a highly specialized 0.65% to the national aggregate as detailed in the comprehensive production layout below.

Year	Mulberry (MT)	Tasar (MT)	Eri (MT)	Muga (MT)	Total (MT)
2020–21	23,896	2,689	6,946	239	**33,770**
2021–22	25,818	1,466	7,364	255	**34,903**
2022–23	27,654	1,318	7,349	261	**36,582**
2023–24	29,892	1,586	7,183	252	**38,913**
2024–25	31,119	1,884	7,886	232	**41,121**

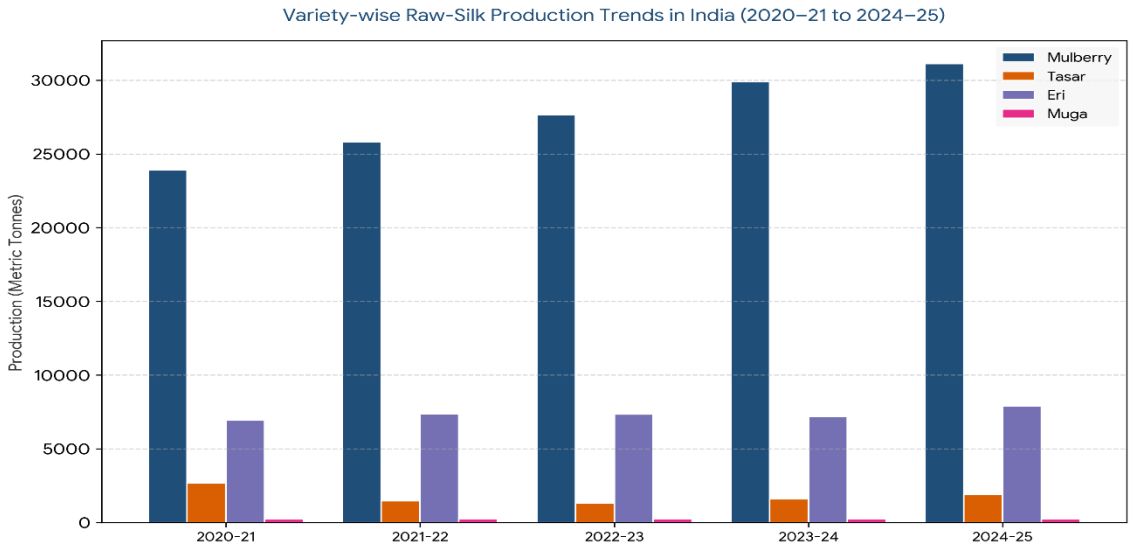


Figure 1: Comparative Variety-wise Raw Silk Production (MT) Trends in India

4. Export Performance and Value-Chain Transformation

The commercial evolution of Indian silk trade is most prominently reflected in its export earnings and the structural reconfiguration of its outbound basket. Total nominal silk export earnings grew at an impressive compound annual growth rate of approximately 19.5% over the analysis window, shifting from ₹1,466.60 crore in 2020–21 to ₹2,361.75 crore in 2024–25, and experiencing a massive 51.5% single-year surge to reach ₹3,578.76 crore in 2025–26. This dramatic fiscal improvement should not be misconstrued as a simple replication of volume expansion, but rather as an explicit manifestation of enhanced downstream value addition and a highly successful commercial pivot toward finished goods.

A granular dissection of the export items demonstrates that primary raw materials have effectively disappeared from the outbound mix, with raw silk exports dropping to a negligible 0.06% share by 2025–26. Conversely, the downstream segments consisting of high-value Fabrics & Made-ups and Readymade Garments have consolidated an absolute dominance over trade returns, collectively commanding 84.66% of total export values. Readymade garments alone witnessed an extraordinary leap from ₹486.31 crore in 2024–25 to ₹1,101.58 crore in 2025–26, capturing a 30.78% share of the total portfolio. This transition aligns seamlessly with modern empirical trade theories which prove that India's international revealed comparative advantage is overwhelmingly concentrated in processed silk commodities, designer garments, and blended fabrics, rather than in upstream primary raw fibers.

Export Item (₹ Cr)	2020–21	2021–22	2022–23	2023–24	2024–25	2025–26
Cocoons	0.01	6.94	–	–	–	–
Raw Silk	1.43	11.27	1.79	15.45	25.42	2.16
Silk Yarn	27.93	34.41	36.95	34.69	42.17	45.73
Fabrics & Made-ups	729.50	837.41	973.49	1,119.13	1,443.98	1,928.21
Readymade Garments	449.56	671.13	489.61	443.79	486.31	1,101.58
Silk Carpet	107.56	79.12	92.34	96.84	99.21	193.94
Silk Waste	150.61	208.67	179.19	317.66	264.66	307.14
Total Export Value	**1,466.60**	**1,848.96**	**1,773.38**	**2,027.56**	**2,361.75**	**3,578.76**

5. Diagnostics of the Import Paradox

The continuous growth of domestic silk cultivation has remarkably failed to eliminate India's reliance on foreign raw silk, revealing a deep structural anomaly within the textile value chain. Total raw silk imports exhibited a sharp, volatile peak in 2022–23, reaching 3,874 MT valued at ₹1,713.68 crore, before stabilizing at 2,627 MT valued at ₹1,299.55 crore in 2025–26. A rigorous diagnostic analysis reveals that this import pattern is driven by qualitative parameters rather than an absolute supply shortage. Modern domestic high-speed automated power looms require highly uniform, international standard 4A-grade and above bivoltine filaments to maintain operational speed and minimize warp breakage. Because domestic production is dominated by cross-breed multivoltine silk characterized by higher filament variations, weavers actively prefer high-grade imports sourced predominantly from Vietnam and China. Furthermore, India's status as a massive consumer market means that a significant volume of these premium imports is absorbed internally to fulfill consumer demand for luxury bridal attire and traditional handloom products rather than being re-exported, making import substitution a complex technical goal.

6. Strategic Imperatives: Digital Traceability, ESG Integration, and Youth Enterprise

In order to convert its extensive production infrastructure into sustainable global competitive leverage, the Indian silk industry must immediately implement advanced strategic layers focused on transparency and technology. Global luxury markets and premium fashion houses are increasingly operating under strict environmental, social, and governance compliance mandates. By embedding decentralized digital ledger frameworks and blockchain-based traceability networks from the initial silkworm seed rearing stage down to the final retail garment, Indian

exporters can reliably certify authentic processing and secure premium pricing tiers. This technology can be coupled with an aggressive international positioning of India's unique Geographical Indication silk marks—such as Muga of Assam, Bhagalpur Tasar, and Kanchipuram weaves—to insulate traditional artisans against counterfeiting and build an elite global brand. Additionally, the policy core must focus on transforming sericulture from an analog, legacy occupation into an attractive, high-tech agricultural enterprise. By providing young rural entrepreneurs with modern digital marketing platforms, automated micro-reeling systems, and direct-to-consumer sales infrastructure, the industry can reverse the demographic aging of rearers while driving localized value capture and economic resilience.

7. Policy Architecture and Conclusion

The institutional roadmap formulated under the national Silk Samagra-2 framework, supported by an allocated outlay of ₹4,679.86 crore, represents a vital mechanism for addressing the sector's long-term technical bottlenecks. Government programs must move away from simplistic volumetric tracking and focus instead on targeted funding for automated reeling units, climate-resilient host plant plantations, and scientific disease surveillance networks. Differentiated fiscal support executed via the Tribal Sub-Plan and Scheduled Castes Sub-Plan remains foundational to upgrading the pre-cocoon rearing safety nets for marginalized communities across eastern and central Indian vanya silk hubs like Odisha and Jharkhand. Ultimately, India's silk economy stands at a historic crossroads where long-term commercial success will depend on an integrated farm-to-fashion paradigm. By systematically replacing broad import restrictions with precise domestic quality substitution, upgrading post-cocoon automation, and prioritizing sustainable green production methodologies, India can successfully link its magnificent heritage production base with high-value global luxury consumer channels.

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Sustainable Agriculture for Food Security

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Abstract

Feeding a growing population without exhausting the natural resources that food production depends on is one of the central challenges of this century. Conventional intensive farming raised yields dramatically, but often at the cost of soil degradation, water depletion, biodiversity loss and rising greenhouse gas emissions. Sustainable agriculture offers a way forward. It combines ecological principles, efficient resource use, farmer knowledge and supportive policy to produce enough nutritious food today while protecting the capacity to do so tomorrow. This article explains the link between sustainability and the four dimensions of food security: availability, access, utilization and stability. It reviews key practices, including conservation agriculture, integrated nutrient management, crop diversification, efficient irrigation, agroforestry and integrated crop-livestock systems. It also discusses the enabling role of technology, institutions and policy, and the barriers smallholders face.

Keywords: sustainable agriculture, food security, agroecology, conservation agriculture, soil health, climate resilience, smallholder farmers, natural resource management

Introduction

Every day, farmers around the world face a double demand. They must produce more food for a population projected to approach 10 billion by mid-century, and they must do so on land that is increasingly degraded, with water that is increasingly scarce, under a climate that is increasingly unpredictable. The Food and Agriculture Organization estimates that around 733 million people faced hunger in 2023, roughly one in eleven people worldwide (FAO et al., 2024). Hunger persists even though the world produces enough calories to feed everyone, which shows that food security is about more than total production.

The Green Revolution proved that science can transform farming. Improved varieties, fertilizers and irrigation saved millions from famine, but heavy reliance on external inputs also brought costs: declining soil organic matter, groundwater overdraft, nutrient pollution and pesticide resistance (Tilman et al., 2002). The question today is no longer whether to produce more, but how to produce more sustainably. The classic definition of sustainable development, meeting present needs without compromising the ability of future generations to meet theirs (WCED, 1987), applies directly to the farm.

What Is Sustainable Agriculture?

Sustainable agriculture is not a single technique or a return to the past. Pretty (2008) describes it as farming that makes the best use of natural processes and services, such as nutrient cycling, nitrogen fixation, natural pest regulation and soil regeneration, while minimizing damage to the environment and keeping farming economically viable and socially fair. It rests on three linked pillars:

1. Environmental health: protecting soil, water, air and biodiversity.
2. Economic viability: ensuring farmers earn a stable, fair livelihood.
3. Social equity: supporting rural communities, women and smallholders, and ensuring access to nutritious food.

A farm that is productive but ruins its soil is not sustainable. Neither is a farm that protects the environment but leaves the farmer in poverty.

Understanding Food Security

The 1996 World Food Summit defined food security as existing "when all people, at all times, have physical and economic access to sufficient, safe and nutritious food" to meet their dietary needs for an active and healthy life (FAO, 1996). This definition has four dimensions:

- Availability: enough food produced, stored and traded.
- Access: households have the income and resources to obtain it.
- Utilization: food is safe, nutritious and properly used by the body.
- Stability: availability and access hold up through shocks such as droughts, floods and price spikes.

Sustainable agriculture influences all four. Healthy soils support steady yields, diversified farms support dietary diversity and income, and resilient systems protect against climatic shocks.

Key Practices for Sustainable Food Production

Soil health management

Soil is the foundation of food security. Practices that raise soil organic carbon, such as residue retention, cover cropping, composting and green manuring, improve fertility and water-holding capacity, and also sequester carbon (Lal, 2004). Healthy soils make yields more stable, especially in rainfed regions.

Conservation agriculture

Conservation agriculture rests on minimal soil disturbance, permanent soil cover and crop rotation. It reduces erosion, saves fuel and labour, conserves moisture and can improve yields over time, and it has spread across millions of hectares worldwide (Kassam et al., 2009).

Integrated nutrient and pest management

Balancing chemical fertilizers with organic manures and biofertilizers improves nutrient-use efficiency and limits pollution. Integrated pest management combines resistant varieties, biological control, crop rotation and judicious pesticide use, cutting costs and protecting beneficial organisms and human health.

Efficient water management

Agriculture accounts for the largest share of freshwater withdrawals globally. Drip and sprinkler irrigation, alternate wetting and drying in rice, rainwater harvesting, mulching and scheduling irrigation by crop need can raise “crop per drop” and ease pressure on aquifers.

Crop diversification and agroforestry

Mixed cropping, intercropping, rotations and trees on farms spread risk, improve soil, provide fodder, fuel and fruit, and raise household income. Diverse farms are also better placed to supply varied, nutritious diets, which addresses hidden hunger as well as calorie shortages.

Integrated crop–livestock–fish systems

Combining crops with livestock, poultry, fisheries or apiculture recycles nutrients and residues within the farm and provides regular income, which is especially valuable for small and marginal farmers.

Organic and agroecological approaches

Organic farming typically yields less than conventional farming, but it often delivers greater profitability, environmental benefits and ecosystem services, and the yield gap can narrow with good management and diversified rotations (Reganold and Wachter, 2016). Agroecology more broadly applies ecological principles to the design of farming systems and values local and traditional knowledge (Altieri, 1995).

Technology and Innovation

Sustainability and modern technology work together. Precision tools such as soil testing, remote sensing, sensors and decision-support apps help farmers apply the right input in the right amount at the right time. Climate-smart practices, including stress-tolerant varieties, weather-based advisories and crop insurance, build resilience against projected climate impacts on yields (Lobell et al., 2008). Solar pumps, energy-efficient machinery and post-harvest storage cut energy costs and food losses. Foley et al. (2011) argue that closing yield gaps, using inputs more efficiently, shifting diets and reducing waste together offer a far better route than simply clearing more land.

Enabling Policy and Institutions

Farmers adopt sustainable practices when it pays and when they know how. Effective strategies include:

- Extension and farmer-field-school models that build skills and trust.
- Remunerative and stable prices, with markets that reward quality and sustainable production.
- Access to credit, insurance, quality seed and farm machinery for smallholders.
- Secure land and water rights, with incentives for conservation.
- Farmer producer organizations that improve bargaining power and market access.

- Investment in research, with attention to women farmers, who contribute much of the labour but often lack equal access to resources.

Challenges

Several barriers slow progress. Transition costs can be high, and benefits such as improved soil may take years to appear while the farmer bears the risk. Small and fragmented landholdings limit mechanization and scale. Knowledge gaps, weak market linkages and subsidies that favour input-intensive systems also discourage change. Climate variability adds further uncertainty. Godfray et al. (2010) stress that no single solution will suffice, and that a combination of approaches, tailored to local contexts, will be needed.

Conclusion

Food security and environmental sustainability are not competing goals; each depends on the other. Without healthy soil, clean water and stable ecosystems, long-term food production cannot be maintained. Without secure and prosperous farmers, sustainable practices will not endure. Meeting future food needs will require a balanced mix of improved soil and water management, diversified and resilient farming systems, appropriate technology, and supportive policies and institutions that reach the smallholder. Sustainable agriculture is therefore not an option but a necessity: the pathway by which we can nourish today's population while safeguarding the resources that will nourish tomorrow's.

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EL NINO AND ITS IMPACT ON FOOD AVAILABILITY, NUTRITION AND HUMAN HEALTH

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Introduction

El Nino is the phenomenon which happens in the Central and eastern Pacific Equatorial Pacific Ocean which initially warms the oceanic water on the surface. When we talk about India, an emerging nation which is dependent on agriculture, which in-turn is totally dependent on the monsoon. This exists in mostly rural India and about 70% of Indian population lives in rural India. This kind of cataclysm directly impacts the social and economic life of rural population. The Indian rural population is about 95% dependent on agriculture and the rest on animal rearing, fisheries and other MSMEs. When the rain or monsoon is uneven because of El- Nino then this kind of uneven monsoon leaves the impact on the agriculture and agricultural will directly impact on the social, economic and cultural life of the rural and urban Indian population.

El Niño and Food Production



Agriculture is one of the sectors most sensitive to changes in rainfall and temperature. Drought associated with El Nino can reduce soil moisture, hinder crop establishment and lower yields. High temperatures can increase crop water requirements and cause heat stress in crops and livestock. Conversely, excessive rainfall and flooding can damage standing crops, wash away fertile topsoil and disrupt agricultural operations. FAO's 2026 assessment identifies parts of South and Southeast Asia, the Sahel, Southern Africa and Central America as regions where El Nino-related drought poses substantial risks to crops and pasture. Reduced agricultural production may, in turn, limit the availability of cereals, pulses, vegetables, fruits, livestock products and other nutritious foods. Lower production may also reduce farm incomes, particularly among small and marginal farmers.

Impact on Food Availability and Food Prices



The effects of El Nino does not stop at the farm gate. When crop production declines, food supply chains are affected as well. Transportation, storage, processing and local markets may be disrupted by droughts, floods and other extreme events. Lower supply can push up food prices and make nutritious foods less affordable for vulnerable households. Smallholder farmers and pastoral communities are especially exposed, because they often depend on rainfall and local markets. Food availability has two dimensions: the physical supply of food and people's economic ability to access it. A household may find food in the market and still struggle to afford a diverse, nutritious diet.

El Nino and Nutrition

Nutrition is closely connected with food availability, food access and dietary diversity. When household income decreases or food prices increase, families may reduce the quantity and variety of foods purchased. They may

depend more heavily on inexpensive staple foods while reducing consumption of fruits, vegetables, pulses, milk, eggs and other nutrient-rich foods.



This can increase the risk of inadequate intake of protein, iron, calcium, zinc, vitamin A and other essential nutrients. Children, pregnant and lactating women, older persons and economically vulnerable households can be particularly affected when nutritious foods become less accessible. Climate-related disruptions can also interfere with health, nutrition and social services. Importantly, the relationship between El Nino and nutrition is complex. A 2025 systematic review of evidence from low- and middle-income countries in the Indo-Pacific found that El Nino is likely to reduce agricultural production and productivity, but also highlighted important gaps in direct evidence linking El Niño specifically with nutrition outcomes in the region.

From Farm to Plate: The Nutrition Pathway

The impact of El Niño on nutrition can be understood as a chain:

El Niño → rainfall/temperature changes → crop and livestock losses → reduced food availability → higher prices/lower household income → reduced dietary diversity → nutritional risk

Impact on Human Health



Climate-related changes can affect health through several pathways. WHO reports that ENSO can influence food security, water and air quality, ecosystems and health infrastructure. Changes in rainfall and temperature can also alter the transmission patterns of some vector-borne, rodent-borne and waterborne diseases. Extreme heat can increase the risk of heat-related illness, particularly among outdoor workers, older adults and vulnerable populations. Flooding can contaminate drinking-water sources and increase sanitation challenges. Drought can reduce access to safe water and increase pressure on household resources. Poor nutrition can further reduce resilience to illness, creating a cycle in which climate shocks, food insecurity, disease and malnutrition reinforce one another.

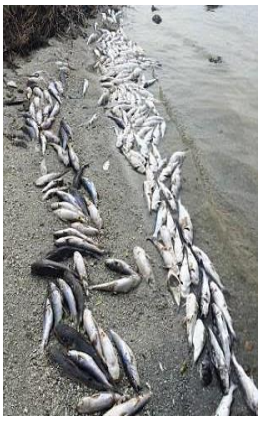
Children and Vulnerable Groups

Children are particularly sensitive to disruptions in food and nutrition. Inadequate dietary intake during critical stages of growth can affect physical development, immunity and learning. WHO has documented historical examples linking major ENSO events with food crises and health consequences. For example, research from Peru found that children exposed to the 1997–98 El Niño period experienced poorer growth indicators than expected in the absence of the event, after accounting for other factors. Therefore, nutrition surveillance and early intervention are important components of climate preparedness.

Impact on Livestock and Fisheries



El Nino can affect not only crops but also livestock and fisheries. Drought can reduce pasture and fodder availability, while water scarcity can affect livestock productivity. Heat stress may reduce animal feed intake and productivity.



Marine ecosystems can also respond to changes in ocean temperature. Changes in fish distribution and availability can affect communities that depend on fisheries for food and livelihoods. FAO identifies farmers, pastoralists and fishers among groups that can experience direct impacts from El Nino.

Households can improve resilience through simple food and nutrition strategies:

- Maintain a nutri-garden/kitchen garden wherever water is available.
- Grow drought-tolerant vegetables and traditional crops.
- Preserve seasonal fruits and vegetables through drying, dehydration and other safe processing methods.
- Store cereals, pulses and other essential foods properly.
- Include affordable sources of protein such as pulses, groundnuts, milk and eggs where available.
- Use locally available millets and other climate-resilient crops.
- Avoid unnecessary food wastage.
- Ensure safe drinking water and good sanitation.
- Give special attention to children's, pregnant women's and elderly people's nutritional needs.

Climate-Resilient Food Systems



Long-term resilience requires action from farmers, communities, institutions and governments. Climate-smart agriculture, efficient irrigation, water harvesting, drought-tolerant varieties, improved livestock management and better storage facilities can reduce production losses. Food processing and value addition can also help. Drying vegetables, fruits and mushrooms, preparing millet-based products, producing nutritious mixes and improving food storage can extend shelf life and reduce post-harvest losses. Early-warning systems are equally important. In 2026, El Nino has prompted international agencies to emphasize anticipatory action before droughts, floods and other shocks cause major losses. WFP reports that early action can help communities prepare for climate shocks and reduce humanitarian needs.

The Role of Nutrition Education



Nutrition education is an important low-cost intervention. Families need practical information on how to maintain dietary diversity when food prices rise or certain foods become temporarily unavailable. **"**Eat locally, diversify your diet, preserve seasonal foods and reduce food wastage" can become an important household-level strategy during climate stress. Schools, Anganwadi centres, Self-Help Groups, Farmer Producer Organisations, KVKs and community organizations can support awareness programmes on climate-resilient nutrition, kitchen gardens, food preservation and healthy diets.

Way Forward

El Nino should not be viewed only as a weather phenomenon. Its effects can travel through the entire food system—from soil and water to farms, markets, households, diets and human health. Recent WFP assessments warn that the strengthening 2026 El Nino could worsen food insecurity in vulnerable regions into 2027, highlighting the importance of preparedness and early action. At the same time, evidence should be interpreted carefully. The effects of El Nino differ substantially by location, season, crop, livelihood and socioeconomic conditions.

Conclusion

El Nino can influence food availability, food access, dietary diversity, nutrition and health through a series of interconnected pathways. Protecting nutrition during climate shocks requires more than increasing food production. It requires resilient agriculture, water management, food preservation, affordable nutritious diets, social protection, health services and timely climate information.

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Grain Storage Management in India: Bridging Traditional Practices and Emerging Digital Technologies

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Abstract

India loses an estimated 12 to 16 million metric tonnes of food grain every year after harvest, with storage alone accounting for a large share of that loss. Most of the country's grain is still kept in traditional farm-level structures - earthen pots, mud bins, bamboo baskets, and thatch or straw enclosures - that offer little protection against moisture migration, insect infestation, rodents, and fungal growth. Government agencies such as the Food Corporation of India rely heavily on the low-cost Cover and Plinth (CAP) method rather than scientifically engineered silos, leaving a persistent gap between the country's production growth and its storage capacity. At the same time, a distinct global literature has emerged around digitally enabled storage: Internet of Things (IoT) sensor networks, artificial intelligence (AI) and machine learning (ML) analytics, hermetic and modular storage systems, automation in grain handling, and blockchain-based traceability. This paper brings the two bodies of work together. It summarizes the structural and biological factors that govern safe grain storage in Indian conditions, reviews the traditional and improved storage structures currently in use, and evaluates how emerging digital technologies could be adapted to close India's storage gap. The review concludes that while large commercial operations are best positioned to adopt sensor- and AI-driven systems, the greatest reduction in national post-harvest loss will come from low-cost, scalable adaptations - such as hermetic bags paired with simplified moisture sensors - that are appropriate for smallholder farmers, who store the majority of India's grain.

Keywords

Post-harvest loss, grain storage, Cover and Plinth (CAP), hermetic storage, IoT sensors, artificial intelligence

1. Introduction

Agriculture remains central to the Indian economy, contributing roughly 14% of national GDP and about 11% of exports, and it is the principal livelihood for close to half the population. Food grain production has grown steadily over recent decades, yet post-harvest loss has stayed roughly constant at around 10% of output - an amount the World Bank estimates could feed a third of India's poor, with an annual monetary value exceeding Rs. 50,000 crores. Storage alone is responsible for a substantial share of this loss, generally attributed to the continued dependence of small and marginal farmers on traditional storage structures rather than scientifically engineered facilities.

Historically, efforts to reduce these losses centred on physical infrastructure: improved bins, concrete and steel silos, and mechanical aeration. Over the past decade, however, a parallel and largely separate literature has developed around digitally enabled storage management - sensor networks, predictive analytics, hermetic sealing, and traceability platforms - that is reshaping storage practice in commercial grain-handling industries elsewhere in the world. This review integrates both strands. Section 2 outlines the structural landscape of grain storage in India. Section 3 summarizes the abiotic and biotic factors that govern safe storage. Section 4 reviews emerging digital and hermetic technologies. Section 5 discusses how these technologies map onto the Indian context, and Section 6 concludes with directions for future research.

2. Storage Structures in India

About 60-70% of the food grain produced in India is stored at the household level in indigenous structures built from locally available materials - paddy or wheat straw, bamboo, mud, brick, and cow dung. Design varies sharply by region and is shaped by farm size, family size, consumption pattern, and local building tradition. In southern India, tall mud bins known as *Kuthir* are common for storage of different grains, while wooden granaries such as

Kodambae hold up to 1,000 kg grains. Himachal Pradesh uses rectangular mud structures called *Kothi* and *Kuthla*, and the wooden *Tunn*, which can remain in service for 40-50 years. The *Adi* tribes of Arunachal Pradesh use a rat-proof granary called *Nahu*, built on a stone pad with an airtight upper compartment, while Punjab's brick-and-mud *Bukhari* and portable earthen *Bharola* serve similar functions at smaller scale. These structures allow free air movement, which helps prevent condensation but also leaves grain exposed to insects and rodents.

Engineered improvements on these designs include the Pusa bin, which uses a polythene moisture barrier sandwiched between brick or masonry layers, and the PAU bin, a galvanized-metal structure developed by Punjab Agricultural University with a capacity of 1.5 to 15 quintals. At commercial scale, the Food Corporation of India (FCI), Central Warehousing Corporation, and State Warehousing Corporations manage a nationwide network of godowns and open storage. The dominant method remains Cover and Plinth (CAP) storage - grain bags stacked on raised, damp-proof plinths and covered with 250-micron polythene sheeting - chosen for its low cost and rapid construction (under three weeks) despite offering less protection than a sealed silo. India operates only four large-scale steel silos (Calcutta, Madras, Bombay, and Hapur-Ghaziabad); the Hapur facility, for example, has a capacity of around 500 tonnes with integrated grain-cleaning, drying, and temperature-monitoring equipment. Public-private pilots, such as a temperature-controlled silo project developed with the Punjab government and a private rice exporter, point toward gradual expansion of scientific storage capacity.

3. Factors Governing Safe Storage

Safe storage depends on the interaction between abiotic factors like moisture content, temperature, storage duration, inter-granular atmosphere, structure type etc. and biotic factors, principally insects, mites, rodents, and microorganisms. These variables are tightly linked: moisture and temperature largely determine whether insect and fungal populations can establish and multiply. Under warm, moist conditions, insects, mites, and fungi both generate additional moisture and heat through respiration, accelerating spoilage in a self-reinforcing cycle. Grain held at sufficiently low moisture and temperature, by contrast, can remain stable for years.

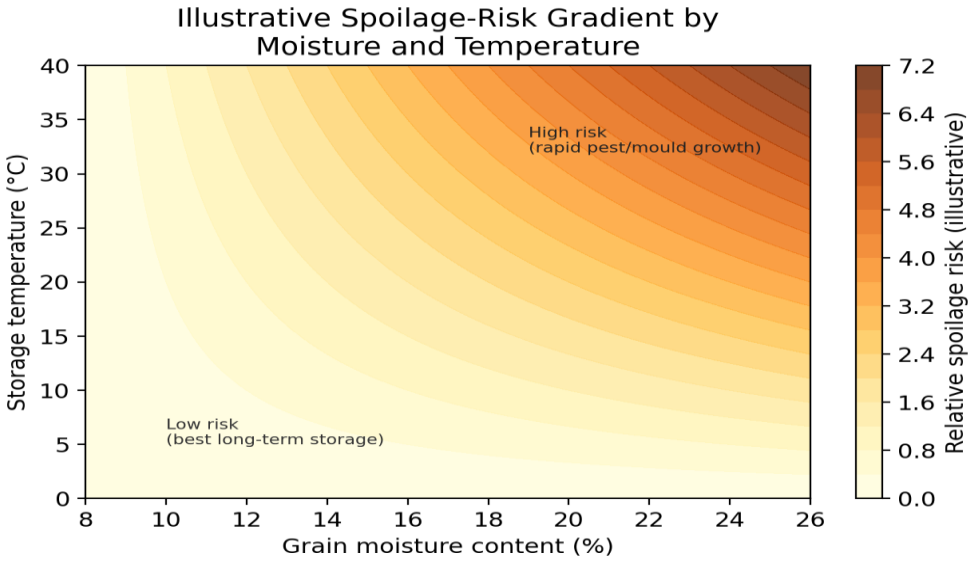


Figure 1. Illustrative relationship between grain moisture content, storage temperature, and relative spoilage risk. Lower moisture and cooler temperatures support long-term storage; the combination of high moisture and elevated temperature creates conditions favorable to rapid mould growth and pest reproduction.

The major insect pests of stored grain in India include the lesser grain borer, saw-toothed grain beetle, rice weevil, khapra beetle, red flour beetle, pulse beetle, and Indian meal moth. Most stored-product insects can survive across a wide range of temperatures (roughly 8-41°C) and humidity levels, with an optimum development range around 25-35°C, closely overlapping typical harvest-season conditions in much of India. Because pulses are stored largely in gunny bags or baskets with minimal sealing, they are markedly more vulnerable to insect

damage than cereals: a district-level survey in Coimbatore found storage losses as high as 40% in black gram, compared with roughly 2% in paddy.

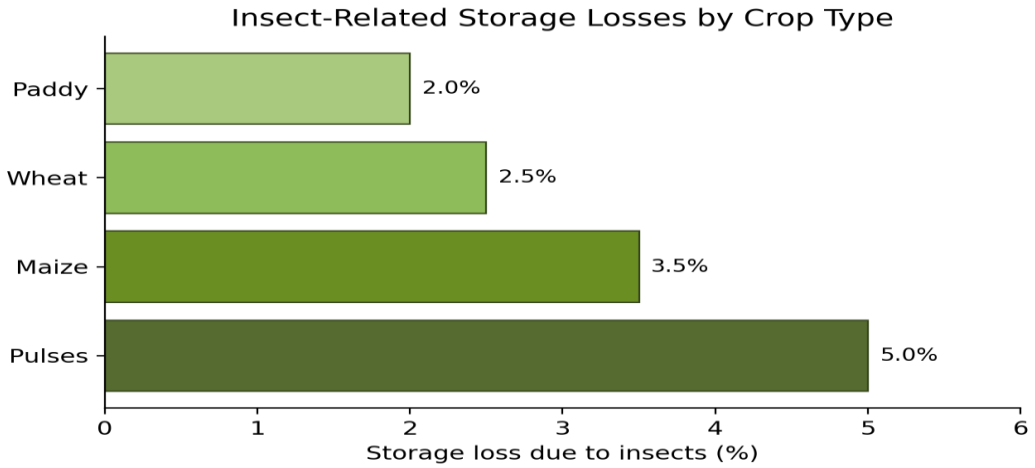


Figure 2. Relative storage losses attributable to insect activity across major stored grain and pulse crops.

Within the broader post-harvest chain, storage consistently accounts for the largest share of loss. For pulses, storage alone is responsible for roughly three-quarters of total post-harvest loss, well ahead of processing, threshing, and transport combined.

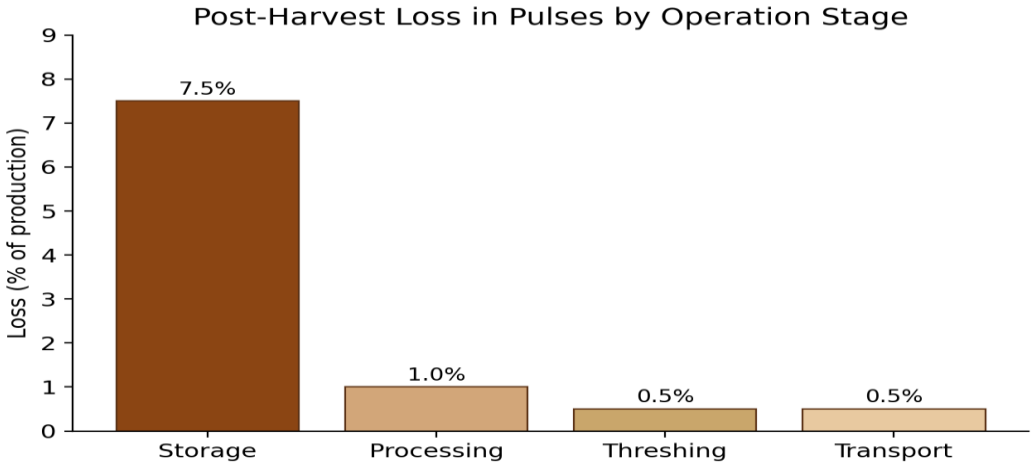


Figure 3. Distribution of post-harvest loss in pulses across handling stages, showing storage as the dominant contributor.

4. Emerging Technologies in Grain Storage

4.1 IoT-Enabled Sensor Networks

Storage bins and silos are increasingly fitted with embedded sensor networks that continuously track temperature, humidity, and grain condition, replacing periodic manual probing with data streams that can be monitored remotely through smartphone or desktop applications. Newer bin-lid designs integrate wireless humidity and temperature sensors directly into the sealing hardware, combining airtight protection with connected monitoring in a single component, and automated ventilation systems paired with these sensors have been reported to improve moisture control and overall storage efficiency.

4.2 Artificial Intelligence and Machine Learning Analytics

AI and ML techniques - including neural networks, fuzzy logic, deep learning, and anomaly detection - are increasingly applied to the data generated by sensor networks. Reported applications include pest and insect-damage detection, automated grain classification and quality grading, early detection of mycotoxin contamination, and predictive analytics for inventory and supply-chain management. Commercial systems have

also begun using AI-based image recognition within physical insect-capture probes to automatically identify pest species as part of integrated pest management, reducing reliance on manual identification.

4.3 Hermetic and Modular Storage Systems

Hermetic (airtight) storage creates a low-oxygen environment that suppresses insect and microbial activity without chemical intervention. Tightening regulatory restrictions on chemical fumigants have been identified as a key driver of demand for hermetic solutions, spurring development of sealed bags, containers, and modular bins with improved sealing and moisture control suited to both smallholder and specialty-grain applications - a category with direct relevance to India's household-level storage sector.

4.4 Automation in Grain Handling

At the facility level, grain handling is shifting from manual controls toward automated receiving, conveying, drying, and load-out systems. Centralized control rooms and remote monitoring allow operators to manage multiple processes with fewer errors, while predictive maintenance approaches aim to reduce unplanned downtime in large-scale elevators and terminals - a model with clear application to India's larger FCI and CWC facilities.

4.5 Block chain-Based Traceability

Block chain technology is being explored to improve traceability across storage and distribution chains. By recording immutable data on crop origin, storage duration, and handling conditions, such systems aim to give producers, distributors, and consumers greater confidence in provenance and quality, supporting food-safety compliance and market transparency - a function that could complement India's public distribution system.

5. Discussion: Applying Emerging Technology to the Indian Context

Read together, the two literatures suggest a common trajectory: from passive, structure-based grain protection toward active, data-driven management. In India specifically, this shift is likely to be uneven. Large commercial operators - FCI, CWC, SWCs, and private silo operators - are best positioned to adopt sensor networks, AI-based quality grading, and automated handling, since they already operate at a scale that justifies the capital and connectivity investment. The country's small number of large steel silos illustrates both the potential and the current limitation: modern facilities exist and perform well, but capacity remains far short of national need.

For the roughly two-thirds of Indian grain stored at the household level, the more relevant emerging technologies are hermetic bags and modular bins rather than full sensor-and-AI systems. Hermetic sealing directly addresses the biotic risk factors documented in traditional Indian structures - insect infestation and fungal growth driven by uncontrolled moisture and air exchange - without requiring electricity, connectivity, or technical training. Simplified, low-power moisture and temperature indicators, even without full IoT connectivity, could meaningfully close the visibility gap that currently forces farmers to rely on periodic manual inspection.

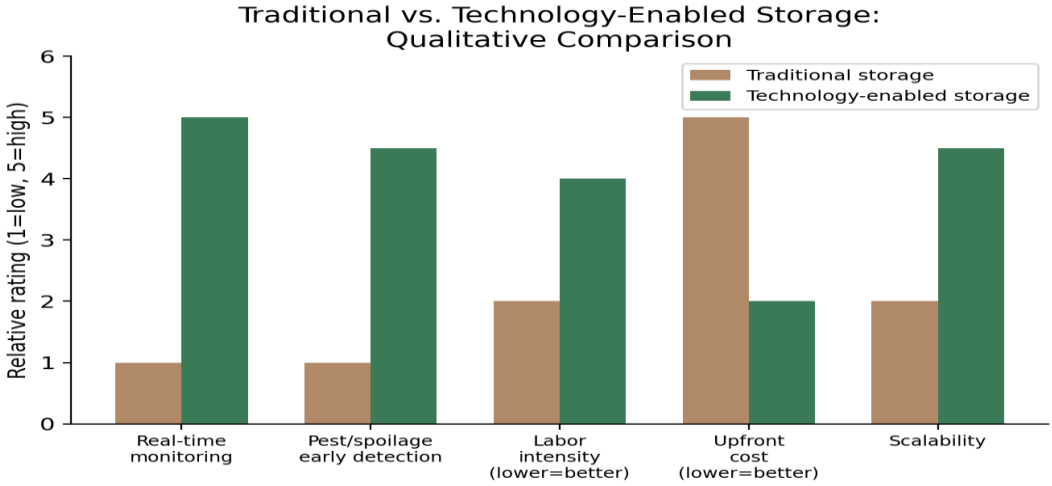


Figure 4. Qualitative comparison of traditional and technology-enabled storage approaches across factors relevant to Indian smallholder adoption. Ratings are illustrative, drawn from the characteristics reported in the reviewed literature rather than measured field data.

Cost, connectivity, and technical expertise remain the binding constraints. Sensor-equipped bins and cloud-based analytics carry high upfront and recurring costs that are difficult to justify at smallholder scale, and rural connectivity gaps limit real-time monitoring even where hardware is affordable. This mirrors a conclusion already implicit in the Indian literature on traditional storage: safe-storage guidelines and drying protocols specific to Indian climatic conditions and crop varieties remain underdeveloped, and this same research gap extends to evaluating which digital technologies can be adapted at low cost for Indian conditions.

6. Conclusion

India's grain storage capacity has not kept pace with production growth, and storage continues to account for a large share of the country's post-harvest losses. Traditional structures, while inexpensive and well adapted to local materials and climate, offer limited protection against moisture, insects, and rodents, and the dominant commercial method - Cover and Plinth storage - remains a compromise between cost and protection rather than a long-term solution. The emerging technology literature offers a complementary set of tools: IoT sensing and AI analytics for large-scale facilities, and hermetic sealing for smallholder and household-level storage. Realizing these benefits at national scale will require continued research into low-cost, offline-capable, and climate-appropriate adaptations of these technologies, alongside the safe-storage and drying guidelines that Indian-specific research has long called for. Bringing the country's storage infrastructure and its digital storage-management capability forward together offers the clearest path to reducing losses, protecting grain quality, and strengthening food security.

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BIOFUMIGATION – INDUCED MICROBIOME SHIFT

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ABSTRACT

Soil-borne phytopathogens are major constraints to agricultural production, causing diseases such as seed rot, wilt and root rot. Although chemical fumigants such as methyl bromide have been effective in pathogen management, their environmental and health impacts have encouraged the development of sustainable alternatives. **Biofumigation** is an eco-friendly approach that uses plant-derived compounds, particularly glucosinolates from Brassicaceae plants, to suppress soil-borne pathogens and modify the soil microbial community. When plant tissues are damaged and incorporated into soil, glucosinolates are hydrolysed by the enzyme myrosinase, producing biologically active compounds such as **isothiocyanates (ITCs)**. These compounds inhibit fungal growth and spore germination and can disrupt bacterial cell membranes, enzymes, mitochondrial functions, and cellular metabolites. Biofumigation can also induce shifts in the soil microbiome by promoting beneficial microorganisms such as *Pseudomonas*, *Bacillus*, and Actinobacteria, which contribute to plant growth and disease suppression. Therefore, biofumigation represents a promising component of integrated and sustainable soil-borne disease management.

KEY WORDS: Soil borne pathogens, Biofumigation, Isothiocyanates, Cell Wall degarding enzymes, Microbiome shifts and integrated approach.

INTRODUCTION

Soil-borne phytopathogens such as *Rhizoctonia spp., Fusarium spp., Verticillium spp., Sclerotinia spp., Pythium spp., and Phytophthora spp.* result in substantial agricultural losses ranging from 50% to 75% (Mihajlović *et al*., 2017). These pathogens cause diseases like seed rot, wilts and root rot in several crops. Methyl bromide has been widely used since 1930's as an effective fumigant to control soil-borne pathogens and pests in agriculture system. It has been utilized in plant nurseries, open fields, and greenhouses globally to ensure health of economically important crops like vegetables, fruits and flowers. However, the phase out of methyl bromide started under the montreal protocol due to its ozone depleting nature as well as detrimental effects on human life including damage to nervous and respiratory systems, eyes, skin etc. resulting in the search for alternative methods. Soil solarisation and hot water treatments, due to expensive nature and practical difficulty, cannot be used under all cases (Goud *et al.,* 2004). This eventually resulted in the need for natural and ecofriendly plant derived compounds for disease management.

BIOFUMIGATION

Biofumigation is an effective means of modifying the soil microbiome. Biofumigation is an eco-friendly soil amendment method widely used in many countries. It can be carried out by growing Brassicaceae plants in fallow fields and then burying them in the soil to react the soil with the volatile organic compounds they contain. The active substances are mainly glucosinolates (GSLs), which are known to suppress soil-borne pathogens and improve the quality of the following crop. Biofumigation is not only about pathogen suppression, but also about more complex changes in the soil microbiome. Long-term biofumigation application was found to enrich AMF, increasing soil aggregate stability and soil carbon (Dangi *et al.,* 2017).

GLUCOSINOLATES

Glucosinolates, the secondary metabolites constitutively present in plant cells are synthesized and stored in vacuoles. These natural products are exclusively found in the order Capparales, which includes different families viz., Brassicaceae, Caricaceae, and Capparaceae. Among these, Brassicacea family contains high concentration of glucosinolates, and are responsible for their distinct flavour. These are water stable compounds having limited biological activity, but the hydrolysis products derived from them by the action of myrosinase are of great

importance due to their antimicrobial properties (Rask *et al.,* 2000). They are classified into three different groups which includes aromatic (derived from phenyl alanine or tyrosine), aliphatic (from methionine, alanine, valine, leucine and isoleucine) and indoyl (from tryptophan) side chains that influences their nature and biological activities. Among them, only the aliphatic and aromatic glucosinolates release isothiocyanates upon hydrolysis.

The developmental stage of Brassica determines the amount of glucosinolates accumulated in the plants. GSL concentration increases during vegetative stage, tends to decline with the onset of flowering and it declines to the lowest in mature tissues. The pre-flowering stage is the optimum period to apply as biofumigant, since it is the stage where the GSL production is maximum. In Brassica plants, the concentration of GSL in reproductive organs are10-40 times higher than that in the vegetative parts (Brown *et al.,* 2003). Within the same plant, the GSL concentration varies with the growth stage, which is evident from the seeds and sprouts having higher concentration of GSL when compared to adult plants. Compared to shoots, sprouts contain higher concentration of glucosinolates during the same developmental stage in the Brassicacea crops because of difference in the regulatory mechanisms of GSL biosynthesis and turnover (Bhandari *et al.,* 2015).

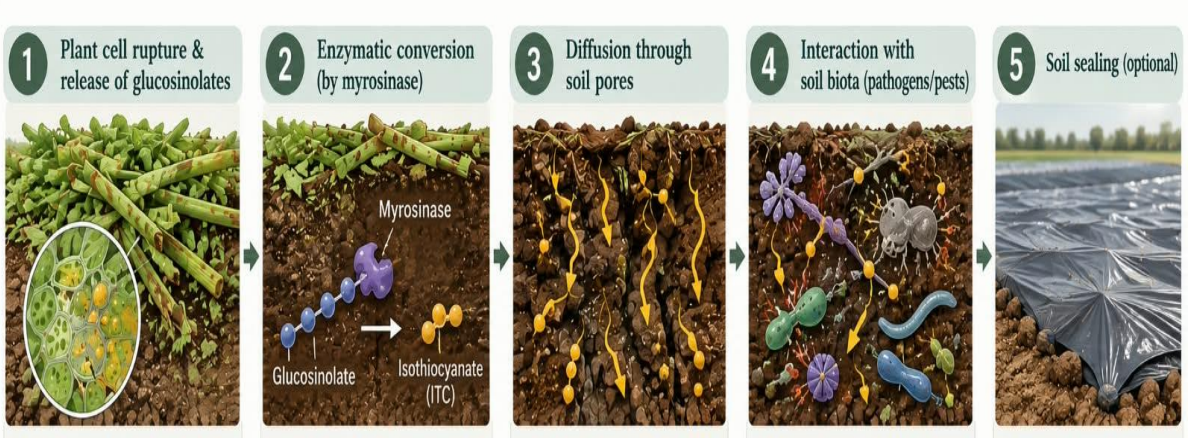
KEY SPECIES AND IT' S TARGETS

Species	Biocidal Substances	Targets
Indian Mustard	Allyl-ITC	Root knot nematode, *Verticillum*
Turnip	3-butenyl ITC	*Fusarium, Phytophthora*
Radish	4-methly thiobutyl ITC	Cyst nematode and *Rhizoctonia*
Marigold	ά -terthienyl	*Meloidogne, Pratylenchus,* Cyst nematodes

SCIENCE BEHIND BIOFUMIGATION

The plants with glucosinolates produces an enzyme called myrosinase. Myrosinase is basically a β-thioglucosidase, with amino acid sequence and are similar to the glycosylhydrolase family. There is a physical separation between cells containing glucosinolates and myrosinase in normal intact tissues. But, whenever there is a tissue damage due to chewing, heating or insect attack, the glucosinolates and myrosinase will come in contact with each other. Thus, upon tissue damage, the enzyme act on its substrate in the presence of water and the sulfate moiety is liberated non enzymatically from the aromatic and aliphatic chains of glucosinolates to generate the thiohydroxamate-O-sulfonate. ITCs are produced from thiohydroxamate-O-sulfonate under natural pH, warm temperature and high water dilution ratio.

In soil, the isothiocyanate formation is influenced by different factors. These include the quantity of plant material, the myrosinase activity of both the soil and plant material, the extent of tissue damage, temperature of the soil, and the water content. In addition to all these, the initial glucosinolate concentration of the plant material which is usually highest prior to flowering also affect the ITC formation. The ITCs and other hydrolysis products have a short persistence in soil and within few days, their concentration reduces rapidly with mean persistence in soil for about 12 days (Gimsing &Kirkegaard, 2006). ITC concentration increases if the water content in the soil increases. Even though the thiocyanate is less toxic than isothiocyanates, through electrostatic interaction it can destroy the tertiary structure of proteins and at high concentration it might also act as soil sterilants.



APPLICATION METHODS AND IT' S SUITABILITY

As a green manure crop	Open fields
Seed meal treatment	Green house
Strip or inter row crop	Orchards, Vineyards, perennials
Pelletized products	Spot treatments, small farms
Liqiud drench	Inject ITC extracts via drip irrigation

MODE OF ACTION IN FUNGI

Isothiocyanates are compounds produced from the hydrolysis of glucosinolate- myrosinase system possess broad antagonistic activity against plant pathogens. It hinders the mycelial growth of fungal pathogen and inhibits the spore germination thereby preventing their growth. In addition to this, downregulation of genes related to energy metabolism, melanin biosynthesis, and cell wall-degrading enzymes also contributes to their fungistatic effect (Yu *et al.,* 2022). In plants, the role of glucosinolates in control of plant pathogen is to be clarified but their hydrolysis yields products including ITC which can control the fungal infection through the activation of host innate immune responses and cytotoxicity. When compared to aromatic ITCs, the aliphatic ITCs usually have greater inhibitory activity under *invitro* conditions. The other mechanisms involve disruption of mitochondrial membrane potential, decreased oxygen consumption rate and depletion of intracellular glutathione (Calmes *et al.,* 2015).

MODE OF ACTION IN PLANT PATHOGENIC BACTERIA

Several mechanisms of action of ITC was described against plant pathogenic bacteria. In Gram negative bacteria, the treatment with ITC can result in disruption of the outer cell membrane, which results in change in the cell membrane potential and ultimately leading to cell metabolites leakage. In addition to these ITC can also act on the bacterial enzymes viz., thioredoxin reductases and acetate kinases. ITC bind to these bacterial enzymes and damages the tertiary structure which will affect its functions. Some of the ITCs like the allyl-ITC are highly toxic to the phytopathogenic bacteria due to their multiple targets (Luciano & Holley, 2009).

INDUCED MICROBIOME SHIFT

Biofumigation has been observed to favour several bacteria genera, including *Pseudomonas*, which are known to possess advantageous characteristics. *Pseudomonas* species are helpful for plant growth because they improve sulfate uptake and function as antagonists against soil-pathogenic fungi. Additionally, the suppression of soil-borne diseases is facilitated by the presence of numerous Actinobacteria phyla members that possess plant growth-promoting properties (Palaniyandi *et al*., 2013). The growth and health of plants are significantly influenced by the microbial community in the soil, which includes both pathogenic and beneficial strains. The bacterial and fungal diversities were unaffected by 1 percent biofumigant after four weeks of fumigation. On the contrary, the microbial diversity and network complexity were diminished by 2–4% biofumigant amendments, irrespective of the fumigation period. A negative correlation was observed between the diversity of soil bacteria and Phytophthora blight incidence. The biofumigation with rapeseed meal increased the population of *Bacillus* and *Actinobacteria*, whereas it decreased the incidence of blight caused by *P. capsici* (Wang *et al.,* 2014). When soils treated with non Brassica based amendments were compared with soils subjected to repeated biofumigation with Sinapis alba and *B. carinata* pellets an increase in population of bacteria, *Pseudomonas* ssp. and Actinomycetes were observed. The potential to promote beneficial microbiota by glucosinolate hydrolysis products improves the efficiency of biofumigation. application of *B. juncea* resulted in increased abundance of Thermoactinomycetaceae, Nocardiaceae and Paenibacillaceae.

CONCLUSION

Biofumigation using plant residues can be used in the integrated management of soil borne pathogens. Brassicas are most commonly used as biofumigants due to the release of biocidal compounds upon the enzymatic hydrolysis of glucosinolates. Along with these Brassica members, certain non Brassica members can also be employed in biofumigation. This particular technique can be utilized in organic production due to their more sustainable nature and the fact that, it can be integrated with biological control methods. They also have other beneficial effects like addition of organic matter to soil, improved soil structure and effect on soil microbial community. Since multiple components are involved, the type of biofumigant, the amount of its biomass, soil characteristics and targeted

microorganisms are to be studied in detail. More studies are to be conducted to understand its effect on different pathogens, their efficacy and on how they can be utilized in large scale agricultural systems.

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Nature's Time Capsule: Glassy State Formation in Orthodox Seeds

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Abstract

Orthodox seeds allow extremely long-term storage and resistance to desiccation through their capacity to form a noncrystalline and amorphous state in their cytoplasm, which acts like a glass. Orthodox seeds are capable of undergoing a process known as vitrification that involves the production of a dense hydrogen-bonding network of soluble sugars, including sucrose and raffinose-family oligosaccharides, and Late Embryogenesis Abundant (LEA) proteins by the cells at around 10-20% moisture. This phenomenon lowers down the rate of metabolism through a reduction in molecular motion to a great extent and by inhibiting any significant amount of metabolism that could accelerate aging during seed storage. It is a process that prevents rapid aging by forming a glass-like matrix that encapsulates cellular constituents such as macromolecules, membranes, and even water molecules. Reactive oxygen species (ROS) are tagged down and limited in their diffusion by the glass matrix, thereby lowering oxidative damage in the seed during storage. The properties of the glass transition temperature are determined by the amount of moisture in the cytoplasm and the temperature at which the orthodoxy is stored. The basic understanding of cytoplasm vitrification is key to seed banking, biodiversity conservation, and cryopreservation research.

Keywrods: Orthodox seeds, Vitrification, Cytoplasmic glass, Desiccation tolerance, Seed longevity, Glass transition temperature, Soluble sugars, LEA proteins

Introduction

Seeds are among nature's most elegant solutions to survival in an unpredictable world. A single orthodox seed—think of wheat, rice, or tomato—can endure years, even decades, in a dry, dormant state, then spring back to life when water and warmth return. This remarkable resilience hinges on a physical transformation inside its cells: the formation of a glassy, or vitrified, cytoplasm. Understanding how and why seeds form this "biological glass" is not only a fascinating story in plant physiology but also a cornerstone of food security, biodiversity conservation, and the science of long-term biological preservation.

Orthodox versus Recalcitrant Seeds: Two Strategies for Survival

Not all seeds are built alike. Botanists broadly classify seeds into two categories based on their response to drying: **orthodox** and **recalcitrant**.

- **Orthodox seeds** tolerate extreme desiccation, often drying down to 3–8% moisture content (on a fresh-weight basis) without losing viability. They can be stored dry and cold for long periods, making them ideal for seed banks and agricultural use.
- **Recalcitrant seeds**, by contrast, cannot survive significant drying. They remain metabolically active, retain high moisture, and lose viability quickly if dehydrated or chilled. Examples include many tropical tree species like mango and avocado.

The key difference lies in **desiccation tolerance**: the ability to endure and recover from near-complete water loss. Orthodox seeds acquire this trait during maturation on the mother plant, when they undergo a carefully orchestrated drying process accompanied by biochemical and biophysical changes. One of the most critical of these changes is the transition of the cell's interior from a fluid to a glassy solid.

What Is a Glass? The Biophysics of Vitrification in Seeds

In everyday language, "glass" conjures images of window panes or drinking vessels—hard, transparent, and brittle. In physics and materials science, however, a **glass** is any non-crystalline (amorphous) solid that forms

when a liquid is cooled or concentrated so rapidly that its molecules do not have time to arrange into an ordered crystal lattice.

During seed maturation, water is progressively removed from embryonic cells. As moisture drops, the cytoplasm—a complex mixture of water, sugars, proteins, ions, and other solutes—becomes increasingly concentrated. At a critical threshold, typically around 10–20% moisture content (depending on species and temperature), the cytoplasm undergoes a **glass transition**: it solidifies into an amorphous, highly viscous state without crystallizing. This process is called **vitrification**.

The main drivers of vitrification in seeds are **soluble sugars**, particularly sucrose and raffinose-family oligosaccharides (RFOs) such as raffinose and stachyose. These molecules accumulate to high concentrations during late maturation. As water leaves, they form a dense, hydrogen-bonded network that traps proteins, membranes, and other macromolecules in place. Residual water molecules become tightly bound within this matrix, further stabilizing it. The result is a **cytoplasmic glass**—a solid-like interior that behaves mechanically like a brittle solid but structurally resembles a supercooled liquid.

An intuitive analogy: imagine honey left out on a cold day. As it cools and loses moisture, it thickens, eventually becoming so viscous it appears solid. Yet it has not crystallized; it has vitrified.

Molecular and Cellular Mechanisms: How the Glass Protects

The glassy state is not merely a passive consequence of drying; it is an active, protective strategy. Several interrelated mechanisms explain how vitrification preserves seed viability:

Cytoplasmic Vitrification and Metabolic Arrest

In the fluid state, molecules diffuse freely, enzymes catalyze reactions, and metabolism proceeds. In the glassy state, molecular mobility drops by many orders of magnitude. Diffusion of water, oxygen, and reactive metabolites is severely restricted. This metabolic quiescence prevents the seed from "aging" rapidly during storage, as most deteriorative processes—respiration, lipid peroxidation, protein denaturation.

Membrane Stabilization

Cell membranes are especially vulnerable during drying. As water is removed, lipid bilayers can collapse, fuse, or undergo phase transitions that compromise integrity. Sugars in the glassy matrix act as water substitutes: they form hydrogen bonds with phospholipid head groups, mimicking the stabilizing effect of water and preventing membrane fusion or leakage. Upon rehydration, the glass dissolves, and membranes regain their fluid, functional state.

Macromolecular Immobilization

Proteins, nucleic acids, and other macromolecules are prone to denaturation, aggregation, or enzymatic degradation in the dry state. The glassy matrix physically immobilizes these structures, preventing unfolding or harmful interactions. Late Embryogenesis Abundant (LEA) proteins—small, hydrophilic proteins that accumulate during seed maturation—also contribute by acting as molecular shields or chaperones, further stabilizing proteins and membranes within the glass.

Suppression of Oxidative Damage

Even in the dry state, low levels of metabolic activity or residual oxygen can generate reactive oxygen species (ROS), which damage lipids, proteins, and DNA. The glassy state limits oxygen diffusion and slows ROS-generating reactions. Additionally, orthodox seeds often accumulate antioxidants (e.g., tocopherols, ascorbate, glutathione) during maturation, providing a chemical defense that complements the physical protection of the glass.

Temperature, Moisture, and the Glass Transition Temperature (Tg)

The stability of the glassy state is not absolute; it depends critically on **temperature** and **moisture content**. Each seed species (and even each seed lot) has a characteristic **glass transition temperature (Tg)**—the temperature below which the cytoplasm behaves as a glass and above which it becomes rubbery or fluid.

- **Lower moisture content** raises Tg: drier seeds form more stable glasses at higher temperatures.
- **Higher temperature** lowers the effective viscosity of the glass: even below Tg, warmer storage accelerates molecular motion and aging.

Practically, this means that for long-term storage, seeds should be kept **dry and cold**. The widely used "100-year rule" in seed banking—reduce moisture content by 1% or lower temperature by 5°C to double seed lifespan—reflects this biophysical reality. For most orthodox seeds, storing at 3–7% moisture and −18°C (as in gene banks like the Svalbard Global Seed Vault) ensures the cytoplasm remains deeply vitrified, maximizing longevity. However, there are limits. Over-drying can cause mechanical damage or destabilize the glass. Too much moisture, even at low temperatures, can plasticize the matrix, lowering Tg and allowing detrimental reactions to proceed.

Ecological and Evolutionary Significance

The evolution of desiccation tolerance and glass formation was a pivotal innovation in plant history. It enabled embryophytes (land plants) to colonize terrestrial habitats where water availability is erratic. Orthodox seeds, with their ability to enter a reversible, glass-protected dormancy, became the primary dispersal and survival units for most flowering plants.

Ecologically, this trait allows seeds to persist in soil seed banks for years, buffering populations against environmental fluctuations and disturbances. In agriculture, it underpins the global seed system: farmers and breeders rely on the predictable longevity of orthodox seeds to store, transport, and exchange genetic material across seasons and continents.

From a conservation perspective, understanding glassy state formation is essential for preserving crop wild relatives and endangered species in ex situ gene banks. It also informs strategies for cryopreservation of recalcitrant seeds and embryonic tissues, where inducing vitrification at ultra-low temperatures (using cryoprotectants) mimics the natural process in orthodox seeds.

Open Questions and Frontiers in Seed Glass Research

Despite decades of study, many aspects of seed glass formation remain active areas of research:

- **Molecular architecture of the glass**: What is the precise arrangement of sugars, proteins, and water in the vitrified matrix? Advanced spectroscopy and molecular dynamics simulations are beginning to map this nanoscale landscape.
- **Species-specific variation**: Why do some orthodox seeds (e.g., lettuce) have shorter lifespans than others (e.g., lotus) despite similar moisture contents? Differences in glass composition, antioxidant capacity, and repair mechanisms upon rehydration are likely contributors.
- **Aging within the glass**: Even in the vitrified state, slow chemical reactions (e.g., Maillard reactions, non-enzymatic browning) can accumulate damage over decades. How do seeds mitigate this, and can we enhance it artificially?
- **Engineering resilience**: Can we transfer desiccation tolerance traits—such as sugar accumulation or LEA protein expression—to recalcitrant seeds or even vegetative propagules? Early experiments in transgenic plants show promise but face physiological and regulatory hurdles.

Recent advances in biophysics, metabolomics, and genetic engineering are converging to answer these questions, with implications not only for agriculture but also for bio stabilization of vaccines, probiotics, and other biologics.

Conclusion

The glassy state in orthodox seeds is a masterclass in biological engineering—a seamless integration of chemistry, physics, and evolution to solve the problem of survival in time and space. By transforming their cytoplasm into a stable, protective glass, seeds achieve a form of suspended animation that rivals science fiction. As climate change, biodiversity loss, and food insecurity intensify, the humble seed—and the glass that protects it—will remain central to our efforts to safeguard plant genetic resources and ensure a resilient future. Understanding and harnessing the principles of glassy state formation is not just an academic pursuit; it is a vital investment in the continuity of life on Earth.

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Conservation Agriculture: Benefits for Soil Health, Crop Production and Plant Disease Management

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1. Introduction

Conservation agriculture (CA) is a resource-efficient production approach built on three linked principles: minimum soil disturbance, permanent soil cover, and crop diversification through rotations or suitable intercrops (Hobbs *et al.,* 2008; Kassam *et al.,* 2019). Intensive tillage, residue burning and continuous monocropping can accelerate erosion, deplete soil organic matter and disrupt soil biological processes. CA can help conserve soil and water, improve resource-use efficiency and support resilient production, but outcomes depend on climate, soil, crop sequence and implementation. Its value should therefore be assessed as a locally adapted system—not as a universal package that guarantees higher yields or fewer diseases.

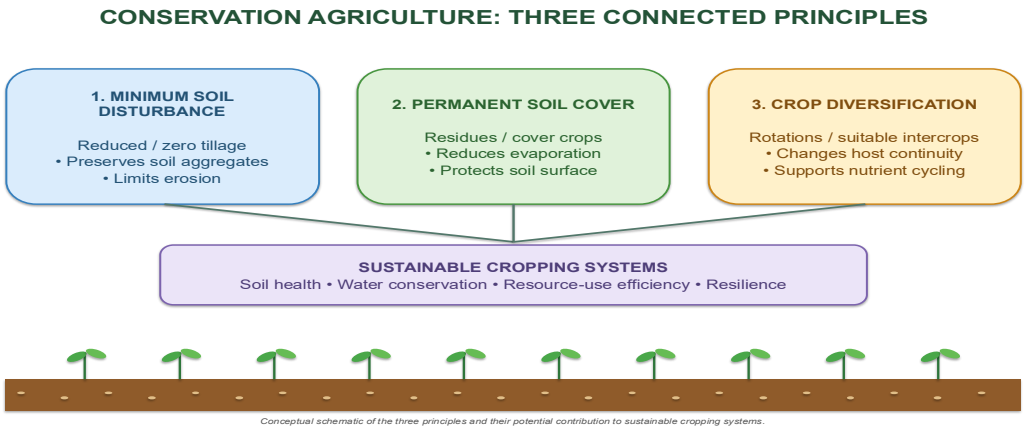


Figure 1. Three core principles of conservation agriculture and their potential contribution to sustainable production.

2. Conservation Agriculture and Soil Health

Reduced tillage limits physical disruption of soil aggregates, while residues protect the surface from raindrop impact, runoff and wind erosion. Residue retention and diversified rotations can increase organic inputs, support soil organisms and improve aggregation and infiltration (Haddaway *et al.,* 2017; Blanco-Canqui and Ruis, 2018). However, no-tillage effects on soil organic carbon vary with soil depth and duration; carbon accumulation near the surface should not automatically be interpreted as an equivalent whole-profile gain (Powlson *et al*., 2014). CA may also reduce evaporation and moderate soil temperature, improving water conservation in some environments (Hobbs *et al*., 2008). Potential constraints include compaction, temporary nitrogen immobilization and slower soil warming. Soil-health monitoring should combine physical indicators (bulk density and infiltration), chemical indicators (organic carbon, pH and nutrient availability) and biological indicators (microbial biomass, earthworms and enzyme activity).

3. Effects on Crop Production and Agricultural Sustainability

CA can improve production efficiency by reducing tillage passes, fuel use and the time between successive crops. In the Indo-Gangetic Plains, timely wheat establishment after rice harvest is particularly important because delayed sowing can expose wheat to terminal heat stress (Hobbs *et al*., 2008; Jat *et al.,* 2020). Nevertheless, a

global meta-analysis found that yield responses to no-tillage vary with crop, climate and accompanying management; no-tillage alone does not consistently maximize yield in every environment (Pittelkow *et al.,* 2015). Benefits are more likely when reduced tillage is combined with suitable residue management, crop rotation, balanced nutrition, effective weed control and appropriate machinery. Legume inclusion can contribute nitrogen through biological fixation and diversify crop sequences. Adoption barriers include residue competition with livestock, equipment costs, weed shifts and the need for locally relevant extension support (Kassam *et al*., 2019; Jat *et al*., 2020).

Table 1. Major effects of conservation agriculture on soil health, crop production and resource-use efficiency.

Component	CA practice	Potential benefit	Important limitation
Soil structure	Minimum soil disturbance	Preserves aggregates and reduces erosion	Compaction may occur in some soils or traffic conditions
Soil organic carbon	Residue retention and diverse rotations	Can increase carbon near the soil surface	Response varies with depth, climate and duration
Soil moisture	Surface cover	Reduces evaporation and protects against runoff	Benefit depends on rainfall, soil and residue quantity
Nutrient cycling	Residue retention and legumes in rotation	Adds organic inputs and may improve nutrient cycling	Temporary nitrogen immobilization may occur
Crop productivity	Reduced tillage plus suitable agronomy	Can improve timeliness and resource-use efficiency	Yield response is crop- and environment-specific
Farm costs	Fewer tillage operations	Potential fuel and labour savings	Machinery investment and transition costs can be high
Weed management	Rotation, cover and integrated control	Can suppress some weed species	Weed communities and herbicide needs may shift

Sources: Hobbs *et al*. (2008), Pittelkow *et al*. (2015), Powlson *et al.* (2014), Haddaway *et al*. (2017), and Blanco-Canqui and Ruis (2018).

4. Conservation Agriculture and Plant Disease Management

For plant pathology, CA has potentially opposing effects on disease. Surface residues may provide survival sites for pathogens that persist in infected plant debris, and reduced tillage can leave this inoculum near emerging crops. For example, wheat tan spot, caused by Pyrenophora tritici-repentis, is associated with infected wheat residue; disease risk depends on residue load, rotation, weather and crop susceptibility (Bockus and Shroyer, 1998). Prolonged soil moisture and continuous host cultivation can also favour certain pathogens. Therefore, retaining infected residues without considering pathogen biology may increase disease pressure in particular systems. Conversely, diversified rotations can interrupt host availability and reduce pathogen multiplication, while residue decomposition and soil microbial interactions may contribute to suppression of some soilborne diseases (Bailey and Lazarovits, 2003; Sturz *et al*., 1997). Increased microbial abundance or diversity, however, does not automatically mean that soil is disease-suppressive. Disease outcomes must be evaluated for each crop–pathogen system.

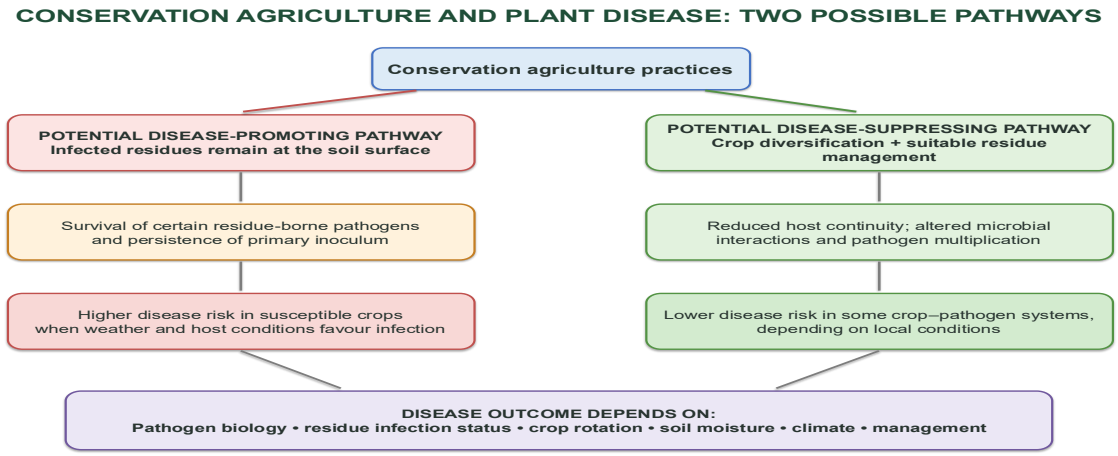


Figure 2. Conceptual pathways showing how conservation agriculture may promote or suppress plant disease depending on the crop–pathogen system.

5. Integrating Conservation Agriculture with Plant Disease Management

CA should be combined with integrated disease management (IDM). Select rotation and cover crops according to the host range of the target pathogen; use resistant cultivars and healthy planting material; maintain balanced nutrition; and manage irrigation and drainage to avoid conditions that favour infection. Residue decisions should be pathogen-specific: healthy residues may be valuable for erosion control and soil moisture conservation, whereas heavily infected residues may require strategic decomposition, targeted management or a non-host rotation. Selected Trichoderma and Bacillus strains can complement other practices against particular pathogens, but performance depends on strain, formulation, crop and environment. Field scouting, diagnostic confirmation where needed, and records of disease incidence and severity are essential when CA is introduced. Long-term trials should measure yield, soil properties, pathogen inoculum, disease outcomes and farm-level costs together.

Table 2. Integration of conservation agriculture practices with plant disease management strategies.

Practice	Disease-management mechanism	Potential limitation	Complementary measure
Crop rotation	Interrupts host availability and may reduce pathogen multiplication	Broad-host-range pathogens may persist	Choose crops based on pathogen host range
Residue retention	Conserves soil and water resources	Infected debris may harbour residue-borne pathogens	Assess residue infection and pathogen biology
Minimum tillage	Reduces soil disturbance and erosion	May leave infected debris on the surface	Combine with rotation and targeted residue management
Cover crops	Protect soil and can alter microbial interactions	Some species may act as alternative hosts	Choose non-host species where appropriate
Resistant cultivars	Reduces susceptibility to target pathogens	Resistance may be incomplete or overcome	Combine with rotation and monitoring
Biological control	Selected Trichoderma or Bacillus strains may suppress pathogens	Efficacy varies by strain and environment	Validate products under local field conditions
Water management	Avoids prolonged moisture favourable to some pathogens	Disease responses differ among pathosystems	Adapt irrigation and drainage to crop needs
Disease monitoring	Supports early response and diagnosis	Needs regular scouting and diagnostic capacity	Record incidence, severity and pathogen identity

Sources: Bockus and Shroyer (1998), Bailey and Lazarovits (2003), Hobbs *et al.* (2008), and Kassam *et al.* (2019).

6. Conclusion

Conservation agriculture can protect soil, conserve water, improve operational efficiency and strengthen the resilience of cropping systems. Its effect on plant disease is not uniformly positive or negative: it depends on residue infection, pathogen biology, crop sequence, soil moisture, climate and management. The central challenge is to optimize soil conservation and plant health simultaneously. Integrating CA principles with pathogen-informed residue management, diversified rotations, resistant cultivars, biological options and disease monitoring offers a more reliable route to productive and disease-resilient agriculture than adopting any single practice in isolation.

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Green Ammonia and Low-Carbon Fertilizers: Emerging Approaches to Sustainable Nutrient Management

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Abstract

Fertilizers underpin modern crop production, yet conventional nitrogen fertilizer manufacture is energy-intensive and depends heavily on fossil fuels. Green ammonia, produced using hydrogen from water electrolysis powered by renewable electricity, offers a pathway to reduce production-stage carbon emissions. Other low-carbon options—including renewable-powered fertilizer manufacturing, improved urea and ammonia production efficiency, enhanced-efficiency fertilizers, biological nitrogen fixation and precision nutrient management—can contribute to more sustainable nutrient systems. However, a fertilizer labelled low-carbon does not automatically reduce field emissions: nitrogen application rate, timing, placement, soil moisture and crop uptake strongly influence nitrous oxide losses and nitrogen-use efficiency. This article reviews the production pathways, agronomic opportunities, limitations and policy needs associated with green ammonia and low-carbon fertilizers, emphasizing integrated nutrient management and practical relevance to Indian agriculture.

Keywords: green ammonia, low-carbon fertilizers, nitrogen-use efficiency, precision nutrient management, renewable hydrogen, nitrous oxide

1. Introduction

Nitrogen, phosphorus, potassium and secondary and micronutrients are essential for crop growth, yield formation and food security. At the same time, fertilizer systems contribute to greenhouse-gas emissions through fossil-fuel use in manufacturing, energy-intensive transport and field emissions—especially nitrous oxide from nitrogen cycling. Green ammonia has gained attention because ammonia is a major feedstock for nitrogen fertilizers and can be produced with renewable hydrogen instead of hydrogen derived from natural gas or coal. For agronomy, the key question is not only how fertilizer is manufactured, but whether nutrients are supplied efficiently and recovered by crops. A credible low-carbon strategy therefore combines cleaner production with sound fertilizer recommendations, soil testing, crop-demand-based timing and measures that reduce nutrient losses.

2. What are green ammonia and low-carbon fertilizers?

Ammonia (NH_3) is commonly synthesized by combining hydrogen with nitrogen separated from air. In conventional production, hydrogen is often obtained from natural gas or coal, generating substantial carbon dioxide unless emissions are captured. Green ammonia generally refers to ammonia made using renewable electricity to power water electrolysis, producing hydrogen that is then combined with nitrogen through the Haber–Bosch process. Terminology varies across markets, so claims should be checked against the stated electricity source, process boundary and lifecycle emissions. Low-carbon fertilizers are a broader category: they may include fertilizers made with renewable energy, production processes with lower emissions, carbon capture, recycled nutrients, biological nutrient sources or products that improve nutrient-use efficiency. These categories are not interchangeable, and lifecycle assessment is needed to compare them fairly.

3. Emerging approaches to lower the fertilizer carbon footprint

3.1 Renewable hydrogen and green ammonia

Renewable electricity can power electrolysers that split water into hydrogen and oxygen. The hydrogen is combined with nitrogen to produce ammonia. The potential climate benefit depends on the carbon intensity and

reliability of electricity, electrolyser performance, plant utilization, water supply and transport. Renewable ammonia can serve as a feedstock for urea and other nitrogen fertilizers, but conversion steps also consume energy and may introduce additional emissions. Cost, infrastructure, storage safety, renewable-power availability and access to water remain important deployment challenges.

3.2 Energy-efficient fertilizer manufacturing and carbon capture

Existing ammonia plants may reduce emissions through improved heat integration, process efficiency, electrification and, where suitable, carbon capture and storage. The net benefit of carbon capture depends on capture rate, energy penalty, transport and long-term storage integrity. These pathways may help reduce emissions during the transition, but their climate performance should be compared using transparent lifecycle boundaries rather than labels alone.

3.3 Enhanced-efficiency fertilizers

Controlled-release fertilizers, urease inhibitors and nitrification inhibitors are designed to better synchronize nitrogen availability with crop uptake or slow specific loss pathways. Their effectiveness depends on soil, climate, crop, product formulation and management. They may reduce ammonia volatilization or nitrous oxide emissions in certain situations, but they are not universal substitutes for correct nitrogen rates and timing. Product cost and locally validated evidence should guide adoption.

3.4 Biological nitrogen fixation and recycled nutrients

Legume-based rotations, green manures and suitable microbial inoculants can contribute biologically fixed nitrogen and improve nutrient cycling. Recovered nutrients from manure, compost, digestate and other safe organic streams can partly replace mineral fertilizers, although nutrient content and release rates vary. These options require appropriate handling, pathogen and contaminant safeguards, and balanced nutrient planning; biological sources should not be assumed to meet every crop nutrient requirement.

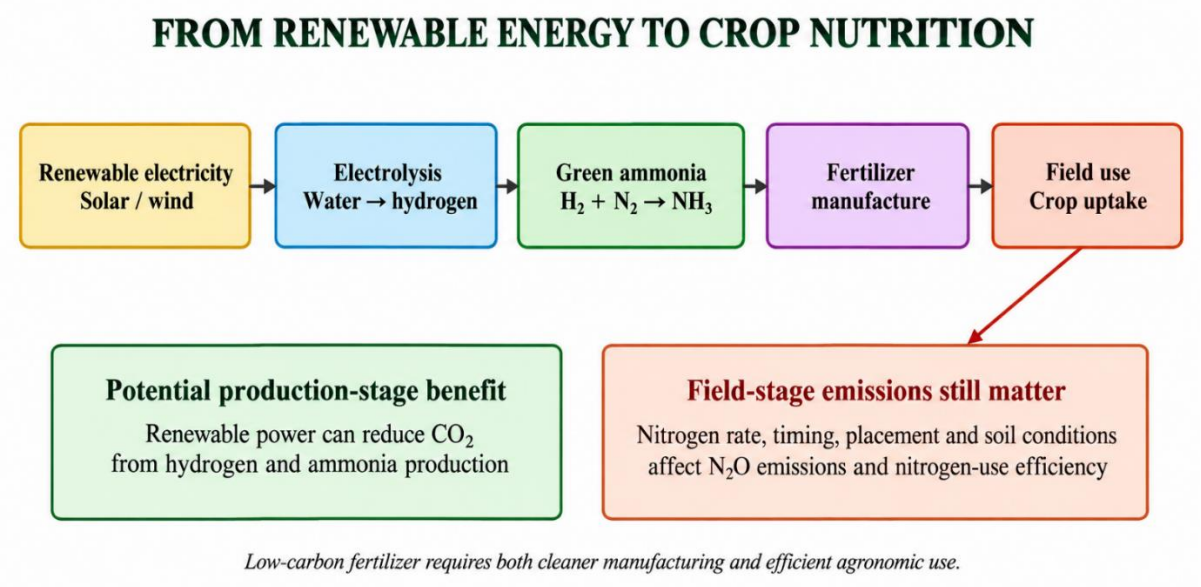


Figure 1. Conceptual pathway from renewable electricity to green ammonia and fertilizer use, distinguishing manufacturing emissions from field-stage emissions.

4. Agronomic management remains essential

Cleaner fertilizer production lowers the upstream footprint, but farm-level performance still depends on nutrient management. The 4R principles—right source, right rate, right time and right place—provide a practical framework. Soil testing and crop nutrient budgets help set rates; split applications can match nitrogen supply to growth stages; placement can improve root access; and irrigation management can reduce leaching. Avoiding excess nitrogen is especially important because surplus nitrogen can be lost as ammonia, nitrate or nitrous oxide. Farmers should evaluate yield, quality, nitrogen-use efficiency, cost per unit of produce and environmental effects together.



Figure 2. Coloured illustration of three complementary strategies: lower-emission fertilizer sources, crop-demand-based timing and root-zone placement.

Table 1. Comparison of emerging low-carbon nutrient approaches

Approach	Potential contribution	Important limitation
Green ammonia	Can lower production-stage CO_2 when renewable electricity and hydrogen are used	Higher current costs, power and infrastructure requirements; lifecycle verification needed
Energy efficiency/ carbon capture	Can reduce emissions from existing production systems	Performance depends on process, energy penalty and storage integrity
Enhanced-efficiency fertilizers	Can improve nutrient synchronization and reduce selected losses	Benefits are context-specific; cost and field validation matter
Legumes and biological N fixation	Adds biologically fixed nitrogen and diversifies rotations	N contribution varies; cannot meet every crop's immediate demand
Recycled organic nutrients	Returns nutrients and organic matter to production systems	Variable nutrient availability and need for quality/safety controls
Precision nutrient management	Reduces unnecessary applications and improves crop recovery	Needs reliable recommendations, monitoring and extension support

5. Relevance and opportunities for Indian agriculture

India uses large quantities of nitrogen fertilizers, making manufacturing efficiency, domestic renewable energy and improved nutrient-use efficiency strategically important. Green ammonia could help decarbonize nitrogen fertilizer supply as renewable electricity and electrolysis scale, but the economics depend on capital costs, renewable-power availability, storage and distribution infrastructure, and reliable demand. At farm level, soil-test-based fertilizer recommendations, balanced nutrition, legumes in crop rotations, precision placement and improved irrigation scheduling are immediately relevant regardless of the source of fertilizer. In Gujarat and other water-limited regions, efficient irrigation and split nutrient applications can help synchronize nitrogen availability with crop uptake, while avoiding excessive irrigation that may move nitrate below the root zone.

6. Challenges and research priorities

Key challenges include the price gap between green and conventional ammonia, renewable electricity intermittency, electrolyser and storage costs, water requirements, fertilizer distribution, standards for carbon intensity and uncertainty in farm-level responses. Research priorities include region-specific lifecycle assessment, field trials comparing fertilizer sources at equal nutrient rates, measurement of nitrous oxide and ammonia losses, long-term soil effects, economic analysis for smallholders and robust certification systems. Studies should distinguish the carbon footprint of manufacturing from emissions after application and report functional units clearly—for example, emissions per kilogram of nitrogen and per tonne of crop produced.

7. Conclusion

Green ammonia and low-carbon fertilizers offer promising pathways to reduce the upstream emissions associated with nutrient supply. Their climate benefits, however, depend on production technology, electricity sources, transport and transparent lifecycle assessment. At field level, the greatest value comes from combining cleaner

fertilizer sources with balanced, crop-specific nutrient management that improves nitrogen recovery and limits losses. A sustainable transition should therefore connect renewable-energy innovation with agronomic research, farmer advisory services, affordability and measurable environmental outcomes.

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Regenerative Agriculture and Plant Health: Evaluating the Interactions Among Soil Carbon, Microbial Communities and Crop Diseases

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Abstract

Regenerative agriculture combines crop diversification, cover cropping, residue retention, reduced soil disturbance and organic amendments to restore soil function. These practices can influence plant health through changes in soil organic carbon, soil structure and microbial communities, but their effects on disease are not uniformly beneficial. This article examines links among carbon cycling, microbiome assembly and crop disease suppression, while highlighting context-specific risks and practical priorities for integrated plant health management.

Keywords: Regenerative agriculture; soil organic carbon; soil microbiome; disease-suppressive soil; crop disease; integrated disease management

1. Introduction

Agricultural soils are living systems in which carbon, minerals, roots and microorganisms interact to determine crop performance. Regenerative agriculture (RA) is a principle-based approach intended to rebuild soil function through practices such as keeping soil covered, reducing unnecessary disturbance, maintaining living roots, diversifying crops and returning organic materials. There is no single universally accepted definition, and outcomes depend on how practices are combined and adapted to local conditions. Its relevance to plant pathology lies in the possibility that improved soil habitat and microbial functioning can reduce disease pressure while supporting productivity. However, RA is not an automatic disease-control method: a practice may suppress one pathogen yet favour another, so outcomes require crop- and pathogen-specific assessment (Newton *et al.,* 2020; Schlatter *et al.,* 2017).

2. Soil carbon as a driver of soil function

Cover crops, retained residues, diversified rotations and suitable organic amendments increase the amount and diversity of carbon entering soil. Some carbon is respired by microorganisms, while some becomes particulate organic matter or is transformed into microbial residues that can associate with minerals. These pools contribute to aggregation, nutrient cycling and water regulation. Better aggregation can improve aeration and infiltration, while organic matter can increase water-holding capacity in many soils. Such changes may support vigorous roots and reduce stress that predisposes plants to infection. Carbon accumulation is nevertheless variable: it depends on texture, climate, depth, duration, tillage, input quantity and the balance between carbon additions and decomposition. Surface carbon increases under reduced tillage do not always mean equivalent gains throughout the soil profile. Carbon sequestration claims should therefore rely on repeated, depth-consistent measurements rather than assumptions based on practice adoption alone (Lal, 2020; Newton *et al.,* 2020).

3. Microbial communities and disease suppression

Soil carbon supplies energy to bacteria, fungi and other soil organisms, but the quality and timing of inputs are as important as their quantity. Root exudates and decomposing residues shape the rhizosphere microbiome, influencing which organisms colonize roots and compete for resources. Disease-suppressive soils can limit

pathogens through competition for nutrients and infection sites, production of inhibitory metabolites, parasitism or predation, and stimulation of plant defence. Beneficial groups may include Pseudomonas, Bacillus, Trichoderma and arbuscular mycorrhizal fungi, although effects depend on strain, crop, soil and environment. Plants can also influence microbial recruitment in response to pathogen attack, contributing to protective soil legacies. Importantly, greater microbial diversity alone does not prove disease suppression; community composition and functional activity matter more than a simple diversity score (Berendsen *et al.*, 2012; Bonanomi *et al.,* 2018; Spooren *et al.,* 2024).

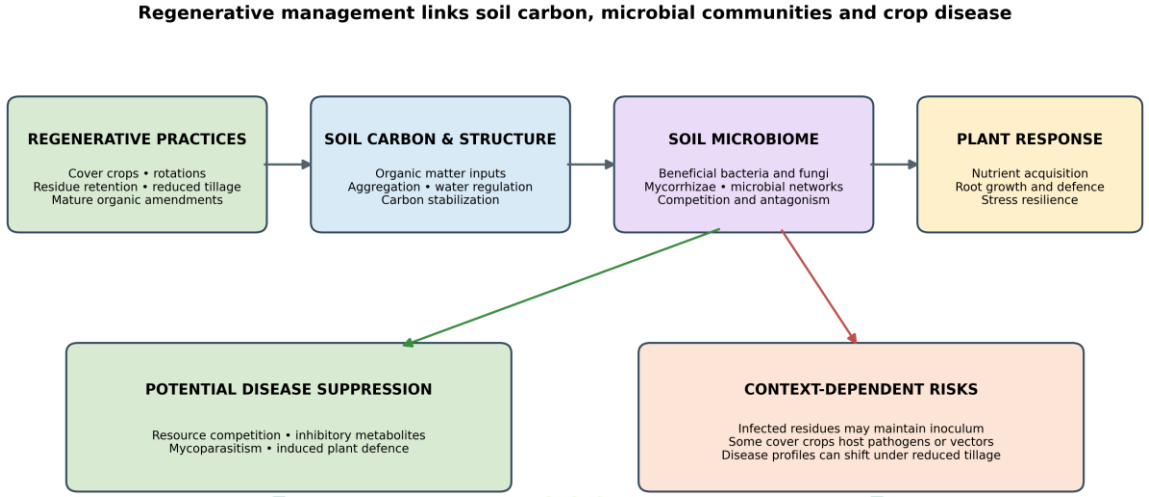


Figure 1. Conceptual links between regenerative practices, soil carbon, microbial communities and crop disease. Arrows represent plausible pathways; outcomes vary with crop, pathogen, climate, soil and management history.

4. Agronomic practices and disease outcomes

Crop rotation can interrupt pathogen life cycles when the sequence avoids suitable hosts and reduces pathogen carry-over. Cover crops may improve soil structure and provide resources for beneficial organisms, but a cover species can also act as a host or green bridge for particular pathogens and insect vectors. Residue retention protects soil and returns carbon, yet infected residues can preserve inoculum for necrotrophic fungi and some bacterial pathogens. Reduced tillage limits disturbance and erosion but may leave infected plant material near the soil surface, changing the timing and distribution of inoculum. Mature composts and well-managed organic amendments can support suppressive microbial communities; immature, contaminated or poorly processed materials may introduce risks. Recommendations should therefore be based on pathogen biology, residue decomposition, host range and local weather rather than applying a uniform regenerative package (Bailey & Lazarovits, 2003; De Corato, 2020; Holland, 2004).

5. Integrating regenerative agriculture with plant disease management

A practical approach begins with diagnosis and risk assessment. Farmers should identify the causal pathogen, determine whether it survives in soil, seed, residues, weeds or alternate hosts, and then select compatible regenerative practices. Rotation should be designed around pathogen host range; cover crops should be screened for host status; and diseased residues should be managed according to pathogen survival biology. Soil testing can track organic carbon, pH, nutrients and physical condition, while disease incidence and severity should be recorded across seasons. Where justified, compatible biocontrol agents or microbial inoculants can complement cultural practices, but field performance depends on formulation, survival and environmental fit. Integrated disease management remains essential, including clean seed or planting material, resistant cultivars, sanitation, balanced nutrition, irrigation management, scouting and targeted registered plant-protection products when necessary. Regeneration and crop protection are complementary goals, not competing philosophies (Dignam *et al.,* 2016; Fierer, 2017; Sowmiya *et al.,* 2025).

6. Research priorities and conclusion

The main research need is to move from measuring practice adoption to testing mechanisms and outcomes. Long-term, replicated trials should compare combinations of cover crops, rotations, residue management and reduced

tillage across soil types and climates. Measurements should integrate soil organic carbon by depth, aggregate stability, microbial biomass and function, pathogen inoculum, disease severity and marketable yield. Amplicon sequencing and metagenomics can describe microbial communities, but they should be paired with culture-based assays, pathogen quantification and field validation. Studies should report trade-offs, including disease increases, yield variability, labour and input costs. Recent syntheses emphasize that regenerative systems can reshape soil microbial processes, while important gaps remain in predicting when microbiome changes translate into reliable plant protection (Nishu & Islam, 2026; Spooren *et al*., 2024). In conclusion, regenerative agriculture can contribute to plant health when it rebuilds soil carbon and supports beneficial microbial functions, but outcomes are context-dependent. The strongest strategy is adaptive, evidence-based integration with plant pathology principles and long-term monitoring.

Table 1. Potential effects of regenerative practices on soil health and plant disease

Practice	Potential soil / microbial benefit	Possible disease risk	Plant pathology recommendation
Cover crops	Living roots and carbon inputs; may support beneficial rhizosphere organisms.	Some species host pathogens or vectors between cash crops.	Check host status and terminate at an appropriate time.
Residue retention	Returns carbon, protects soil and feeds decomposer communities.	Infected residues may maintain inoculum of residue-borne pathogens.	Use pathogen-specific residue management and rotation.
Reduced tillage	Limits disturbance and erosion; may improve surface aggregation.	Surface residues can alter inoculum survival and disease timing.	Monitor disease patterns and adapt to pathogen biology.
Crop rotation	Diversifies root inputs and may disrupt pathogen cycles.	Rotation crops may share hosts or maintain broad-host-range pathogens.	Choose non-host crops using confirmed host-range information.
Compost / organic amendments	Adds organic matter and may encourage suppressive microbial activity.	Immature or contaminated material can cause phytotoxicity or introduce pathogens.	Use mature, quality-controlled materials at suitable rates.
Diversified cropping	Broadens carbon inputs and microbial niches.	Diversity alone does not guarantee suppression; alternate hosts may persist.	Combine diversity with scouting, sanitation and risk assessment.

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Atmospheric Pressure Plasma Processing: A New Frontier in Food Safety and Preservation

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Abstract

Atmospheric pressure plasma (APP) has emerged as a transformative non-thermal technology with significant implications for food safety and preservation. Generated through electrical discharges at or near ambient pressure, APP produces a complex mixture of reactive oxygen and nitrogen species (RONS), ultraviolet radiation, charged particles, and ozone, all of which collectively contribute to its potent antimicrobial activity. Unlike conventional thermal processing, APP operates at near-room temperatures, thereby preserving the sensory and nutritional integrity of food products. Its applications span microbial decontamination, mycotoxin degradation, pesticide residue reduction, and food quality enhancement. This article synthesizes current research on the mechanisms, applications, and challenges of atmospheric pressure plasma in the food industry, with an emphasis on its potential as a sustainable and commercially scalable food processing technology.

1. Introduction

The global demand for safe, minimally processed, and nutritionally rich food has intensified research into novel non-thermal food processing technologies. Traditional thermal methods, while effective in microbial inactivation, often compromise the sensory quality and heat-sensitive nutrient content of food, particularly in fresh and minimally processed products (Usman et al., 2023). In response to these limitations, a range of non-thermal alternatives including pulsed electric fields, high-pressure processing, ultraviolet light, ozone treatment, and irradiation have been explored (Keewan et al., 2025). However, each of these approaches carries its own set of limitations, including residue generation, variable efficacy across food matrices, and scalability challenges.

Atmospheric pressure plasma (APP) has rapidly gained attention as a versatile and effective food decontamination strategy. APP is generated by subjecting a gas to a high-frequency electrical field or direct current field, which ionizes the gas to produce an energized state comprising free radicals, electrons, negative and positive ions, excited atoms and molecules, and photons of electromagnetic radiation (Usman et al., 2023). At atmospheric pressure, plasma is typically generated via dielectric barrier discharges (DBD), gliding arc discharges, corona discharges, and radiofrequency plasma (Usman et al., 2023). This distinguishes it from thermal plasma, which operates at elevated pressures with high power input and requires thermodynamic equilibrium between electrons and heavy species.

What makes APP particularly attractive for the food industry is that it operates without requiring vacuum conditions, harsh chemicals, or elevated temperatures, making it a viable candidate for continuous, in-line food processing (Liu et al., 2025). As both a decontamination and preservation tool, APP has demonstrated effectiveness against a broad spectrum of foodborne pathogens, spoilage microorganisms, fungal toxins, and chemical residues. The following sections outline the mechanisms underlying APP activity, its key applications in food safety and preservation, the effects on food quality, and the challenges that must be overcome before full commercial implementation.

2. Mechanisms of Action of Atmospheric Pressure Plasma

The antimicrobial and decontaminating effects of APP arise from the combined action of several reactive species and physical factors generated during the plasma discharge. Chief among these are reactive oxygen species (ROS) such as ozone (O_3), hydrogen peroxide (H_2O_2), and hydroxyl radicals (OH•), as well as reactive nitrogen species (RNS) including nitric oxide (NO•) and nitrogen dioxide (NO_2•) (Ahmed et al., 2025). These species act synergistically to damage microbial cell membranes, denature proteins, and degrade nucleic acids, thereby achieving high rates of microbial inactivation without the thermal damage associated with conventional processing (Ahmed et al., 2025).

In the context of mycotoxin degradation, RONS drive oxidative fragmentation of toxic molecules by targeting their chemically reactive functional groups. For example, reactive species attack the C8=C9 double bond in the terminal furan ring of Aflatoxin B1 (AFB1), which is the structural feature primarily responsible for its carcinogenic activity, leading to the production of lower-molecular-weight byproducts with significantly reduced biological activity (Huang et al., 2026). The elucidation of these degradation pathways has been facilitated by advanced characterization techniques such as high-resolution mass spectrometry and nuclear magnetic resonance spectroscopy, which have confirmed both selective cleavage of toxic functional groups and a parallel series of complex oxidative reactions (Huang et al., 2026).

Beyond chemical activity, APP also generates ultraviolet (UV) radiation and charged particles that contribute to microbial inactivation through mechanisms such as DNA strand breakage and membrane disruption (Ahmed et al., 2025). The type of processing gas used during plasma generation significantly influences the composition and concentration of reactive species produced, and consequently the overall decontamination efficacy. Gases such as oxygen, nitrogen, and argon each produce different reactive species profiles, and the selection of gas type is therefore a critical parameter in optimizing plasma treatment outcomes (Keewan et al., 2025).

3. Applications in Microbial Decontamination

One of the most extensively studied applications of APP in the food sector is the inactivation of foodborne pathogens and spoilage microorganisms. APP has demonstrated broad-spectrum antimicrobial activity against bacteria, viruses, fungi, spores, and biofilms on a variety of food surfaces and matrices (Ahmed et al., 2025). Cold atmospheric plasma has been shown to effectively eliminate a wide range of pathogens including *Escherichia coli*, *Salmonella*, *Listeria monocytogenes*, and *Staphylococcus aureus* in meat and vegetable matrices (Ahmed et al., 2025). In studies comparing cold plasma with other non-thermal technologies, cold plasma achieved 2 to 3 log reductions in surface pathogen counts including *Listeria monocytogenes* and *E. coli* with minimal lipid oxidation in meat products (Keewan et al., 2025).

The inactivation mechanism against gram-negative bacteria such as *E. coli* involves synergistic disruption of cell membranes by ROS and RNS, followed by protein denaturation and DNA fragmentation (Ahmed et al., 2025). UV radiation generated during plasma discharge contributes further to DNA strand breakage, particularly in spore-forming organisms that are otherwise resistant to conventional surface decontamination methods (Usman et al., 2023). Plasma treatment also shows efficacy against bacterial biofilms, which are particularly challenging to eliminate with conventional sanitizers due to their structural complexity and resistance to antimicrobial agents (Ahmed et al., 2025). For plant-based foods including fruits and vegetables, atmospheric cold plasma has been applied to reduce surface microbial contamination while maintaining fresh-like qualities (Liu et al., 2025). Growing global concerns over pesticide residues and microbial contamination in plant-derived foods have intensified demand for sustainable decontamination solutions, and APP has emerged as a promising approach capable of addressing these challenges at near-ambient temperatures (Liu et al., 2025). Conventional physical, chemical, and biological methods are often hampered by operational inefficiency, secondary pollution risks, and nutritional degradation, limitations that APP substantially overcomes (Liu et al., 2025).

4. Mycotoxin Degradation and Chemical Contaminant Removal

Beyond microbial inactivation, APP has shown considerable promise in the degradation of chemical contaminants, particularly mycotoxins and pesticide residues. Mycotoxins are secondary metabolites produced by filamentous fungi that frequently contaminate cereal grains, oilseeds, and processed food products, and their persistence poses significant public health concerns including carcinogenicity, immunotoxicity, and hepatotoxicity (Huang et al., 2026). Cold plasma is a novel non-thermal food processing technology characterized by low processing temperatures, high efficiency, and a pollution-free nature, demonstrating promising application potential in food sterilization, preservation, and the degradation of mycotoxins (Huang et al., 2026). APP degrades mycotoxins such as Aflatoxin B1 (AFB1), Ochratoxin A (OTA), and Deoxynivalenol (DON) through three primary mechanisms: direct molecular decomposition by reactive species, inactivation of toxigenic fungi or spores, and interference with mycotoxin biosynthesis pathways (Liu et al., 2025). The application efficacy of plasma across various food matrices has been summarized in recent studies, demonstrating significant potential

to reduce microbial loads and degrade major mycotoxins with minimal impact on food quality (Huang et al., 2026). Furthermore, toxicological safety assessment of the degradation products generated following plasma treatment, using both in vitro and in vivo models, has cited evidence of significantly reduced cytotoxicity in treated food systems (Huang et al., 2026).

The capacity of APP to degrade pesticide residues in plant-based foods also represents a meaningful advancement in food safety. APP leverages the generation of RONS, ultraviolet radiation, and ozone to address pesticide contamination at near-ambient temperatures (Liu et al., 2025). Additionally, APP has been observed to inactivate undesirable enzymes, lower allergen residues, and preserve or even enhance bioactive compounds in treated food products, thereby offering both safety and nutritional benefits simultaneously (Keewan et al., 2025).

5. Effects on Food Quality and Shelf Life

A critical consideration in the adoption of any food processing technology is its impact on the sensory and nutritional attributes of the treated product. APP offers several distinct advantages in this regard, including low-temperature microbial inactivation and higher nutrient retention compared with conventional thermal methods (Keewan et al., 2025). Plasma treatment has been shown to preserve textural integrity throughout cold storage and to maintain the color and surface properties of treated products by stabilizing surface pigments through alterations in surface structure (Keewan et al., 2025).

Treatment parameters can alter the physicochemical properties of plant-based foods, including color, texture, flavor, acidity, and water activity, as well as nutritional constituents such as antioxidants, proteins, lipids, and carbohydrate content (Liu et al., 2025). These changes are highly dependent on the plasma treatment parameters, including exposure time, power input, gas composition, and the specific food matrix being treated. As an environmentally friendly, low-energy-consumption technology with high reactivity, APP offers transformative potential for enhancing food safety, preserving quality, and fostering sustainable agricultural and food processing systems (Liu et al., 2025).

APP has also been reported to improve the functional properties of food ingredients. Its application has been shown to modify properties such as protein solubility and emulsification, thereby enhancing the functional performance of food ingredients used in product formulation (Keewan et al., 2025). In the context of food packaging, plasma treatment has demonstrated the ability to enhance packaging films with improved mechanical strength and antimicrobial capabilities, further extending the shelf life of packaged food products (Keewan et al., 2025). The plasma treatment of food also significantly reduced oil uptake and acrylamide formation in fried products such as potato strips, which was attributed to microstructural changes and partial inactivation of asparagine-related enzymatic pathways (Keewan et al., 2025).

6. Challenges and Future Prospects for Commercial Implementation

Despite the considerable promise of APP technology, several challenges must be addressed before its broad-scale adoption in the food industry. One of the most significant technical limitations is the restricted penetration depth of plasma reactive species, which constrains its efficacy to surface decontamination and makes it less effective for treating solid food matrices with complex geometries or high water content (Huang et al., 2026). Achieving uniform plasma treatment across irregular or porous food surfaces remains a practical challenge for equipment design and scale-up (Huang et al., 2026). Key safety concerns associated with APP include the formation of ozone, a potent reactive oxygen species known for its strong oxidizing properties. Although ozone is effective for microbial inactivation, its concentration must be strictly regulated to prevent adverse effects on food quality and human health (Keewan et al., 2025). While the US Food and Drug Administration has established guidelines for permissible levels of ozone in food processing applications, similar regulatory frameworks for other reactive species such as hydrogen peroxide and nitric oxide are currently lacking, underscoring the need for comprehensive safety evaluations and standardized regulatory guidelines (Keewan et al., 2025).

The use of plasma in food processing offers promising potential owing to its different attributes including non-thermal operation, enzyme inactivation, removal of pesticides and toxins, less damage to food, low nutritional loss, and high quality of final products (Usman et al., 2023). However, the need for standardization of treatment parameters, optimization of plasma systems for specific food matrices, and the development of cost-effective, scalable equipment remain significant hurdles to commercialization (Usman et al., 2023). Future research trends

include optimizing plasma parameters for different food types, investigating effects on nutritional quality and sensory attributes, understanding microbial inactivation mechanisms, and developing efficient and scalable plasma-based processing systems (Usman et al., 2023).

7. Conclusion

Atmospheric pressure plasma processing represents a scientifically validated and increasingly viable approach to addressing the pressing challenges of food safety and preservation. Its ability to inactivate a broad spectrum of foodborne pathogens, degrade mycotoxins and pesticide residues, and enhance packaging material performance, while largely maintaining food quality, positions it as a highly competitive alternative to conventional thermal and chemical decontamination methods. Nevertheless, realizing the full commercial potential of this technology will require concerted efforts in regulatory standardization, equipment engineering, and safety evaluation of treated food products. With continued multidisciplinary research and industry collaboration, atmospheric pressure plasma processing is well-positioned to become a cornerstone technology in the future of sustainable and safe food production.

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Credit Constraints and Farm Investment: Evidence from Smallholder Agriculture in Developing Economies

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Abstract

Smallholder farmers often need to spend on seed, fertilizer, hired labour, irrigation, or equipment well before harvest revenue arrives. When savings are scarce and loans are unavailable or costly, they may reduce input use, postpone productive investment, or avoid technologies with high upfront costs. This article explains how credit constraints shape farm investment and why outcomes differ across households and settings. It distinguishes lender-side rationing from farmers' own reluctance to borrow, and discusses risk, collateral, gender, and institutional barriers. Empirical studies from Burkina Faso, Ethiopia, Tanzania, Peru, Ghana, and India show that financial constraints can affect input choices, technology adoption, and productivity, but also that credit alone may not resolve investment problems. The article argues for finance tailored to farm cash flows and combined, where appropriate, with insurance, savings, extension, and market access. It concludes with policy and research priorities for more inclusive rural finance.

Keywords: Credit constraints, smallholder agriculture, farm investment, rural finance, technology adoption, agricultural productivity, developing economies

Introduction

A farmer may know that improved seed, fertilizer, irrigation, or a small pump could raise future earnings, yet still be unable to make the purchase when the crop season begins. Costs arrive before harvest income, and revenue depends on weather, pests, and prices. For a household with little savings, a missing or expensive loan can shape not only how much it invests but also which crops and technologies it chooses (Feder et al., 1988; Foltz, 2004).

The link between credit and investment is central to agricultural economics. Credit can relax cash-flow constraints and support spending on working inputs; longer-term finance can enable investment in irrigation, machinery, livestock, storage, or land improvement (Stiglitz & Weiss, 1981; Carter & Olinto, 2003). Yet a loan does not guarantee a beneficial outcome. Farmers may face repayment obligations after a poor harvest, while lenders must assess borrowers amid uncertainty and limited collateral. A synthesis of 43 experimental and quasi-experimental studies finds that financial services can support investment and livelihoods, while stressing the importance of product design and context (FAO & IPA, 2024).

What is a credit constraint?

A household is credit constrained when it cannot borrow the amount it wants on acceptable terms, or when expected costs and risks keep it from applying. This differs from simply having no loan: a farmer who chooses not to borrow may not be constrained, while an applicant denied credit faces a supply barrier. Researchers distinguish supply-side barriers such as collateral rules, high interest rates, distance, or limited lender capacity from demand-side barriers such as risk aversion, lack of information, low trust, and uncertainty about loan terms (Boucher et al., 2008; Boucher et al., 2009).

The distinction matters for policy. More bank branches will not necessarily help farmers who fear losing assets after a bad season. Financial-literacy programmes cannot by themselves solve exclusion caused by land-title requirements or inflexible repayment schedules. Evidence from Ethiopia and Tanzania finds that demand and

supply-side constraints both matters, with credit affecting technology adoption differently across the two settings: women were more likely to face both kinds of constraint (Balana et al., 2022).

Why agriculture needs suitable finance

Agricultural production has a seasonal cash flow pattern. Land preparation, seed, fertilizer, hired labour, and irrigation expenses may arise months before sales. Rural households also meet needs for food, schooling, health care, and emergencies. Without liquidity, farmers may use less fertilizer than they consider profitable, plant less land, sell assets, or rely on lower-cost but lower-return practices.

Lending to farms can also be difficult for institutions. A drought or flood may affect many borrowers at once, while small farms may lack formal titles or documented income. Small loan amounts, remote locations, and high transaction costs further complicate lending. Research on rural credit describes how imperfect information and limited collateral can produce credit rationing even when borrowers are willing to pay (Stiglitz & Weiss, 1981; Feder et al., 1988). Property rights can affect both the amount and composition of farm investment, although formalizing rights alone does not guarantee access if credit supply remains limited (Carter & Olinto, 2003).

Using national farm-household survey data, Ramasamy and Malaiarasan (2023) report that credit access was associated with higher farm investment, expenditure on inputs, farm income, and household consumption, while access remained limited and uneven. A state level analysis by Shivaswamy et al. (2020) finds regional disparities in institutional credit outreach and a positive association between institutional credit and agricultural productivity. These results underline that expanding total lending and ensuring equitable access are related but distinct policy tasks.

How constraints affect investment

Credit limitations can influence investment through several channels. Farmers may buy fewer inputs or buy them too late; they may avoid technologies with high upfront costs and they may choose lower-risk, lower-return activities because they cannot absorb a loss. They may also use scarce cash to protect immediate consumption rather than build productive assets, a rational response where food and health needs are urgent (Guirkinger & Boucher, 2008).

The effects concern not only total spending but also the mix of seed, fertilizer, manure, labour, and land. Among maize smallholders in Burkina Faso, financial constraints were associated with non-optimal input use, and the study estimated potential productivity losses of roughly 25% in that sample (Combary, 2022).

Credit interacts with risk. A farmer may hesitate to borrow when harvest income is uncertain but repayment is fixed. In northern Ghana, experiments that relaxed credit and risk constraints found that insurance could encourage agricultural investment and riskier production choices (Karlan et al., 2014). A related randomized trial found that bundling loans with index insurance increased fertilizer adoption, underscoring that finance and risk management can be complements (Takashi et al., 2023).

Narayanan (2016), using state level panel data, finds that greater institutional credit flow is associated with increased use of fertilizers and pesticides and more tractor purchases, although the study cautions that higher input use does not automatically translate into proportionate agricultural GDP growth in India. Ramasamy and Malaiarasan (2023) report effects on both fixed farm assets such as machinery and livestock and variable farm expenditure. The distinction matters: short-term crop loans and longer-term investment loans support different decisions and should not be treated as interchangeable.

Global Evidence on Agricultural Credit

Evidence across countries points to substantial variation. In Ethiopia and Tanzania, credit constraints affected adoption and intensity of irrigation, fertilizer, and improved seed differently (Balana et al., 2022). Research in Rwanda has linked credit constraints with farm productivity and rural non-farm participation (Ali et al., 2014). In Peru, credit rationing has been examined as a determinant of farm productivity and investment choices (Guirkinger & Boucher, 2008). Results should therefore be interpreted in relation to crops, institutions, financial products, and local risks.

A review by FAO and Innovations for Poverty Action synthesizes 43 experimental and quasi-experimental studies on finance for agrifood investment. It reports that well designed financial services can support investment, but barriers such as collateral requirements and limited financial capability can prevent poorer farmers from

benefiting (FAO & IPA, 2024). Savings also matter; they can help households accumulate funds and manage seasonal expenses without taking on debt.

Comparisons between borrowers and non-borrowers do not automatically show that credit caused different outcomes. Borrowers may also differ in wealth, skills, networks, land quality, or willingness to take risks. Credible analysis requires designs that address this selection problem, such as randomized interventions, panel data, natural experiments, or carefully justified quasi-experimental methods (Boucher et al., 2009).

In India, Ramasamy and Malaiarasan (2023) use propensity-score matching to examine national household survey data and find positive estimated effects of credit access on investment, input expenditure, and income, while documenting gaps in coverage. Kumar et al. (2017), using a national farmers' survey and an instrumental-variable approach, report that institutional credit increases net farm income and household consumption expenditure.

Evidence and policy questions in India

India has a large institutional agricultural credit system, including cooperative banks, commercial banks, Regional Rural Banks, and the Kisan Credit Card (KCC) framework. The existence of these channels does not mean that every cultivator can use them equally. Studies point to differences by farm size, social group, region, land documentation, and whether a farmer is an owner-cultivator or tenant. Ramasamy and Malaiarasan (2023) highlight lower access among some disadvantaged groups and recommend making crop loans and KCC facilities more accessible to tenant farmers.

Shivaswamy et al. (2020) find that credit outreach per hectare varied considerably across Indian regions in their study period, with lower outreach in eastern and north-eastern regions than in the south. Their panel analysis reports a positive relationship between institutional credit and agricultural productivity across the states and years studied. These findings raise a useful policy question: should evaluation focus mainly on the aggregate amount of credit, or also on who receives it, when it arrives, what it finances, and whether it reaches cultivators whose land tenure is informal?

Recent qualitative work by Hiranya and Joshi (2025), based on focus-group discussions in Karnataka, identifies implementation and perception barriers, including accessibility, inclusion, and digital adoption.

Gender and unequal access

Women farmers may face overlapping barriers like land may be registered in another household member's name, collateral may be unavailable, and financial products may not fit their crops, schedules, or control over income. Research on rural women's access to credit highlights the interaction between market imperfections and intrahousehold dynamics (Fletschner, 2009). The Ethiopia–Tanzania evidence likewise reports that women are more likely to face credit constraints on both the supply and demand sides (Balana et al., 2022).

Improving access requires asking more than how many loans were issued. Researchers should examine who applies, who is approved, who controls the funds, what activities are financed, and who receives returns. Group lending, movable collateral, savings-linked finance, and alternative credit assessments may help in some settings, but each needs local evaluation and safeguards.

Designing better rural finance

Financial products should match the investment and the farmer's cash flow. Seasonal working-capital loans can be repaid after harvest; longer-term loans may need grace periods and schedules suited to the asset's returns. Terms should be transparent and avoid pushing households into unmanageable debt. Credit paired with insurance or other risk-management tools may support investment where uncertainty is a major barrier (Karlan et al., 2014; Takashi et al., 2023).

Finance also depends on the wider environment. Farmers are more likely to invest when inputs are available on time, extension advice is credible, and roads, storage, and buyers connect them to markets. Digital delivery may lower transaction costs, but it cannot replace consumer protection, privacy, grievance channels, or reliable connectivity (World Bank, 2016).

Evaluation should look beyond accounts opened or loans disbursed. Useful measures include loan timing and total cost, investment type, technology adoption, yields, net profits after repayment, resilience, debt stress,

and distribution by gender and farm size. The goal is not maximum borrowing, it is finance that enables productive investment without shifting excessive risk to vulnerable households (FAO & IPA, 2024).

Future Research Directions

Several areas warrant further investigation-Which combinations of credit, insurance, savings, and extension produce the strongest returns for different farms? Do seasonal repayment schedules increase investment while limiting default? How do land tenure and informal rental arrangements shape access? Which barriers matter most for women, tenants, youth, and remote communities? Do digital lending products broaden inclusion or reproduce existing exclusions?

For India, useful questions include whether short-term KCC loans support durable investment or mainly finance seasonal inputs? whether tenant farmers and women cultivators can access credit in practice? and whether lending reaches regions with historically lower credit outreach?

Answering these questions calls for clear definitions of credit constraint, disaggregated data, and impact designs that distinguish access from self-selection. A programme that increases input purchases but leaves farmers with lower net income after fees and interest should not be judged successful only because uptake rose.

Conclusion

Credit constraints are not simply a matter of whether a farmer can obtain a loan. They influence when farmers can act, which investments they can afford, and how much risk they are able to take. When finance is missing or poorly suited to the farming calendar, a household may delay buying inputs, pass up a productive technology, or avoid improving its land or equipment. These decisions can limit a farm's future potential, even when the farmer understands the possible benefits of investing.

At the same time, borrowing is not automatically the answer. A loan can support production only when its timing, cost, repayment schedule, and purpose fit the farmer's circumstances. If repayment is due before income arrives, or a climate or price shock damages the harvest, debt can add pressure rather than create opportunity. Responsible rural finance should therefore give farmers useful choices and not encourage borrowing for its own sake.

A stronger approach combines suitable credit with other forms of support. Savings can help households prepare for seasonal expenses, insurance can reduce the consequences of some production shocks, extension services can help farmers make informed investment decisions, and reliable input and output markets can make those investments more worthwhile. Together, these services can help farmers manage both the opportunities and uncertainties involved in production.

The needs of smallholders are diverse. Farm size, crop choice, land tenure, household responsibilities, gender, location, and access to markets all shape the kind of financial service that may work. Policies and products should take those differences seriously, explain costs clearly, protect borrowers from unsuitable terms, and avoid excluding cultivators simply because they lack conventional documents or collateral.

Ultimately, the success of rural finance should be judged by what happens after money is made available. Do farmers make productive investments? Do those investments improve net returns or resilience without creating unsustainable debt? Are women, tenants, and more remote households able to benefit? Answering these questions requires careful evaluation and attention to farmers' own experiences. When finance is designed around real farm conditions and supported by functioning services and markets, it can help smallholders turn productive ideas into investments and investments into more secure livelihoods.

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Soil Acidity: Characteristics, Causes, Effects on Plant Growth and Plant–Microbe Interactions

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Abstract

Soil acidity is a major constraint to agricultural productivity, affecting nutrient availability, plant growth and soil microbial activity. It is influenced by natural processes, excessive leaching, acidifying fertilizers and intensive agricultural practices. Low soil pH reduces the availability of essential nutrients, particularly phosphorus and molybdenum, while increasing the solubility of toxic elements such as aluminium and manganese. These conditions restrict root development, nutrient uptake and crop yield. Plant–microbe interactions play an important role in alleviating acid stress through nutrient solubilization, phytohormone production and improved stress tolerance. Integrating beneficial microorganisms with appropriate soil management practices can promote soil fertility and sustainable crop production.

Keywords: Soil acidity, Aluminium toxicity, Plant–microbe interactions, Acid-tolerant microorganisms, Soil fertility

Introduction

Soil is the biologically active, porous upper layer of the Earth's crust that provides essential resources for terrestrial life. It acts as a reservoir of water and nutrients, supports plant growth, regulates biogeochemical cycles and provides a habitat for diverse microorganisms. Soil also plays a crucial role in organic matter decomposition, nutrient recycling, carbon sequestration and the maintenance of ecosystem stability. However, intensive agricultural practices, imbalanced fertilizer application and the increasing demand for food have contributed to soil degradation and declining soil fertility in many regions. Among the major abiotic constraints affecting agricultural productivity, soil acidity is particularly important because of its influence on nutrient availability, microbial activity and plant growth (Gondal et al., 2021).

Soil acidity refers to a condition in which the soil pH is below neutral (pH 7.0), although its agricultural classification and effects depend on soil properties and crop sensitivity. Soil pH represents the negative logarithm of hydrogen ion activity and determines the chemical environment in which nutrients and toxic elements interact. Acidic soils are commonly associated with high rainfall, intensive leaching, specific parent materials and prolonged agricultural use. In India, approximately 90 million hectares have been reported to be affected by soil acidity, highlighting its importance as a constraint to agricultural production (Ganeshamurthy et al., 2016). Understanding the causes and consequences of soil acidity, together with the responses of plants and microorganisms, is essential for developing sustainable soil management strategies.

Characteristics and Causes of Soil Acidity

Acidic soils generally have a pH below 6.5, although strongly acidic soils commonly have a pH below 5.5. Their characteristics vary according to parent material, climate, texture, clay mineralogy and organic matter content. Many acidic soils have low concentrations of exchangeable calcium and magnesium because these basic cations are removed through leaching. The availability of phosphorus and molybdenum may decline, whereas the solubility of aluminium and manganese can increase to levels that are toxic to plants. Soil acidity may also reduce the activity of beneficial microorganisms, particularly those involved in nitrogen fixation and nutrient mineralization.

The development of soil acidity involves several natural and agricultural processes. In regions receiving high rainfall, the downward movement of water removes basic cations from the soil profile, gradually increasing acidity. The decomposition of organic residues produces organic acids, while the oxidation of certain sulphur-containing minerals can generate acidity under suitable conditions. Atmospheric deposition of acidifying compounds, including sulphur dioxide and nitrogen oxides, may further contribute to soil acidification.

Agricultural practices can accelerate this process. Repeated application of acidifying nitrogen fertilizers, including ammonium-based fertilizers and urea under particular soil and management conditions, can increase acidity through nitrogen transformations and subsequent nitrate leaching. The removal of harvested crops also exports basic nutrients from agricultural fields. Nutrient uptake by plants, root-associated processes and the accumulation of organic matter can contribute to changes in soil pH. The magnitude of acidification depends on fertilizer type, application rate, crop removal, soil buffering capacity and management practices (Goulding, 2016).

Effects of Soil Acidity on Plant Growth

Soil acidity affects plant growth primarily by altering nutrient availability, increasing the solubility of toxic elements and restricting root development. Its effects become particularly severe when soil pH falls below approximately 5.0, although the critical threshold varies among crops and soil types. At moderately acidic pH, many crops can grow satisfactorily; however, sensitive crops may experience nutrient deficiencies or metal toxicity even at higher pH values.

Phosphorus availability is frequently reduced in acidic soils because phosphate ions react with aluminium and iron to form sparingly soluble compounds. This limits phosphorus uptake and may restrict root development, energy transfer and reproductive growth. Deficiencies of calcium and magnesium can also occur because these nutrients are displaced from exchange sites or leached below the rooting zone. Molybdenum availability generally decreases with increasing acidity, potentially impairing nitrogen metabolism and biological nitrogen fixation. Conversely, iron, manganese and aluminium may become excessively soluble, resulting in toxicity under susceptible soil conditions.

Soil acidity can also affect plant water and nutrient uptake indirectly by damaging root tissues and reducing root elongation. Poor root development limits access to water and nutrients, thereby reducing plant vigour, biomass accumulation and yield. Under severe conditions, aluminium toxicity can interfere with cell division, root cell elongation and membrane functioning. Plants may respond to these stresses by modifying root architecture, altering nutrient transport and producing protective metabolites. However, the ability to tolerate acidic conditions varies considerably among crop species and genotypes. Consequently, the severity of crop damage depends on the intensity of acidity, the concentration of toxic elements, soil moisture and the plant's inherent tolerance mechanisms.

Specific Ion Toxicity in Acidic Soils

Aluminium toxicity is one of the most important constraints to crop production in strongly acidic soils. Although aluminium is abundant in the Earth's crust, its toxicity to plants increases when soil pH decreases because more soluble forms, particularly aluminium ions, become available. These ions accumulate around root tips and interfere with normal root development.

A major symptom of aluminium toxicity is the rapid inhibition of root elongation. Aluminium interacts with cell walls, plasma membranes and cellular processes, affecting cell expansion and root meristem activity. It can alter cell wall properties, disrupt membrane function and interfere with the uptake and transport of essential nutrients such as calcium, magnesium, phosphorus and potassium. Aluminium-induced root damage also reduces water absorption, making plants more susceptible to drought stress. Furthermore, aluminium can decrease phosphorus availability by forming poorly soluble aluminium–phosphate compounds.

The resulting nutrient imbalance affects photosynthesis, respiration and overall plant metabolism. Reduced root growth limits the exploration of soil for nutrients and water, ultimately restricting plant establishment and productivity. Aluminium toxicity may also affect beneficial plant–microbe associations, particularly the interaction between leguminous plants and nitrogen-fixing rhizobia. The sensitivity of plants to aluminium varies according to species, genotype and soil conditions. Some plants possess tolerance mechanisms, including organic acid exudation from roots, which can bind aluminium and reduce its toxic effects (Kochian et al., 2004).

Manganese toxicity can also occur in acidic soils when its soluble concentration increases. Excess manganese may interfere with photosynthesis, enzyme functioning and nutrient balance. Therefore, correcting soil acidity and selecting tolerant crops are important strategies for reducing metal toxicity and improving crop performance.

Plant–Microbe Interactions under Soil Acidity

Plant–microbe interactions are essential for maintaining soil fertility and supporting crop growth under environmental stress. The rhizosphere, the soil region influenced by plant roots, contains diverse bacteria and fungi that contribute to nutrient acquisition, organic matter decomposition and plant health. Beneficial microorganisms can improve plant tolerance to abiotic stresses through nutrient solubilization, biological nitrogen fixation, phytohormone production and the synthesis of protective compounds.

Under acidic conditions, microbial communities may undergo changes in composition, diversity and metabolic activity. Acid-sensitive microorganisms may decline, whereas acid-tolerant species can survive and remain metabolically active. These changes can influence nutrient cycling, organic matter decomposition and the availability of nutrients to plants. For example, low pH can restrict the activity of certain nitrogen-fixing bacteria, reducing biological nitrogen fixation and nitrogen supply to crops.

Plant growth-promoting bacteria may help plants withstand acidic soil conditions by producing indole-3-acetic acid and other growth-regulating compounds, solubilizing phosphorus, producing siderophores and improving nutrient acquisition. Some microorganisms also produce extracellular substances and stress-associated metabolites that support root development and plant adaptation. In addition, microbial communities can influence plant responses through interactions with root exudates and the regulation of plant defence pathways.

Nevertheless, the effectiveness of beneficial microorganisms depends on their ability to survive, colonize roots and function under acidic conditions. Microbial strains selected for acid tolerance and specific plant growth-promoting characteristics may therefore be valuable components of biofertilizer formulations. Combining appropriate microbial inoculants with soil acidity management may improve nutrient-use efficiency and reduce dependence on chemical fertilizers.

Microbial Responses to Acid Stress

Microorganisms have evolved several mechanisms to maintain intracellular pH and survive in acidic environments. Since essential cellular processes require a relatively stable internal pH, excessive proton accumulation can damage proteins, membranes and metabolic pathways. Acid-tolerant microorganisms employ physiological and biochemical strategies to maintain cellular homeostasis.

One mechanism involves proton-consuming decarboxylation reactions, in which amino acids are converted into corresponding products while consuming intracellular protons. These reactions can help maintain intracellular pH and support microbial survival. Some microorganisms also produce alkaline compounds that neutralize acidity in their immediate environment. In addition, membrane-associated proton-translocating systems, including the F_1F_o-ATPase, help regulate intracellular proton concentrations by transporting protons across the cell membrane. These mechanisms require energy and may become particularly important under severe acid stress (Krulwich et al., 2011).

Microorganisms may also modify their membrane composition, regulate stress-response genes and produce protective proteins to maintain cellular integrity. Such adaptations allow selected bacterial and fungal populations to survive in acidic soils and contribute to nutrient cycling. However, microbial tolerance varies considerably among species and strains. Identifying acid-tolerant, plant-beneficial microorganisms is therefore important for developing microbial formulations suitable for acidic agricultural soils.

Conclusion

Soil acidity is a major constraint to agricultural productivity because it affects nutrient availability, increases the risk of aluminium and manganese toxicity, restricts root development and alters microbial activity. Its development is influenced by natural factors, rainfall, nutrient leaching and agricultural management practices. Plant–microbe interactions offer opportunities to improve nutrient acquisition and stress tolerance, particularly through the use of acid-tolerant, plant growth-promoting microorganisms. Integrating suitable microbial inoculants with balanced fertilization, appropriate liming where required, organic matter management and tolerant crop varieties can contribute to sustainable soil fertility management and improved crop productivity.

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Insect Pests of Okra and Their Integrated Management

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Abstract

Okra (*Abelmoschus esculentus* L. Moench) popularly known as bhindi or lady's finger is one of India's most widely grown vegetables and the crop behind India's position as the world's leading okra producer. Yet a persistent complex of insect and mite pests attacks the crop from seedling to fruiting stage, eroding much of this yield potential. This article reviews the major insect pests of okra jassid (*Amrasca biguttula biguttula*), whitefly (*Bemisia tabaci*), spotted/shoot and fruit borer (*Earias vittella*), and red spider mite (*Tetranychus* spp.) covering their taxonomic placement, damage symptoms, and yield losses reported in research literature, which can reach 50-70 percent when unmanaged. It concludes with an integrated management strategy combining cultural, mechanical and biological control with chemical recommendations drawn from the Punjab Agricultural University (PAU) Package of Practices for vegetable cultivation.

Keywords- Okra, Insect pests, Jassid, Whitefly, Shoot and fruit borer, Red spider mite, Integrated Pest Management.

1. Introduction

Okra, *Abelmoschus esculentus* (L.) Moench (family Malvaceae), is an annual, warm-season vegetable of African origin, valued for its tender, mucilaginous pods rich in vitamins, protein, calcium and fibre, and for its role in India's fresh vegetable export basket. India's horticulture sector produced about 353.19 million tonnes from 28.98 million hectares in 2023-24 (vegetables: 205.80 million tonnes), rising to roughly 367.7 lakh tonnes in 2024-25. Within this, India is the world's largest okra producer, contributing 60-70 percent of global output about 6.35 million tonnes from 0.519 million hectares (ICAR/FAOSTAT). Gujarat leads national production (2024-25), followed by Madhya Pradesh, West Bengal, Bihar and Andhra Pradesh, with Odisha, Karnataka, Assam and Punjab as other key growing states. Despite this scale, okra remains heavily pest-infested: the sucking-pest complex (jassid, whitefly, aphid, mite) causes 17.46-54.04 percent yield loss, while the shoot and fruit borer complex alone damages 45-57 percent of fruits together capable of cutting yield by up to 70 percent without timely protection. This underscores the need for an integrated, science-based management approach, discussed below through each pest's identification, symptoms, and cultural, mechanical, biological and chemical control per the PAU Package of Practices.

2. Major Insect Pests of Okra

2.1 Jassid / Leafhopper - *Amrasca biguttula biguttula* (Ishida)

Order: Hemiptera Family: Cicadellidae

Jassid is a seedling-to-harvest pest of okra that causes damage mainly during May-September. Both greenish adults and nymphs remain on the underside of leaves and suck cell sap, and their toxic saliva causes yellowing and curling along the leaf margins. Affected leaves gradually turn pale and then bronze in colour, and in severe cases premature defoliation occurs, weakening the plant and reducing fruit set. Research trials have recorded yield losses of up to 54.04 percent when jassid is left uncontrolled in the early crop stages, and the economic threshold level (ETL) for spraying is 4 nymphs per leaf, monitored from the top, middle and bottom canopy of the plant.

Management

- Sow the crop timely on ridges with recommended spacing and balanced nitrogen to avoid dense canopies that favour jassid build-up; remove infested lower leaves and bund weeds.

- Conserve natural enemies (coccinellids, Chrysoperla, spiders) and use bio-pesticides like neem-based formulations or Beauveria bassiana where feasible.
- Monitor 3 leaves/plant (top, middle, bottom) on 10 random plants per quarter-acre, spray on reaching ETL of 4 nymphs/leaf, in 100-125 litres water/acre.
- Vegetable crop: 80 ml Ecotin 5% or 40 ml Confidor 17.8 SL (imidacloprid) or 40 g Actara 25 WG (thiamethoxam) or 560 ml Malathion 50 EC or 100 ml Sumicidin 20 EC.
- Seed crop: 250 ml Rogor 30 EC (dimethoate), repeat after 15 days if needed.
- Pick fruits before spraying, observe a 1-day waiting period after Confidor/Actara, never use seed-crop schedules on vegetable-purpose crop.

2.2 Whitefly - *Bemisia tabaci* (Gennadius)

Order: Hemiptera Family: Aleyrodidae

Whitefly causes maximum damage during July-September. Its adults and nymphs congregate on the underside of leaves and suck sap, excreting honeydew that makes leaves sticky; the honeydew subsequently supports the growth of sooty mould, turning affected leaves black and reducing photosynthesis. Whitefly is also of particular concern as it is the vector of Yellow Vein Mosaic Virus (YVMV), a disease that can cause severe yield and quality loss in okra.

Management

- Avoid staggered okra planting near old cotton/vegetable fields carrying residual whitefly; grow YVMV-tolerant varieties where available.
- Use yellow sticky traps for monitoring and mass trapping; eradicate weeds on bunds, wastelands and irrigation channels that serve as alternate hosts.
- Conserve natural enemies (Encarsia spp., coccinellids); avoid synthetic pyrethroids, which trigger whitefly resurgence.
- Spray 80 ml Ecotin 5% (neem-based) OR 2000 ml PAU neem extract in 100-125 litres water/acre.
- Pick all ripe fruits before spraying; keep up regular surveillance of the crop and alternate hosts for timely management.

Precautions: Pick all ripe fruits before spraying, avoid synthetic pyrethroids to minimise resurgence.

2.3 Spotted Bollworm / Shoot and Fruit Borer - *Earias vittella* (Fabricius)

Order: Lepidoptera Family: Nolidae

This borer complex (spotted bollworm, along with the closely related spiny bollworm Earias insulana) damages the crop from May to September. Newly hatched larvae bore into tender shoots, causing them to droop downward and dry up ("dead heart" symptom); later, larvae attack developing fruits, boring in and leaving a varying number of holes that make the produce unmarketable. Field studies report that this borer complex alone causes 45-57 percent fruit damage where the crop is left unprotected; the recommended economic threshold level for spraying vegetable-purpose okra is 1 percent fruit infestation.

Management

- Monitor fruit infestation regularly from 10 randomly selected plants in each of the four quarters of one acre, ETL for spotted bollworm is 1% infested fruits.
- On reaching ETL, spray the crop with 100-125 litres of water/acre.
- Vegetable crop: 50 ml Coragen 18.5 SC (chlorantraniliprole) or 200 ml Sumipleo 10 EC (pyridalyl) or 70 g Proclaim 05 SG (emamectin benzoate) or 100 ml Sumicidin 20 EC (fenvalerate).
- Seed crop: when 20-30% shoots show borer damage, spray 100 ml Sumicidin 20 EC or 80 ml Cymbush 25 EC (cypermethrin) or 160 ml Decis 2.8 EC (deltamethrin).
- Uproot and destroy hollyhock and ratooned cotton, as these are host plants for bollworms.
- Pick all fruits before spraying; observe a one-day waiting period after Coragen.
- Remove attacked fruits regularly and bury them deep in the soil.

2.4 Red Spider Mite - *Tetranychus spp.*

Class: Arachnida (Acari) Order: Trombidiformes Family: Tetranychidae

Although not a true insect, the red spider mite is grouped with the okra pest complex because of its comparable economic impact. Mites colonise the underside of leaves in colonies, puncture leaf cells and suck the cell sap,

producing fine webbing on the leaf surface. Heavily infested leaves show stippling, bronzing/necrosis and eventually defoliation, which reduces photosynthetic area and fruit yield, particularly during the hot, dry part of the season.

Management

- Avoid moisture stress through timely irrigation, as mite outbreaks are aggravated by hot, dry conditions.
- Remove and destroy heavily mite-infested and webbed leaves at the first sign of colonisation.
- Conserve predatory mites and coccinellid beetles that feed on Tetranychus colonies; avoid indiscriminate use of broad-spectrum insecticides that flare up mite populations.
- Avoid excess nitrogen application, which promotes tender foliage growth favourable to mite build-up.
- Rotate away from broad-spectrum insecticide use during the season to prevent mite resurgence from loss of natural predators.
- Spray PAU Dharek extract @ 1600 ml/acre or Oberon 22.9 SC (spiromesifen) @ 150 ml/acre.
- Precautions: observe a one-day waiting period after spraying Oberon.

3. Conclusion

Okra's yield potential in India is significantly constrained by a recurring pest complex jassid, whitefly, shoot and fruit borer, and red spider mite capable of causing losses ranging from 17% to over 70% when left unmanaged. As outlined in this review, effective protection depends on regular field monitoring against pest-specific economic threshold levels, timely cultural and mechanical practices, conservation of natural enemies, and judicious use of PAU-recommended insecticides. Adopting this integrated approach, rather than relying on chemical control alone, offers the most sustainable path to safeguarding okra yield and quality for India's farmers.

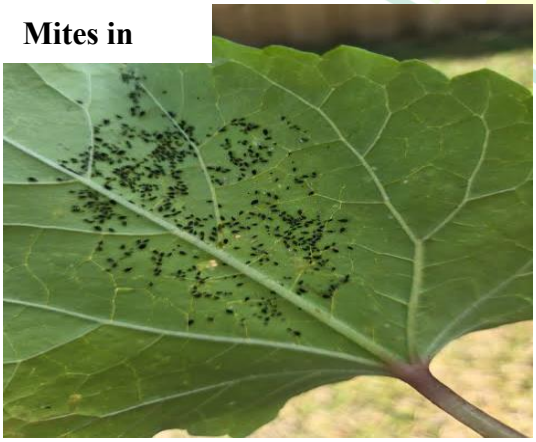
Whitefly in



Shoot and Fruit Borer in



Mites in



Leafhopper in



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Zebrafish as a next-generation model for drug discovery, environmental toxicology and fish health management

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Abstract

The zebrafish (*Danio rerio*) has emerged as a versatile experimental model in pharmacology, toxicology and aquatic environmental research. Its rapid embryonic development, high reproductive capacity, transparent embryos, genetic tractability and suitability for high-throughput screening have expanded its applications in modern scientific investigations. In fisheries pharmacology and toxicology, zebrafish provide opportunities to investigate the biological effects of pharmaceuticals, pesticides, heavy metals, industrial pollutants and emerging contaminants. They are also useful for preliminary screening of candidate therapeutic compounds and plant-derived substances, investigating oxidative stress and inflammation and understanding the mechanisms underlying chemical toxicity. Recent advances in molecular biology, automated imaging, behavioural analysis and omics technologies have further strengthened the potential of zebrafish-based research. Standardised methods, including the Fish Embryo Acute Toxicity test, have contributed to the development of reproducible chemical safety assessments. However, differences between zebrafish and other fish species, variations in exposure conditions and limitations in translating laboratory findings into environmental and aquaculture settings must be considered. This article highlights the major applications, advantages, limitations and future prospects of zebrafish research, emphasising its relevance to drug discovery, environmental protection and sustainable fish health management.

Keywords: *Danio rerio*, zebrafish, fisheries pharmacology, aquatic toxicology, drug discovery, environmental contaminants, oxidative stress, fish health management.

Introduction

Aquatic ecosystems are increasingly exposed to contaminants originating from agricultural activities, industrial discharge, domestic wastewater and pharmaceutical use. These substances can enter freshwater and marine environments, affecting aquatic organisms and potentially disturbing ecological balance. At the same time, aquaculture faces challenges associated with infectious diseases, treatment safety, water quality deterioration and the responsible use of therapeutic chemicals. Understanding these problems requires experimental models capable of revealing the biological effects of chemicals and the mechanisms through which they influence living organisms.

The zebrafish (*Danio rerio*), a small freshwater fish native to South Asia, has become one of the most widely used vertebrate models in modern biological research. Initially recognised for its value in developmental biology and genetics, it is now extensively used in pharmacology, toxicology, disease modelling and environmental research. Its suitability for large-scale screening, combined with the ability to observe developmental and physiological responses in a living organism, makes it an important research tool (MacRae & Peterson, 2015; MacRae & Peterson, 2023).

Zebrafish research is particularly relevant to fisheries pharmacology and toxicology because fish are directly exposed to substances dissolved or suspended in their aquatic environment. These exposures may affect growth, behaviour, reproduction, immunity and survival. By investigating such responses under controlled conditions, researchers can better understand chemical hazards and evaluate promising therapeutic candidates. The importance of zebrafish lies in its ability to connect chemical exposure with measurable biological responses and the underlying mechanisms of toxicity. This makes it a valuable complementary model for drug discovery, environmental risk assessment and fish health research.

Why Zebrafish has become a popular model organsim?

Several biological and practical characteristics explain the increasing popularity of zebrafish in experimental research. Its small size permits laboratory maintenance using relatively limited space, while its high reproductive capacity provides sufficient embryos for replicated experiments. Embryonic development is rapid, enabling researchers to observe developmental processes and selected toxicological effects within a short experimental period.

Another important feature is the transparency of zebrafish embryos during early development. Researchers can observe developmental abnormalities, organ formation and selected physiological responses using microscopy and imaging techniques. In addition, zebrafish possess a well-characterised genome and can be studied using genetic manipulation, transgenic lines and molecular approaches. The combination of rapid development, accessible embryos, genetic tools and whole-organism responses makes zebrafish particularly useful for screening compounds efficiently (Howe et al., 2013; MacRae & Peterson, 2015).

Unlike isolated cell cultures, zebrafish experiments can reveal integrated biological responses involving multiple tissues and organ systems. This is particularly important because a compound that appears harmless in a cellular assay may produce adverse effects when absorbed, metabolised or distributed throughout a living organism. Nevertheless, zebrafish are not universally representative of every vertebrate species. Their suitability depends on the research question, developmental stage, exposure route and biological endpoint being investigated.

Zebrafish in drug discovery and pharmacological research

Drug discovery involves identifying compounds with desirable biological activity and determining whether they produce unacceptable adverse effects. Conventional drug development can be time-consuming and expensive, making early-stage screening important. Zebrafish offer a practical platform for examining the effects of candidate compounds before more extensive investigations are undertaken.

Researchers can expose zebrafish embryos or adult fish to selected compounds and measure endpoints such as survival, morphology, locomotor behaviour, cardiac activity and developmental abnormalities. These observations help identify promising biological responses and potential toxicity. Zebrafish-based screening has also contributed to the identification of compounds that influence disease-associated phenotypes and physiological pathways (MacRae & Peterson, 2015).

In fisheries pharmacology, this approach can be extended to preliminary investigations of candidate treatments, including compounds intended for fish health applications. Natural products and plant-derived substances are particularly interesting because they may contain bioactive molecules with antimicrobial, antioxidant or other pharmacological properties. However, such properties must be demonstrated experimentally rather than assumed from traditional use.

A substance showing biological activity in zebrafish may require further studies of its effective concentration, toxicity, stability, metabolism and mechanism of action. Its performance must also be evaluated in the intended target species before practical use. Zebrafish can support early-stage drug discovery by allowing researchers to examine both biological activity and potential adverse effects in a living vertebrate model (Dash & Patnaik, 2023; Parthasarathy et al., 2025).

Zebrafish in environmental toxicology

Environmental toxicology examines how pollutants affect organisms and ecosystems. Zebrafish have become an important model in this field because researchers can investigate the effects of different chemical exposures using developmental, behavioural, biochemical and molecular endpoints. A bibliometric review by Zhao et al. (2024) documented the extensive use of zebrafish in studies of metal toxicity, nanomaterials, bisphenols, dioxins and other environmental contaminants. The research areas include neurotoxicity, cardiovascular toxicity, endocrine disruption, immunotoxicity and reproductive toxicity.

a) Heavy metals and industrial pollutants

Heavy metals and metalloids, including cadmium, lead, mercury and arsenic, may enter aquatic environments through industrial activities, mining, agricultural runoff and wastewater. Depending on their chemical form and concentration, these contaminants can disturb normal physiological processes and damage tissues.

Zebrafish studies can investigate developmental abnormalities, changes in behaviour, organ toxicity and biochemical responses following controlled exposure. Measurements of antioxidant enzymes and other biomarkers may help explain how exposure affects cellular defence mechanisms. Investigating both physiological changes and molecular responses helps researchers understand the mechanisms underlying metal-induced toxicity (Li et al., 2023; Zhao et al., 2024).

b) Pesticides and Agricultural Chemicals

Pesticides used in agriculture may reach aquatic habitats through runoff, drainage and other pathways. Their effects depend on the active ingredient, formulation, concentration, exposure duration and environmental conditions.

Zebrafish have been used to investigate pesticide-associated developmental toxicity, neurotoxicity, reproductive effects, endocrine disruption and changes in gene expression. The review by Cui et al. (2023) highlights the contribution of zebrafish research to understanding pesticide toxicity and the use of omics techniques to explore possible mechanisms. For fisheries research, such investigations can help identify potential hazards to non-target aquatic organisms. However, laboratory results must be interpreted alongside realistic environmental concentrations and exposure patterns.

c) Pharmaceutical Residues in Aquatic Environments

Pharmaceutical compounds can enter aquatic environments through wastewater discharge, improper disposal and other sources. Some substances may persist in water or sediments, creating opportunities for prolonged exposure of aquatic organisms.

Zebrafish can help researchers investigate the effects of selected pharmaceuticals on development, behaviour, reproduction and physiological function. González-Pleiter et al. (2023) reviewed the use of zebrafish in assessing potential hazards associated with pharmaceutical active compounds in aquatic environments.

This research is relevant to fisheries pharmacology because it links the therapeutic use of chemicals with their possible environmental consequences. It also reinforces the importance of responsible medication use, appropriate waste management and monitoring of pharmaceutical residues.

5. Oxidative stress and molecular mechanisms of toxicity

Many contaminants can disturb the balance between reactive oxygen species and the antioxidant systems that protect cells. When this balance is disrupted, oxidative stress may damage cellular components and affect normal physiological functions.

Zebrafish provide opportunities to investigate oxidative stress using biochemical, molecular and histological techniques. Depending on the experimental objectives, researchers may measure catalase, superoxide dismutase, glutathione-related parameters and lipid peroxidation. These endpoints can be combined with gene-expression analysis and tissue examination to develop a more comprehensive understanding of toxicant effects. Other mechanisms, including inflammation, apoptosis, changes in intestinal microbial communities and disruption of endocrine signalling, may also contribute to toxicity. Zhao et al. (2024) identified oxidative stress and inflammation among the important mechanisms investigated in zebrafish toxicology.

The integration of different endpoints is especially useful because a single biomarker rarely provides a complete explanation of chemical toxicity. For example, an altered antioxidant enzyme activity may indicate a biological response, but it does not independently establish the severity or long-term consequences of exposure. Combining biochemical biomarkers with behavioural, histopathological and molecular evidence provides a stronger basis for interpreting toxicological effects.

6. Emerging contaminants and microplastics

Microplastics and other emerging contaminants have attracted increasing attention because of their widespread occurrence in aquatic environments. Their biological effects can depend on particle size, shape, polymer composition, surface properties, associated chemicals and exposure duration. Zebrafish are used to investigate how microplastic exposure may influence development, behaviour, intestinal function, oxidative stress and other physiological processes. Research can also examine interactions between plastic particles and chemical contaminants.

The review by Li et al. (2023) discusses the use of zebrafish to investigate several groups of environmental pollutants, including nanoparticles and microplastics. More recent research continues to explore the mechanisms through which microplastics may affect freshwater organisms.

However, the effects observed in laboratory experiments depend strongly on the experimental design and the exposure conditions. Findings from one type of particle or concentration should not automatically be generalised to all environmental microplastics. Zebrafish research can help clarify the biological mechanisms of emerging contaminants and support more informed aquatic environmental risk assessments.

7. Applications in fish health management and sustainable aquaculture

Aquaculture is an important component of food production and rural livelihoods, but fish health can be affected by infectious diseases, environmental stress, poor water quality and inappropriate chemical treatments. Research tools that improve understanding of disease mechanisms and treatment safety are therefore valuable to the fisheries sector.

Zebrafish can be used to investigate selected aspects of inflammation, immune responses, infection biology and the toxicity of candidate treatments. They also offer a preliminary platform for examining plant-derived substances that may have potential applications in fish health management. For example, researchers could screen a candidate herbal extract for toxicity and selected biological effects before evaluating it in a relevant aquaculture species. Such an approach may help identify unsuitable concentrations and guide the design of subsequent experiments. Nevertheless, preliminary activity in zebrafish does not establish that a substance will be effective against fish pathogens or safe for cultured fish.

Target species may differ in drug absorption, metabolism, susceptibility to infection and physiological responses. Consequently, promising findings should be followed by appropriate laboratory validation, efficacy studies, residue assessment where relevant and evaluation of environmental safety. Zebrafish should be considered a complementary model for preliminary screening and mechanistic research rather than a complete substitute for studies in commercially important fish species.

8. Standardisation and responsible experimental practice

Reproducible results are essential for reliable toxicological research. Differences in water quality, temperature, exposure duration, developmental stage, chemical concentration and experimental procedures can influence outcomes. Appropriate controls and clearly defined endpoints are therefore necessary. The Organisation for Economic Co-operation and Development provides a standardised Fish Embryo Acute Toxicity test under Test Guideline 236. The method uses newly fertilised zebrafish eggs exposed to a test chemical for 96 hours, with defined observations of lethality (OECD, 2025).

Such guidelines support consistency in chemical testing and improve the comparability of results. Researchers must also consider animal welfare, institutional ethical requirements and the suitability of the selected method for the chemical and research question. Standardised exposure procedures, validated analytical methods and transparent reporting can improve the quality of zebrafish studies and strengthen their usefulness in environmental safety assessment.

9. Future perspectives: Integrating Advanced Technologies

Technological developments are expanding the potential of zebrafish research. Automated imaging and behavioural tracking allow researchers to measure selected responses more efficiently, while genetic and molecular methods help identify pathways affected by chemical exposure. Transcriptomics, proteomics and metabolomics can reveal changes in gene expression, proteins and metabolites. When these data are combined with conventional toxicological endpoints, researchers can investigate complex biological responses in greater detail.

Recent reviews emphasise the growing importance of zebrafish in integrating drug discovery, chemical safety assessment and mechanistic toxicology (Parthasarathy et al., 2025; Zhao et al., 2024). Future work may focus on mixtures of contaminants, chronic and multigenerational exposure, pharmaceutical residues, environmental microplastics and candidate treatments for fish health applications. Another important direction is the integration of laboratory studies with environmental monitoring and validation in locally relevant fish species. This is particularly valuable for fisheries research, where the ultimate objective is to generate findings that can

inform aquatic ecosystem protection and sustainable aquaculture. Combining advanced molecular technologies with carefully designed whole-organism experiments may improve the predictive value of zebrafish research and help translate laboratory findings into practical fisheries applications.

Conclusion

The zebrafish (*Danio rerio*) has become a valuable model organism in modern pharmacology, toxicology and environmental research. Its rapid development, reproductive capacity, genetic tractability and suitability for screening make it useful for investigating drug activity, chemical toxicity and biological mechanisms. In fisheries pharmacology and toxicology, zebrafish can support preliminary drug screening, the assessment of pharmaceutical residues, the investigation of pesticides and heavy metals and the study of oxidative stress and other molecular responses. They can also contribute to research on candidate treatments and the biological effects of emerging contaminants.

Despite these advantages, species-specific differences, exposure conditions and limitations in translating experimental findings must be carefully considered. Combining zebrafish studies with standardised testing methods, environmental monitoring and validation in relevant aquaculture species can improve the reliability and practical value of research. Ultimately, zebrafish offer a promising scientific platform for advancing drug safety, understanding aquatic pollution and supporting evidence-based fish health management. Their continued development as a complementary research model may contribute to more responsible chemical use, healthier aquatic ecosystems and sustainable aquaculture.

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Beyond the Screen: The Erosion of Physical Third Places and the Rise of Hyper-Curated Isolation among Young Adults

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Introduction

Contemporary young adulthood is defined by a profound sociological paradox: while members of Generation Z and younger cohorts enjoy unprecedented levels of digital connectivity, they simultaneously report staggering rates of chronic loneliness and social isolation. Historically, human development during emerging adulthood has relied heavily on shared physical environments-institutions, neighborhoods and informal gathering spaces-that facilitate casual interaction, identity exploration and the formation of social capital. However, structural shifts in urban planning, the intense commercialization of public life and the post-pandemic acceleration of digital substitution have drastically transformed the social landscape.

This article investigates the intersecting crises of the erosion of physical "third places" and the rise of "hyper-curated isolation" among young adults. By examining how the loss of accessible, non-commercial public spaces forces socialization into digital silos, this paper explores the psychological, developmental and social implications of a society retreating behind screens.

The Architecture of Community: Ray Oldenburg's Third Places and Their Decline

In sociological literature, sociologist Ray Oldenburg famously conceptualized "third places"-environments distinct from the domestic home ("first place") and the workplace or educational institution ("second place")-as essential anchors of community life. These include cafes, bookstores, community centers, public libraries, parks and neighborhood barbershops. According to Oldenburg's framework, third places function as neutral grounds where individuals can gather freely, engage in regular conversation, encounter diverse perspectives and cultivate "weak ties"-casual, low-stakes acquaintanceships that provide a sense of belonging and emotional resilience.

For young adults navigating the precarious transitions of higher education, early career entry and financial autonomy, third places historically provided vital developmental support. They offered accessible arenas to practice social roles, manage stress and experience spontaneous joy outside the pressures of structured environments.

However, these physical spaces have faced severe systemic degradation. Urban gentrification, soaring real estate costs and the aggressive commercialization of urban environments have transformed traditional gathering spots into exclusive "pay-to-play" venues. When a simple visit to a local coffee shop or cafe requires purchasing an expensive beverage, financially constrained young adults are effectively priced out, reducing socioeconomic diversity in public interaction. Furthermore, hostile architecture, reductions in public seating and the permanent closure of community-centric businesses in the wake of public health disruptions have left neighborhoods quiet and desolate.

Recent scoping literature emphasizes that the disappearance of physical third places disproportionately harms vulnerable and precarious populations, stripping away the everyday social scaffolding necessary to maintain mental well-being and collective resilience (Laliberte Rudman et al., 2023). Without local, welcoming spaces within walking distance, young people find themselves isolated in domestic isolation, eroding the foundational fabric of neighborhood trust.

The Paradox of Digital Socialization and "Hyper-Curated Isolation"

As physical gathering spaces contract, young adults have increasingly turned to digital platforms-such as video games, Discord servers, Reddit communities and social media applications-to fulfill their social needs. These virtual environments are frequently conceptualized as "digital third places". While digital platforms offer unmatched convenience and overcome geographical barriers, research demonstrates that they fundamentally alter the nature of human association.

Empirical investigations into youth loneliness and digital media reveal a deeply ambivalent dynamic (Käcko et al., 2024). On one hand, young adults utilize online communities as intentional sanctuaries or supportive networks to find peers with niche interests. On the other hand, heavy reliance on hyper-curated digital environments frequently induces a phenomenon known as "hyper-curated isolation".

Unlike physical third places, which encourage unexpected encounters with diverse strangers, digital algorithms are engineered to reinforce echo chambers, ideological polarization and selective exposure to like-minded peers. Moreover, social media platforms often encourage the projection of idealized, flawless personas, creating an environment of intense social comparison. Rather than alleviating distress, passive digital consumption frequently heightens feelings of inadequacy, emotional exhaustion and chronic loneliness (Shah & Househ, 2023).

Young adults navigating this digital shift report that online interactions can lack the neurobiological benefits of physical presence-such as co-regulation, spontaneous laughter and tactile reassurance-that trigger oxytocin release and alleviate stress. Consequently, hyper-connectivity often exacerbates social friction, making face-to-face communication feel increasingly high-stakes and anxiety-inducing.

Developmental Consequences and the Vicious Cycle of Loneliness

The convergence of disappearing physical spaces and isolating digital structures carries profound developmental consequences for emerging adults. Emerging adulthood is characterized by the normative imperative to detach from parental attachments, establish personal autonomy and construct durable social support systems (Shah & Househ, 2023).

When young adults lack access to neutral, forgiving third places where they can experiment with social identities and build confidence, chronic loneliness can take root. Clinical and psychological literature establishes that chronic loneliness functions as a trans diagnostic risk factor, exhibiting bidirectional relationships with anxiety, depression and poor mental health days.

Cacioppo and Hawkley's cognitive-evolutionary model of loneliness highlights how perceived social isolation triggers cognitive hyper vigilance, where individuals become hypersensitive to social threats and anticipate rejection. This defensive posture often leads to behavioral withdrawal, creating a self-reinforcing loop: loneliness fuels anxiety and social avoidance, which in turn deters future engagement, deepening the individual's isolation. For young people transitioning into higher education or unstable modern labor markets, these compounded isolation loops severely impair academic persistence, professional networking and long-term emotional well-being.

Reimagining Community: Towards Hybrid and Accessible Third Spaces

Addressing the crisis of modern youth isolation requires deliberate systemic intervention rather than platitudes urging young adults to "disconnect" from their screens. Urban planners, policymakers, and community leaders must actively invest in the revitalization and creation of inclusive public spaces.

Strategies such as tactical urbanism-low-cost, flexible, and community-driven approaches to transforming underutilized public areas-offer promising avenues to restore pedestrian-friendly gathering spots. Expanding public libraries, community gardens, municipal parks and subsidized arts centers ensures that young people have access to welcoming environments that do not require commercial consumption.

Concurrently, digital designers and platform architects must rethink the structural incentives of online spaces, designing virtual environments that encourage collaborative, low-pressure and community-supportive interactions rather than passive, algorithmic consumption. Bridging the physical-digital divide by fostering hybrid third places can provide young adults with the psychological safety of digital entry points while intentionally scaffolding pathways toward meaningful, in-person connection.

Conclusion

The erosion of physical third places and the rise of hyper-curated digital isolation represent defining social crises of our era, disproportionately impacting young adults striving to establish autonomy and connection. As public squares give way to commercialized environments and physical interactions are increasingly mediated by algorithms, the social fabric of society frays. Reversing this trend necessitates a renewed cultural and infrastructural commitment to shared spaces-both physical and virtual-that prioritize equity, chance and human

belonging. Only by actively rebuilding the architecture of community can society hope to heal the pervasive loneliness epidemic facing the upcoming generation.

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Insects as Sustainable Feed Ingredients in Poultry Nutrition: Opportunities, Bioactive Benefits, and Future Challenges

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Abstract

The rapid global expansion of the poultry industry has intensified the demand for nutritionally high-quality and sustainable feed protein sources, reducing reliance on conventional ingredients like soybean meal and fishmeal. Insect meals—derived from species such as Black Soldier Fly Larvae (Hermetia illucens), Yellow Mealworms (Tenebrio molitor), House Crickets (Acheta domesticus), and Silkworm Pupae (Bombyx mori)—have emerged as viable, nutrient-dense options. Beyond providing essential amino acids and energy-dense lipids, insect meals contain powerful functional bioactive components including chitin, antimicrobial peptides, and lauric acid. These elements actively promote gut health, strengthen immune function, and maintain growth performance, egg production, and carcass traits in poultry. This popular article synthesizes current key insights regarding nutritional composition, functional physiological effects, field performance, and technical or regulatory challenges limiting large-scale commercial adoption.

Introduction

The rapid expansion of global poultry production continues to drive an unprecedented demand for nutritionally efficient and economically reliable feed ingredients (Veldkamp et al., 2012). Protein is one of the most vital and costly components of poultry diets, playing a crucial role in broiler growth rate, feed conversion efficiency, layer egg yield, and overall farm profitability. Currently, commercial poultry diets depend heavily on soybean meal and fishmeal as primary protein benchmarks (Belhadj Slimen et al., 2023). However, continued heavy reliance on these conventional feedstuffs raises critical environmental concerns, including deforestation, biodiversity loss, volatile market pricing, and direct competition with human food supplies (de Souza-Vilela et al., 2019; Khalifah et al., 2023).

To foster a sustainable and resilient poultry sector, animal nutritionists are actively evaluating alternative, high-protein feed resources. Among candidate novel ingredients, edible insects have emerged as exceptionally promising candidates (Moore, 2018; Sogari et al., 2019). Feeding insects to poultry aligns seamlessly with natural avian foraging behavior, as birds naturally consume wild insects under free-range and scavenging conditions (Schiavone and Castillo, 2023). Beyond their high nutrient density—comprising exceptional protein, balanced lipid profiles, essential vitamins, and key minerals—insects possess potent functional bioactive components that actively enhance gastrointestinal health and metabolic resilience (Finke, 2015; Shah et al., 2022).

Nutritional Value and Bioactive Properties

Insect meals are not uniform single ingredients; rather, they represent a diverse category of nutrients whose composition varies based on species, life stage, rearing media substrate, and processing methodology (Hawkey et al., 2021; García-Vaquero and Álvarez García, 2024). The principal insect species routinely evaluated in poultry nutrition include Black Soldier Fly Larvae (Hermetia illucens), Yellow Mealworms (Tenebrio molitor), House Crickets (Acheta domesticus), and Silkworm Pupae (Bombyx mori) (Hong et al., 2020; Lu et al., 2022; Dukare Pradip et al., 2024).

In terms of macronutrient profile, insect meals typically contain 40% to 70% crude protein on a dry matter basis, featuring favorable essential amino acid profiles rich in lysine, methionine, threonine, and valine that compare favorably with soybean meal and approach fishmeal standards (Özek, 2016; Shah et al., 2022). Furthermore, their lipid fraction (10–40%) provides energy alongside key functional fatty acids. Notably, Black

Soldier Fly Larvae oil is exceptionally rich in lauric acid (C12:0), a medium-chain fatty acid renowned for its strong antimicrobial efficacy against Gram-positive pathogenic gut bacteria (Benzertiha et al., 2020).

In addition to basic nutrients, insects synthesize functional bioactive molecules that confer distinct health benefits:

- **Chitin:** A structural polysaccharide forming the insect exoskeleton. While high concentrations can lower fiber digestibility, moderate dietary levels (under 5%) act as effective prebiotics, nourishing beneficial gut microflora and exerting immunomodulatory effects (Koutsos et al., 2019; Abenaim and Conti, 2025).
- **Antimicrobial Peptides (AMPs):** Endogenous defense peptides such as defensins, cecropins, and attacins that help suppress pathogenic enteric bacteria and bolster intestinal barrier defense (Belhadj Slimen et al., 2023).
- **Bioactive Lipids & Minerals:** Lauric acid alongside valuable trace minerals (calcium, phosphorus, zinc, iron) and B-complex vitamins that support physiological metabolic health (Finke, 2015; Christaki et al., 2022).

Impact on Poultry Growth, Production, and Quality

Extensive empirical trials across broilers, layers, and quail demonstrate that insect meals can partially replace soybean meal or fishmeal without compromising productive performance, provided diets are balanced on a digestible amino acid basis (Gasco et al., 2019; Sajid et al., 2023).

In broiler production, inclusion of defatted or full-fat insect meals at 5% to 15% maintains or significantly enhances live body weight gain and improves Feed Conversion Ratio (FCR) (Khalifah et al., 2023; Lee et al., 2024). Studies evaluating replacement levels up to 12% reported improved intestinal histomorphology, specifically increasing duodenal and ileal villus height and villus height-to-crypt depth ratio, which enhances overall nutrient absorption capacity (Vasilopoulos et al., 2024; Sajjad et al., 2024a).

In laying hens, insect meal inclusion up to 10–15% preserves egg production percentages and egg mass while frequently enriching yolk color intensity due to natural carotenoid pigments (Dalle Zotte et al., 2019; Kaddour et al., 2025). Regarding meat quality, moderate insect inclusion maintains core sensory parameters (flavor, tenderness, juice retention) and elevates meat protein concentration, though very high inclusion rates (above 20%) may alter muscle fatty acid profiles by increasing saturated fatty acid ratios if full-fat larvae are used (Daszkiewicz et al., 2022; Malematja et al., 2024).

Practical Challenges and Future Perspectives

Despite the clear nutritional and functional potential of insect ingredients, several operational, technical, and regulatory hurdles must be addressed prior to widespread commercial integration into global poultry feed supply chains:

- **Production Scale and Economic Feasibility:** Current insect biomass production costs remain higher than traditional soybean meal. Establishing large-scale automated rearing facilities utilizing circular agricultural side-streams is vital to reduce unit prices (Veldkamp et al., 2012; Mlambo et al., 2023).
- **Regulatory Frameworks & Safety Assurance:** Legislation governing approved insect species, substrate safety (avoiding heavy metals, mycotoxins, and pathogens), and processing hygiene standards varies globally and requires harmonized safety benchmarks (Józefiak et al., 2016; Kolobe et al., 2023).
- **Standardization & Quality Control:** Nutritional composition fluctuates depending on rearing substrate and processing methods (full-fat vs. defatted). Standardizing processing treatments is essential for feed compounders requiring stable ingredient specifications (Hawkey et al., 2021; Spranghers et al., 2025).

Conclusion

Insect-derived feed ingredients represent a highly viable, sustainable, and functional alternative to conventional dietary protein sources in poultry feeding. Their unique combination of high-quality amino acid profiles, bioactive lipids, chitin, and antimicrobial peptides supports efficient growth performance, enhances gut health, and bolsters immune resilience. As industrial mass-rearing technologies advance, regulatory frameworks align, and production costs decline, insects are poised to become a core component of sustainable circular bioeconomy strategies for global poultry nutrition.

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Sweetening the Rural Economy: How Beekeeping is Catalyzing Farmers' Income in India

An Analysis of Ecological Synergy, Income Diversification, and Institutional Frameworks

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Introduction: The Rural Economic Challenge

Indian agriculture has long struggled with fragmented landholdings, vulnerability to seasonal climate shifts, and fluctuating crop prices. For millions of smallholders and marginal farmers, relying solely on traditional field crops creates financial instability [3]. In response, national agricultural policy has shifted toward diversifying farm revenue and transforming agriculture into a multi-tiered economic ecosystem. Within this strategic pivot, apiculture—or scientific beekeeping—has emerged as a powerful engine for generating secondary income. At the intersection of agriculture, ecology, and small-scale entrepreneurship, beekeeping offers rural households a sustainable pathway to financial security without competing for arable land [2, 3].

Direct Economic Returns: Beyond Just Honey

The primary financial benefit of apiculture comes from harvested honey, but a managed beehive's full commercial value extends to high-value secondary products. While standard natural honey provides a reliable cash flow, hive co-products such as beeswax, propolis, royal jelly, bee pollen, and bee venom carry significantly higher profit margins. Beeswax, highly sought after across the pharmaceutical, cosmetic, and dental industries, fetches roughly twice the market value of crude honey. Similarly, bee pollen is marketed internationally as a nutrient-dense superfood, while bee venom commands premium rates in medical and therapeutic markets [2, 3].

Field operations data show a strong positive correlation between colony scale and farm net revenue. Small-scale apiaries with up to 50 hives yield an average annual income of ₹54,620. As operations scale to mid-sized setups of 151–200 hives, annual earnings rise to about ₹3,20,000, reaching over ₹7,68,800 for commercial apiaries managing over 400 hives (Figure 1). Because beekeeping requires low initial capital, minimal land, and flexible working hours, it integrates seamlessly with routine farm operations [2, 3].

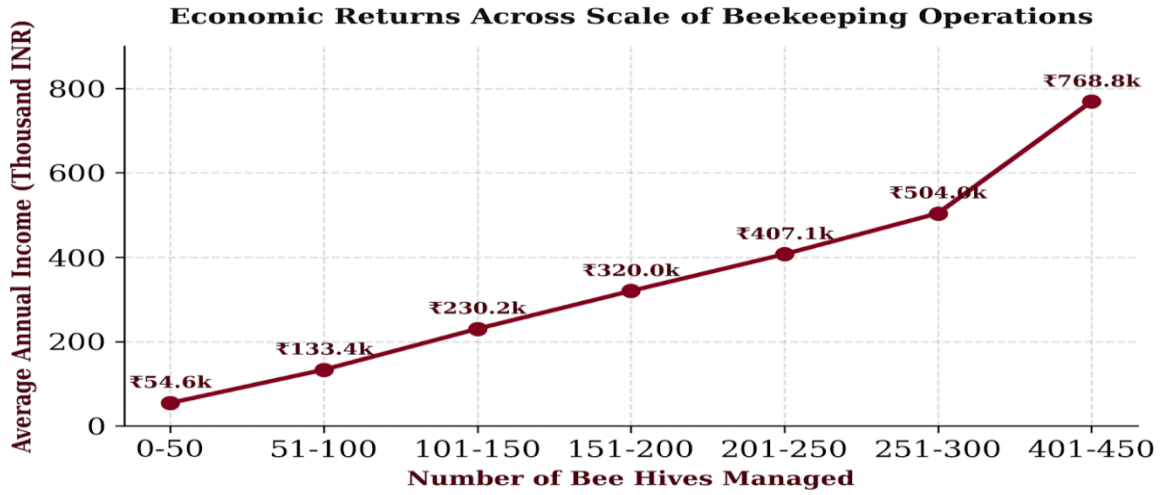


Figure 1: Scaling Effect of Managed Bee Hives on Annual Farmer Income [3]

The Invisible Multiplier: Pollination Efficiency and Crop Yields

While direct sales of hive products provide immediate secondary revenue, the indirect ecological benefits of bee pollination often yield greater long-term economic value. Honeybees are essential natural pollinators for major

horticultural and agricultural crops, including mustard, oilseeds, pulses, fruits, and vegetables. Field trials indicate that managed honeybee pollination increases crop yields by 10% to 80% while improving fruit set, seed weight, and visual quality of produce [2, 3].

This cross-pollination mechanism transforms the economic dynamic for rural farmers. Rather than treating apiculture as an isolated sideline, progressive growers use beehives as a zero-cost yield booster for primary field crops. The resulting combination—higher crop production paired with steady honey harvests—creates a double economic multiplier that directly accelerates farm income growth [2, 3].

Policy Momentum and Institutional Drivers

The institutional framework supporting apiculture in India has expanded rapidly through government-led growth initiatives. In line with the 'Sweet Revolution' (Sweet Kranti) vision, the Ministry of Agriculture and Farmers Welfare established the National Beekeeping & Honey Mission (NBHM) as a central sector scheme managed by the National Bee Board (NBB) [1, 2, 3]. Backed by structured financial assistance under Atmanirbhar Bharat, NBHM focuses on three mini-missions: driving field productivity, building post-harvest infrastructure, and advancing regional research [2].

Institutional investments have driven measurable national growth. India's total honey production rose from 80,530 metric tons in 2014-15 to an estimated 1,51,690 metric tons in 2025-26 (Figure 2) [1, 2, 3]. In addition, infrastructure development has established world-class honey-testing laboratories, processing facilities, and quality queen bee breeding centers nationwide. The launch of the Madhukranti digital portal has further improved supply chain transparency and traceability, enabling smallholder farmers to access premium export markets in the United States, Europe, and the Middle East [2, 3].

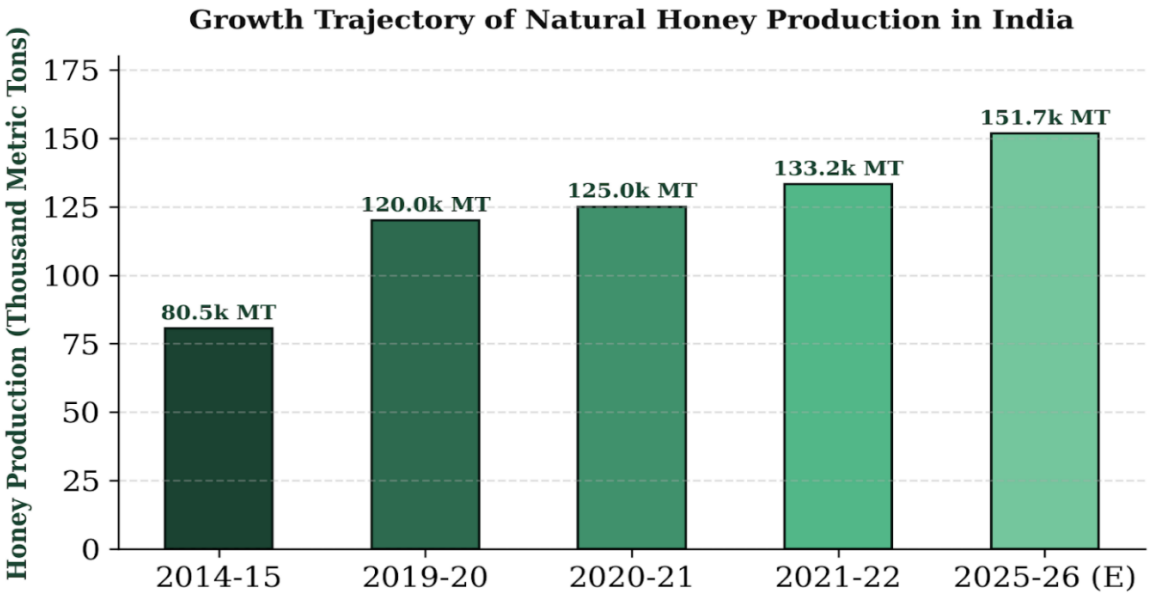


Figure 2: Expansion of Natural Honey Production in India (2014-15 to 2025-26) [1, 2, 3]

Challenges and the Road Ahead

Despite clear gains, apiculture in India faces structural challenges that require ongoing intervention. Key operational hurdles include indiscriminate pesticide use in field crops, seasonal floral scarcity, unorganized local supply chains, and pest or disease infestations, such as Varroa mites and viral infections. Additionally, while India currently maintains around 3.4 million managed bee colonies, national ecological capacity estimates indicate that the country could support up to 200 million colonies [2, 3].

Realizing this full potential requires expanding farmer producer organizations (FPOs), strengthening migratory beekeeping routes, and deploying modern predictive technologies, such as IoT-enabled hive monitors. Closing these technical gaps will help apiculture continue to drive rural economic resilience and income growth across India [2, 3].

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RURAL WOMEN: BRINGING LIFE TO LAND
International Day of Rural Women: Oct.15

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Today is a very important day, a day dedicated to rural women who bring life to land and bring hope for their peoples. According to United Nations, Oct. 15 every year is reserved for rural women to recognize and duly acknowledge the critical role and contribution of rural women, including indigenous women in enhancing agricultural and rural development, improving food security and eradicating rural poverty. Rural women and girls are leaders in agriculture, food security and nutrition, land, managing natural resource management and unpaid and domestic care work. They are at the frontline at a time when natural resources and agriculture are threatened. Their contribution to the agriculture sector is immense. In fact, globally, one in three employed women works in agriculture. From agriculture to food security, nutrition, land and natural resource management, domestic care and work, rural women are at the forefront and are taking charge by being in the driver's seat. Women are responsible for half of the world's food production while working as environmental and biodiversity stewards. Women also collect biomass fuels, manually process food materials, and pump water; eighty percent of households without piped water rely on women and girls for water collection.

Yet, the hard fact is that rural women are laboring under acutely disadvantageous conditions. Even so, women and girls in rural areas suffer disproportionately from multi-dimensional poverty. They may be as productive and enterprising as their male counterparts but are less able to access land, credit, agricultural inputs, markets, and high value agri-food chains and obtain lower prices for their crops. Already insufficient infrastructure and services in rural areas have been stretched to the limit; rural women's invaluable care and productive work during the pandemic and aftermath of it has burgeoned, in many places without clean and safe water, sanitation and hygiene, energy supply or healthcare services. This pandemic has also heightened the vulnerability of rural women's rights to land and resources.

Despite so much of contribution to the agriculture sector, women farmers' typically achieve yields 20-30% less than men due to unequal access to productive resources and services. Studies reveal that closing this gender gap could reduce the number of malnourished people by 12-17%. Gender inequity plays a special role within agriculture as women are often pivotal to ensure household food security. Yet, they are often not given access to resources and have little decision-making power. In order to give them a voice, to raise awareness of rural women's participation in the development process with a focus on their needs and rights, highlighting their contributions to sustainable development, household food security, safeguarding traditional knowledge, biodiversity, and peace building and so much more, a day has been dedicated to these invisible partners of growth. The International Day for Rural Women celebrated every year on Oct. 15 serves a platform for all these activities.

History of the Day:

The International Day of Rural Women was created in 1995 by civil society organizations at the Fourth World Conference on Women in Beijing and was declared an official UN Day in 2007 by the UN General Assembly vide its resolution 62/136 of December 18, 2007 to recognize the critical role and contribution of rural women including indigenous women in enhancing agricultural and rural development, improving food security and eradicating rural poverty. On the International Day of Rural Women, UN Women calls for action to support rural women and girls and grow their capacities to respond to climate change through agricultural production, food security, and natural resources management. Mobilizing relevant Non Government Organizations and grassroots women's groups, organizations, networks and international institutions, as well as the media, to commemorate the Day and celebrate Rural Women Leaders and their communities around the world.

Theme for the International Day of Rural Women 2026:

This year the international Day is being celebrated with the theme "The Rise of Rural Women: Building Resilient Futures with Beijing+30". The theme is promoted by UN Women. The Beijing+30 focus on eradicating poverty, achieving climate justice, and ensuring sustainable development for all women and girls. The focus of the day will be

on raising awareness of inequalities between men and women, the persistent gaps in rural and urban settings between the two sexes, greater recognition and active participation of rural women in community decision-making processes, stronger social protection systems to safeguard livelihoods and well-being, working to bridge the digital divide that limits access to modern tools and resources.

The theme also highlights the role and necessity of empowering rural women to enable them to contribute economically as well as socially to have an overall global impact. Empowering this populace has the potential to boost global GDP, improve food security and lead to more sustainable and resilient communities. Conversely, the unequal access to resources and opportunities widen the gender gap, leads to disempowerment of the fairer sex ultimately affecting the GDP of countries. Various research studies have revealed that closing the gender gap in farm productivity and food system employment could increase global GDP by nearly $ 1 trillion. If the women had same access to resources as men, global farm yields could increase by 20-30% potentially feeding an additional 100 to 150 million peoples. Similarly projects targeting women have shown significant improvements in incomes and household diets. Besides empowering rural women increases their decision making power within their households and communities. It is a direct path to gender equality and is essential for eradicating poverty.

Rural women have suffered a lot particularly in the aftermath of COVID-19. Moreover climate change also has adverse effects more on the women than men. Building rural women's resilience in the aftermath of COVID-19', also calls for strengthening rural women's sustainable livelihoods and wellbeing. Women have been at the front lines of responding to the pandemic even as their unpaid care and domestic work increased under lockdowns, mobility restricted, supply chains disrupted, and climate and conflict crises compound COVID-19 impacts. In India, rural women can be mobilized by organizing them in self-help groups can be linked to banks which can provide credit facilities. With the finance available from the Banks, the rural women can set up their own income generating units. Government has started so many skill development programmes for rural women including farm women. After updating their skills and getting proper training, they can establish their own business units and provide employment to many others also. Many young girls with rural background have already proved themselves in various fields. Even in agriculture and allied sectors there are 50 different type of activities where interested women can start their units.

The progress towards achieving gender equality and empowerment of women has been slow. Discriminatory gender norms and practices impede women's exercise of land and property rights in most countries. Since women's land rights are often dependent on their husbands, COVID-19 widows risk disinheritance. Women's land tenure security is also threatened as unemployed migrants return to rural communities, increasing pressure on land and resources and exacerbating gender gaps in agriculture and food security. There is an urgent need for gender-responsive investments to expand basic infrastructure, healthcare and care services in rural areas have never been more critical. Bolstering women's land rights in law and practice can help protect women from displacement and losing their sources of livelihood. This International Day of Rural Women is a key moment to galvanize action by all stakeholders to support rural women and girls to not only rebuild their lives, but increase their resilience to be better prepared to face future crises. The world needs to commit to gender equality while designing various developmental policies and programmes. Improving equity will allow both men and women to have a say in how resources are used. It will also help decision makers to guarantee policies, promote fair access to agriculture and natural resources. Gender, poverty, and institutions are therefore interlinked, and cannot be dealt with independently**.** We have to identify where, when and how rural women can gain equitable access to water, land and other natural resources. Our goal of sustainable agriculture rests on the premise that enhancing the decision-making power of women over natural resources can improve agriculture production, enable household food security and ensure long-term benefits.

The United Nations has also declared the year 2026 as International year of Farm Women highlighting the crucial role women play in ensuring food and nutritional security for all of us. A UN Women's report, *Beyond COVID-19: A feminist plan for sustainability and social justice,* calls for rebuilding the broken global food system from the bottom up by supporting rural women's livelihoods to produce and distribute diverse and healthy food crops. With less than 10 years to achieve the Sustainable Development Goals, including Zero Hunger (Goal 2) and Gender Equality (Goal 5); it is time to work collectively for a world where rural women enjoy equal access, rights and opportunities as the women and men in urban settings do. This will help build resilience, upgrade skills and develop leadership qualities in them. Achieving gender equality and empowering women is also critical component in the global efforts against extreme poverty, hunger and climate change.

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Poultry Farming: How Artificial Intelligence Can Improve Broiler Health and Productivity

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Abstract

Artificial intelligence (AI), machine learning (ML), sensors and computer vision are creating new opportunities for precision management in broiler farms. These tools can help farmers monitor feed and water intake, house temperature and humidity, bird weight, activity and possible signs of illness. Automated monitoring can identify changes earlier than occasional manual inspection and may support better resource use, flock welfare and farm profitability. Research reviewed in this article reports promising results from sound-based feed monitoring, ultrasonic water meters, camera-assisted weighing and vision-based lameness screening. However, performance depends on sensor placement, data quality, farm conditions, investment and correct interpretation of alerts. AI should support—not replace—good husbandry, veterinary supervision and biosecurity. This article describes practical applications and important considerations for adopting precision technologies in broiler production.

Keywords: Artificial intelligence; broiler farming; precision livestock farming; computer vision; sensors; animal welfare

Introduction

Broiler farming supplies an important source of animal protein, but producers must manage feed costs, water availability, indoor climate, disease risks and bird welfare at the same time. A leaking drinker, overheating or reduced feed intake may affect growth before it becomes obvious during routine inspection. Precision livestock farming uses sensors and digital tools to collect information continuously and help farmers respond to changes in a timely manner. Artificial intelligence (AI) and machine learning (ML) can analyse these data and identify patterns that may be difficult to detect by observation alone (Neethirajan et al., 2024; Taleb et al., 2024).

What do AI and precision poultry farming mean?

Precision poultry farming combines sensors, cameras, microphones, weighing devices and software to monitor conditions inside the poultry house. Sensors collect information such as temperature, humidity, water flow and feed delivery, while cameras and microphones can provide information about bird movement, body size, feeding activity and sounds. AI systems analyse these inputs and may generate alerts when patterns differ from expected conditions. The goal is not simply to install equipment; it is to turn reliable information into practical decisions that improve flock management and welfare.

Monitoring feed and water intake

Feed and water consumption are useful indicators of flock performance. Automated feeders, feed-level sensors and weighing units can help track feed delivery and disappearance. Researchers have demonstrated that microphones placed near feeders can identify pecking sounds and estimate feed intake. One sound-based method detected pecking with 93% accuracy, while a group-level system reported a strong correlation ($R^2 = 0.994$) between sound-derived estimates and scale measurements (Aydin et al., 2014, 2015). Background noise, equipment placement and differences between poultry houses can affect performance.

Water monitoring is equally important because changes in consumption may signal leakage, drinker malfunction, lighting problems or changes in bird health. Ultrasonic water meters connected to house controllers can record water use continuously. A field example reviewed by Engelbrecht et al. (2026) described drinker leakage being detected within 24 hours of chick placement. Farmers can use these records alongside direct

inspection to check whether water reaches all areas and whether consumption changes are consistent with bird age and environmental conditions (Yao et al., 2021).

Managing temperature, humidity, air and lighting

Broilers are sensitive to their surroundings, especially temperature, humidity, airflow and air quality. Excessive heat can reduce feed intake and growth and increase stress, while poor ventilation and wet litter can contribute to ammonia accumulation and health problems. Sensor-based monitoring can track these variables throughout the day. Automated controllers may use readings to regulate fans, heating and other equipment, but settings must suit bird age, stocking conditions and the poultry-house design (Corkery et al., 2013; El-Rahman et al., 2017).

Lighting also affects bird behaviour and performance. Research has examined light intensity, colour and daily lighting programmes. LED systems can offer energy savings and flexible control, but lighting changes should be introduced with attention to bird response and welfare rather than relying on one setting for every flock (Deep et al., 2010; Riber, 2015). AI can bring environmental readings together, identify recurring patterns and help managers review whether house conditions are stable.

Automatic weighing and activity monitoring

Bird weight and flock uniformity are important for assessing growth and planning management. Manual weighing takes time, and handling may disturb birds. Automated platform scales and camera-based systems can collect more frequent measurements with less direct handling. A computer-vision study using 3D depth images explored weight prediction in a commercial setting, while a later system estimated broiler weight from video features (Mortensen et al., 2016; Campbell et al., 2025). These technologies have limitations: birds may overlap, move during measurement or crowd around the weighing area, so estimates should be checked against representative physical measurements.

Cameras can also analyse walking, movement and use of resources such as feeders and drinkers. In one vision-based lameness study, gait-related measures—including step frequency, stride length and speed—were associated with gait scores (Aydin, 2017). Tracking flock activity over time may flag unusual changes that deserve inspection. Such alerts are screening aids, not a veterinary diagnosis, and must be interpreted alongside clinical signs and farm records (Campbell et al., 2023; Okinda et al., 2020).

Early warning of health problems

Changes in movement, vocalisation, body weight, feed and water intake, or droppings may provide early clues that something is wrong. Computer-vision models have been developed to classify broiler droppings and detect abnormal patterns, while sound analysis has been investigated for monitoring bird activity and equipment sounds (Wang et al., 2019; Yang et al., 2021; Nakrosis et al., 2023). Combining several data streams may improve the usefulness of alerts, but models need testing under different flock sizes, breeds, lighting conditions and commercial house layouts. Farmers should investigate alerts promptly and consult a veterinarian when disease is suspected.

Biosecurity remains essential

Digital monitoring cannot replace basic biosecurity. Restricted access, clean clothing and footwear, hand hygiene, cleaning and disinfection, pest control, safe feed and water, and careful management of incoming chicks remain central to disease prevention. Sensors and automated records may help document house conditions and identify unusual events, but they do not prevent pathogen entry by themselves. Biosecurity plans should be adapted to the farm and followed consistently by workers and visitors (Tanquilut et al., 2020; Benameur et al., 2023).

Benefits, limitations and practical adoption

Potential benefits of precision poultry farming include earlier recognition of management problems, more consistent environmental control, reduced routine labour, better tracking of flock performance and improved opportunities for welfare assessment. However, equipment and maintenance can be expensive, internet connectivity may be unreliable in some locations, and the usefulness of AI depends on good-quality data. Systems developed in one research setting may not perform equally well in every commercial house. Farmers should consider starting with a clear problem—such as water leakage or temperature variation—rather than purchasing many technologies at once.

Before adopting a system, compare its cost with the expected practical benefit, check whether it can operate reliably in local conditions, and ensure that staff can understand its alerts. Calibrate sensors, maintain equipment and record how alerts are resolved. Data privacy, vendor support and compatibility with existing controllers also deserve attention. AI works best when it strengthens sound management and trained human judgement rather than replacing either.

Conclusion

Artificial intelligence and precision monitoring offer useful tools for making broiler farming more responsive, efficient and welfare-focused. Feed and water monitoring, environmental sensors, automated weighing, activity tracking and image-based health screening can help farmers detect changes earlier and make decisions using evidence from the poultry house. Nevertheless, results depend on reliable equipment, local validation, appropriate interpretation and good husbandry. A gradual, problem-focused approach—combined with veterinary advice, staff training and strict biosecurity—can help poultry producers assess whether these technologies are suitable for their farms.

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Don't Throw That Banana Leaf: Turning Farm Waste into Value

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Abstract

Banana leaves are often discarded or burnt after harvest, although they are valued for serving food, wrapping and cooking. Their main limitation is perishability, as untreated leaves remain usable for only four to five days. Postharvest studies on cv. Chakkai Peyan showed that dips in ascorbic acid and citric acid, followed by cold storage at about 5 °C, extended shelf life to more than sixteen days, with less weight loss and yellowing. This article describes the uses of banana leaf, practical handling tips for farmers, and value-added options such as fresh-cut leaves, leaf plates, packaging, compost and extracts. These options turn farm waste into income while reducing plastic use and pollution.

Keywords: Banana leaf, postharvest, shelf life, agricultural waste, value addition

1. Introduction

Walk through any banana-growing village in Tamil Nadu after a harvest and you will see a familiar scene: a heap of torn, yellowing or freshly cut leaves piled at the field edge, waiting to be dumped or burnt. To most growers, the banana leaf is simply a by-product, something that must be cleared before the next crop. Yet the same leaf, folded neatly on a dining table, is the plate on which millions of Indians eat their daily meals. The question worth asking is a simple one: if the leaf is valuable on the table, why is it treated as waste in the field?

India is the world's largest producer of bananas and every hectare of the crop produces a large quantity of leaf biomass throughout the crop cycle. Much of this material is left to rot, burnt in the open, or thrown into drains and roadsides, adding to pollution and wasting an opportunity. With growing concern over single-use plastics and rising demand for eco-friendly products, the banana leaf is ready for a second life, and farmers who understand this can add a new stream of income to their orchards.

2. Why the banana leaf is special

The banana leaf is a remarkable natural material. It is large, flexible and smooth, and its surface carries a thin waxy layer that repels water and keeps food from sticking. The leaf is naturally clean, light in weight, and costs almost nothing to produce, since it grows on the plant that the farmer is already managing for fruit. When hot food is placed on it, the leaf releases a mild, pleasant aroma that many people believe improves the taste of the meal.

The leaf also contains natural plant compounds, including polyphenols and other antioxidants, which are being studied for their antimicrobial and health-related properties. Unlike plastic, foil or thermocol, a banana leaf decomposes quickly after use and returns nutrients to the soil. It leaves no harmful residue, needs no factory to produce and can be used by the poorest household and the finest restaurant alike.

3. Traditional uses of the banana leaf

Banana leaves have been part of Indian life for centuries and their uses go well beyond serving meals.

- **Serving meals:** In South India, the meal served on a fresh leaf is part of weddings, temple feasts, festivals and everyday restaurant culture.
- **Cooking and wrapping:** Leaves are used to steam rice cakes, fish, sweets and traditional snacks, which take on a delicate flavour from the leaf. Street vendors use them to wrap hot food.
- **Ritual and decoration:** Leaves and whole plants are used to decorate entrances, stages and homes during ceremonies and festivals.
- **Thatching and shade:** In many rural areas, leaves have been used to cover temporary shelters and to protect produce from sun and rain.

- **Fodder:** Surplus leaves are sometimes fed to cattle and goats, particularly in areas where green fodder is scarce.

4. The problem: a leaf that does not last

If the banana leaf is so useful, why do farmers throw so much of it away? The main reason is that the freshly cut leaf is highly perishable. Once removed from the plant, it begins to lose water quickly. The thin leaf blade splits along the veins, the green colour turns yellow and then brown, the edges dry and curl, and within a few days the leaf is no longer fit for serving food. At normal room temperature, an untreated leaf may stay usable for only four to five days.

This short life makes it difficult to transport leaves to distant markets, to supply hotels and caterers regularly, or to hold stock until demand rises during festival and wedding seasons. As a result, growers who might otherwise sell leaves are forced to dump the surplus and prices swing sharply from one week to the next.

5. What research tells us

Researchers have therefore begun to look at the leaf as a postharvest crop in its own right, much like a fruit or a flower. At the Department of Fruit Science, Horticultural College and Research Institute, Coimbatore, our work on the popular cultivar Chakkai Peyan (Musa spp.) tested simple pre-storage dips and different storage conditions to see how long cut leaves could stay fresh. The leaves were dipped in solutions such as cold water, ascorbic acid and citric acid, which are safe, inexpensive and widely available. Some leaves were then kept at normal room temperature, and others were kept under cold storage at about 5 °C.

The results were encouraging. Untreated leaves kept at room temperature lasted only about four to five days. In contrast, leaves dipped in one per cent ascorbic acid, either alone with a growth regulator or together with one per cent citric acid and then stored under cold conditions stayed fresh and usable for well over two weeks and in the best treatments for more than sixteen days. Treated leaves lost less weight, held their green colour longer, remained supple and showed less yellowing and crinkling.

Ascorbic acid and citric acid are natural antioxidants. They slow down the browning reactions that spoil the leaf surface and help the tissue hold on to its colour and moisture. Cold storage slows down the leaf's own metabolism, so that water loss, chlorophyll breakdown and ageing all happen more slowly. Used together, the dip and the cold chain give a far longer shelf life than either could provide on its own. For the farmer, this means that leaves can be harvested, treated and stored for transport or for sale at a time when prices are favourable, rather than sold in a hurry or discarded.

6. From waste to wealth: value-added opportunities

A longer shelf life is only the first step. Once leaves can be kept fresh, many value-added routes open up.

- **Fresh-cut leaves for hotels and caterers:** Clean, uniformly cut and packed leaves fetch a better price than loose, untrimmed bundles. Hotels, caterers and temple kitchens need a regular supply throughout the year, which is hard to meet without good postharvest handling.
- **Ready-to-use leaf pieces:** Leaves cut to plate size, washed and packed in perforated food-grade bags can be sold in towns and cities where leaves are difficult to find fresh.
- **Pressed leaf plates, bowls and cups:** Dried and pressed banana leaves can be moulded into disposable tableware that is strong, leak-resistant and fully compostable. Small units run by self-help groups and farmer producer organisations can take up this work with modest machinery.
- **Natural food wrap and packaging:** In place of plastic sheets, banana leaf can be used to wrap and pack sweets, rice dishes and street foods, and even to line baskets for transporting vegetables.
- **Compost, mulch and biochar:** Leaves that are too damaged to sell can be chopped and composted, used as mulch around young plants to hold soil moisture, or converted into biochar to improve soil health.
- **Extracts and powders:** Leaf extracts and dried leaf powder, rich in plant antioxidants, are of growing interest as natural preservatives and as ingredients in eco-friendly products. This is a field where research and industry can work together.
- **Handicrafts and decorative items:** Dried leaves and leaf sheaths are used to make baskets, mats, bags and craft items by rural artisans, giving women and youth an additional livelihood.

7. Practical tips for farmers

Farmers who wish to start selling banana leaves can follow a few simple practices. First, protect the plant. The leaves are the food factory of the banana, and the bunch needs them to grow and fill properly. Remove only the leaves that are dry, diseased or surplus to the plant's needs, and do not strip the plant bare. Growers should keep the healthy, functional leaves on the plant until the bunch has developed, and harvest extra leaves mainly from plants that are past fruiting or from ratoon and sucker management.

Second, harvest at the right time and in the right way. Cut leaves in the cool hours of the morning, choosing fully opened, healthy, green leaves that are free from tears, spots and insect damage. Use a clean, sharp knife, and handle the leaves gently, since bruises and splits quickly turn brown. Remove the thick midrib if the buyer wants flat leaf sheets, and wipe or wash the leaf surface with clean water to remove dust.

Third, treat and cool the leaf as soon as possible. A quick dip in a safe, food-grade solution such as ascorbic acid or citric acid, followed by shade drying of the surface water, can help the leaf stay fresh. Store the leaves in a cool place and, wherever possible, under cold storage. Fourth, pack and transport with care. Stack the leaves loosely in clean crates or cartons lined with food-grade sheets, avoid crushing and crowding, and keep them out of direct sun. Finally, build market links. Contact hotels, caterers, temples, restaurants and local traders directly, and consider joining a farmer group so that larger and more regular quantities can be supplied.

8. Benefits for the environment and the community

The shift from waste to resource is not only about extra income. Every banana leaf that is sold, composted or turned into a plate is a leaf that is not burnt in the open or dumped into a water channel. Replacing even a small share of plastic and foam plates with banana leaf products reduces litter and pollution, and supports the move towards a circular economy, in which the output of one activity becomes the input of another. It also fits with the national push against single-use plastics and with the sustainable development goals on responsible consumption and production.

There is also a social side to this story. Leaf cutting, grading, packing and plate making are labour-friendly activities that can be taken up by rural women, youth and small groups with low investment. A banana farm that earns from fruit, leaf, fibre and compost is better protected from the ups and downs of fruit prices than a farm that depends on one product alone.

9. Conclusion

The banana leaf has served Indian kitchens for generations, and modern science is now showing how to make it last longer, travel farther and earn more. Simple treatments such as natural acid dips and cold storage, backed by careful harvesting and packing, can stretch the usable life of the leaf from a few days to more than two weeks. With good handling and market links, a material once burnt or dumped can become a regular income source, a clean alternative to plastic, and a valuable soil input. The next time you see a pile of banana leaves at the edge of a field, remember you are looking at a resource, not rubbish. The farmer who sees this first will have an advantage, and the environment will be better for it.

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The Invisible Hands of Indian Agriculture: Recognising Women as Farmers

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Abstract

Women play a vital role in Indian agriculture, contributing to crop production, seed conservation, livestock management and household food security. Despite their substantial involvement, their contributions often remain under recognised in official records, agricultural policies and public discourse. This article examines the contribution of women to Indian agriculture, the challenges they face in gaining recognition as farmers and the measures required to promote their empowerment. It highlights barriers such as unequal access to land, institutional credit, agricultural extension services, modern technologies, markets and decision-making opportunities. The article also discusses the role of media representation in shaping public perceptions of women farmers and emphasises the importance of recognising women as agricultural knowledge holders, innovators, entrepreneurs and decision-makers. The designation of 2026 as the International Year of the Women Farmer provides an important opportunity to address persistent gender inequalities and strengthen women's participation in agrifood systems. Measures such as improving access to productive resources, promoting financial inclusion, strengthening gender-responsive extension services, supporting collective institutions and increasing women's visibility in agricultural communication are essential. Recognising women as farmers requires moving beyond symbolic acknowledgement towards equal opportunities, institutional support and meaningful participation in agricultural development. Such efforts can contribute to improved rural livelihoods, gender equality, sustainable agricultural development and national food security.

Keywords: Women farmers, Indian agriculture, gender equality, agricultural empowerment, access to resources, agricultural extension, rural development, food security.

Introduction

In Indian agriculture, women had historically played a crucial role in food production, seed saving, livestock management, kitchen gardening and many other agricultural activities. However, their contribution had frequently gone unacknowledged in official documents, public debate and agricultural policymaking. It can be challenging to separate women's economic contributions from their unpaid domestic duties, as noted by Kaur (2004), especially in traditional agrarian countries where productive and household tasks commonly overlap.

In the past, men and women shared complementary roles in agriculture, with women making significant contributions to farming and resource management (Sah et al., 2022; Maurya, 2014). But engaging in agricultural operations doesn't have always corresponded to being acknowledged as independent farmers. The perception that farming is largely a male activity, social conventions, and unequal access to productive resources have all contributed to women's lack of visibility in agriculture.

Beyond social acceptance, this invisibility has ramifications. It can affect women's access to markets, support from the government, contemporary technologies, agricultural training, institutional loans and land. According to Ghosh (2015), regulatory gaps and larger patriarchal institutions that impact women's status in the agricultural economy are linked to their lack of acknowledgment in rural India.

The United Nations' nomination of 2026 as the International Year of the Woman Farmer offers a pertinent chance to reevaluate how women are acknowledged, assisted and represented in agrifood systems. The program draws attention to the structural obstacles that still limit women's possibilities as well as their invaluable contributions (FAO, 2025). Therefore, the question is not whether or not women contribute to Indian agriculture, but rather why their contributions frequently do not result in equal rights, resources, and recognition.

Women's Contribution: Beyond the Fields

Nearly every stage of agricultural production involves women. Women perform these tasks in addition to unpaid housekeeping and childcare duties in many rural families. Official statistics show the extent of women's involvement in Indian agriculture. Women made up 59.8% of all workers engaged in agricultural operations in 2025, according to data released by the Indian government in 2026 based on the Periodic Labor Force Survey (PLFS) (Government of India, 2026).

An additional viewpoint is offered by the Economic Survey 2024–2025. In 2023–2024, 64.4% of working women were employed in agriculture, up from 57.0% in 2017–18. During the same time period, the equivalent share of employed men decreased from 40.2% to 36.3% (Ministry of Finance, 2025). These numbers do not reflect the percentage of women who work in agriculture; rather, they show the distribution of employed men and women across industries. Together, these statistics demonstrate the importance of agriculture as a source of employment for women. However, a significant presence in the workforce does not automatically ensure ownership of land, recognition in official farmer records, control over farm income or participation in agricultural decision-making.

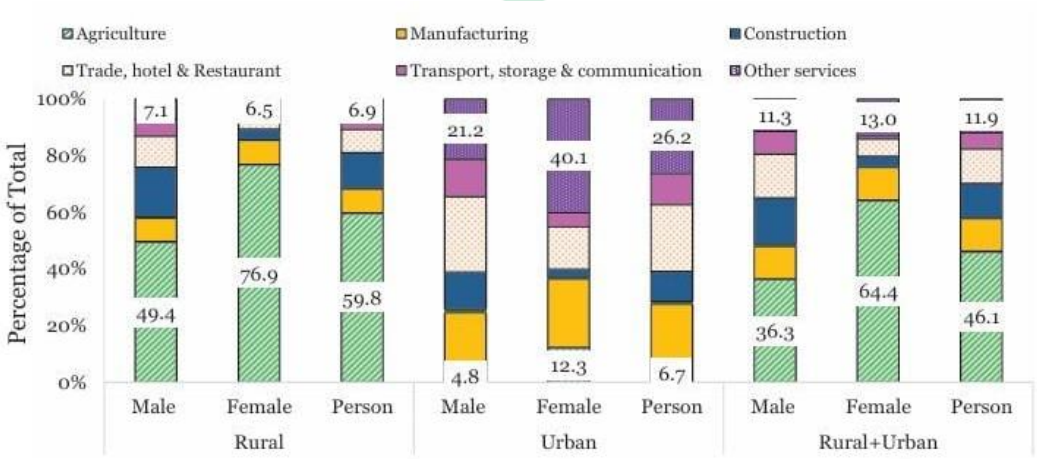


Figure 1. Distribution of employed women and men across broad industry divisions in India, 2017–18 and 2023–24.

Invisible in Recognition: The Challenges Women Farmers Face

Many women still encounter obstacles to being acknowledged as independent farmers, despite their significant contributions. Unequal access to land is one of the biggest problems. Women may find it difficult to get institutional financing, access some farmer-oriented incentives, provide land-related documentation or exercise independent control over farm decisions when agricultural land is registered in the name of a male family member. Formal records may not show their true participation in cultivation.

There are other difficulties in gaining access to markets, technology, and agricultural knowledge. It's possible that women have less access to financial services, sophisticated machinery, technical guidance and extended training. Their capacity to adopt new ideas, increase productivity, and make more money may be hampered by unequal access to resources. Land tenure, financial and technical limitations and restricted access to services and education are among the major issues that women farmers face globally, according to the Food and Agriculture Organization (FAO) (FAO, 2025).

These disparities may be strengthened by societal and cultural norms. While male family members may make the majority of decisions about land, investments, crop selection and produce sales, women's farming efforts may be seen as family duties rather than financial contributions. These situations can limit women's ability to participate in decisions that directly impact their livelihoods and undermine their bargaining power. Public communication also reflects the lack of visibility of female farmers. The Global Media Monitoring Project (GMMP), a long-running international study of gender representation in news media, reported that women accounted for approximately 25 per cent of people seen, heard or spoken about in news coverage in 2025,

compared with 17 per cent in 1995. Women represented 23 per cent of experts and commentators in 2025, down from 24 per cent in 2020 (GMMP, 2025).

These are global media figures, not statistics specifically about Indian agriculture. Nevertheless, they provide a useful context for understanding why women's voices may be overlooked in public discussions. When women farmers receive limited visibility as experts, innovators and decision-makers, their experiences and achievements risk being excluded from conversations about agricultural development. Greater representation of women farmers in agricultural reporting, policy debates and success stories can help challenge stereotypes and strengthen public recognition of their roles.

From Invisible Labour to Recognised Farmers: The Way Forward

Transforming the position of women in agriculture requires coordinated efforts from governments, agricultural institutions, financial organisations, extension agencies, media and rural communities. Improving women's access to land rights, farmer registration, institutional credit and agricultural insurance is essential for recognising them as farmers and strengthening their economic independence. Financial literacy, women-led enterprises and participation in Self-Help Groups (SHGs) and Farmer Producer Organisations (FPOs) can enhance their bargaining power and market access.

Gender-responsive agricultural extension services, flexible training schedules, local-language advisories and digital learning opportunities can improve women's access to agricultural knowledge and technologies. Extension agencies should encourage women's participation in farm-level decisions and leadership roles. Agricultural institutions and media should highlight women's innovations, achievements and expertise to challenge gender stereotypes. Furthermore, collecting gender-disaggregated data can help identify inequalities and develop inclusive policies. These measures can strengthen women's livelihoods, decision-making power and participation in sustainable agricultural development (FAO, 2025; Nyberg & Wetterlind, 2025).The International Year of the Woman Farmer 2026 offers an important opportunity to move from awareness to action. As the FAO emphasises, improving women's access to land, finance, technology, education, services and decision-making can contribute to more equitable and resilient agrifood systems (FAO, 2025).

Conclusion

Ultimately, women must be recognised not merely as agricultural labourers or supportive family members, but as farmers, innovators, entrepreneurs and decision-makers in their own right. Such recognition must go beyond words and translate into meaningful access to productive resources, institutional support, knowledge and markets. Strengthening women's participation in agricultural institutions and farm-level decisions is equally essential to ensure that their contributions are valued and their voices are heard.

Recognising women as farmers is not simply about giving them a title; it is about ensuring that they have the rights, resources and opportunities to shape the future of Indian agriculture. When women are empowered to participate fully in agricultural production and decision-making, the benefits can extend beyond individual households to rural livelihoods, inclusive development and national food security. The invisible hands that sustain Indian agriculture deserve not only recognition, but also the opportunities and institutional support necessary to thrive.

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ERGONOMIC POSTURE ASSESSMENT METHODS FOR AGRICULTURAL WORKS

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INTRODUCTION

Agricultural work is physically demanding and often requires workers to perform repetitive tasks in awkward and uncomfortable postures for long periods. Activities such as transplanting, weeding, harvesting, seedling uprooting and manual handling frequently involve forward bending, squatting, twisting, reaching and prolonged standing. Such postures, when combined with repetitive movements, forceful exertion and inadequate rest, can place excessive stress on muscles, joints and the supporting structures of the body, increasing the risk of work-related musculoskeletal disorders (WRMSDs). A study of women cultivators engaged in rice seedling uprooting reported high levels of musculoskeletal problems, particularly in the lower back, hip, wrist, upper back, shoulder, neck and knee. Therefore, understanding and evaluating posture stress is essential for improving worker safety, comfort and productivity. Ergonomic posture assessment methods such as OWAS, RULA, REBA and QEC provide systematic approaches for identifying awkward postures, estimating the level of risk and determining where corrective measures are required.

What is posture stress?

Posture stress refers to the physical strain imposed on the body when a person performs work in a posture that places excessive or prolonged loading on muscles, joints and other body structures. A posture does not necessarily have to be uncomfortable at the beginning to become harmful, Duration matters, Repetition matters, Force matters. For example, bending forward for a few seconds to pick something from the floor is usually not a major concern. But repeatedly bending forward for several hours while performing agricultural work is a very different situation. Postural stress becomes more significant when several risk factors occur together.

What happens when we work in an awkward posture?

The human body continuously tries to maintain balance. In a normal standing posture, body weight is distributed through the skeletal system and the muscles provide the necessary support and stability. When the body bends, twists or reaches away from its normal position, the body's centre of gravity changes. This means that muscles may have to work harder to maintain stability. Consider a simple example: holding a bucket close to the body versus holding it with the arms stretched forward. The weight of the bucket has not changed, but the mechanical demand on the body can increase because of the changed position of the load. A similar principle applies to agricultural work. During forward bending, the centre of gravity moves away from its normal position. In the study examined, the centre of gravity shifted by 9.17 ± 1.57% of body height during forward bending, whereas squatting produced a downward shift of 8.76 ± 1.89%. The lower back was affected in 91.96% of participants, followed by the hip (91.07%), wrist (83.04%), upper back and shoulder (81.25% each), neck (73.21%) and knee (66.07%).



Figure 1. Awkward working posture while paddy transplanting

Ergonomic Posture Assessment Methods

Simply looking at a worker and saying that a posture appears uncomfortable is not enough for ergonomic intervention. Ergonomists use systematic assessment methods to convert observed postures into scores and risk categories. Four widely used observational techniques are:

1. OWAS – Ovako Working Posture Analysis System
2. RULA – Rapid Upper Limb Assessment
3. REBA – Rapid Entire Body Assessment
4. QEC – Quick Exposure Check

1. OWAS – Ovako Working Posture Analysis System

OWAS (Ovako Working Posture Analysis System) is an observational method used to classify workers' postures and identify the level of postural risk. It evaluates the back, arms, legs, and load handled by the worker. During assessment, the worker's posture is observed and a four-digit posture code is assigned according to the position of the back, arms, legs, and load.

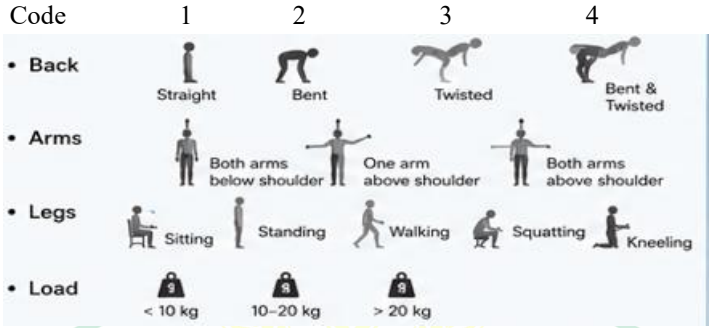


Fig 2 – Codes for different body postures considered in OWAS

The resulting code is then matched with the OWAS action-category table to obtain an action level from 1 to 4, where Level 1 represents an acceptable posture and Level 4 indicates that corrective measures are required immediately. In the rice uprooting study, the forward-bending posture received an OWAS code of 4/3/4/1 and Action Level 4, indicating that corrective measures were required immediately, whereas the squat-sitting posture received a code of 4/1/1/1 and Action Level 2, indicating that corrective measures were needed in the near future.

Action Level	Meaning	Recommendation
1	Acceptable posture	No corrective action required
2	Slightly harmful posture	Corrective action in the near future
3	Harmful posture	Corrective action as soon as possible
4	Extremely harmful posture	Corrective action immediately

Fig 3 – OWAS Action level table

2. REBA – Rapid Entire Body Assessment

REBA (Rapid Entire Body Assessment) is an observational method developed to evaluate the ergonomic risk associated with whole-body postures. It considers the neck, trunk, legs, upper arm, lower arm, and wrist, along with additional factors such as load/force and coupling or grip. The calculation is performed by assigning posture scores to the body segments, combining the neck, trunk, and legs, and combining the upper arm, lower arm, and wrist . The resulting Group A and Group B scores are then combined, with appropriate adjustments for load, coupling, and activity, to obtain the final REBA score. The final score ranges from 1 to 15, with higher scores representing greater ergonomic risk and greater need for corrective action.

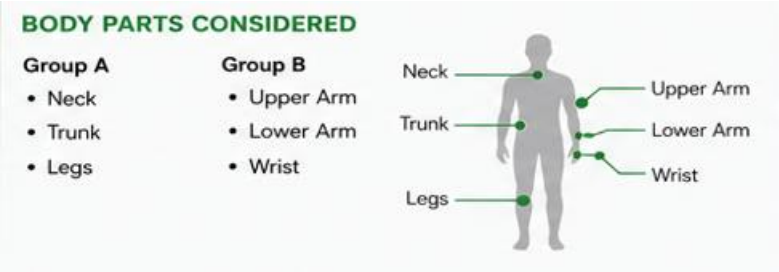


Fig 4 – Body parts consider for REBA

In some studies, the forward-bending posture obtained a REBA score of 12 (Action Level 5), classified as very high risk and requiring implementation of change, while the squat-sitting posture obtained a score of 10 (Action Level 4), classified as high risk and requiring investigation and change.

REBA Score	Risk Level	Action Level	Recommendation
1	Negligible Risk	0	No action required
2 – 3	Low Risk	1	May be necessary
4 – 7	Medium Risk	2	Necessary
8 – 10	High Risk	3	Necessary soon
11 – 15	Very High Risk	4	Necessary now

Fig 5 – Action level according to the score of REBA

3. RULA – Rapid Upper Limb Assessment

RULA (Rapid Upper Limb Assessment) is an observational ergonomic assessment method primarily used to evaluate the risk of musculoskeletal disorders associated with upper-limb and related postures. It assesses the upper arm, lower arm, wrist and wrist twist, together with the neck, trunk, and legs. During calculation, posture scores are assigned to the individual body regions and combined using the RULA scoring tables. Additional consideration is given to muscle use and force/load, and the final score is obtained from the RULA assessment tables. The final RULA score ranges from 1 to 7, where increasing scores indicate increasing ergonomic risk and a greater need for intervention.

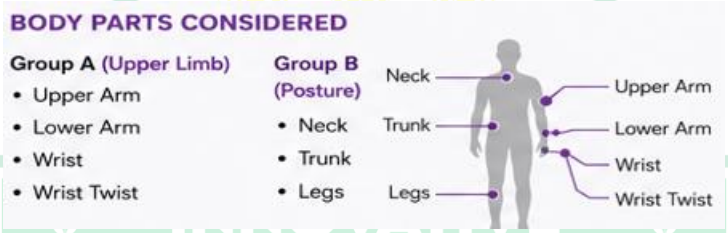


Fig 6 – Body parts considered for RULA

In some studies, the forward-bending posture obtained a RULA score of 7 with Action Level 4, indicating that the posture should be investigated and changed immediately, whereas the squat-sitting posture obtained a score of 6 with Action Level 3, indicating that further investigation and changes should be made soon.

RULA Score	Risk Level	Action Level	Recommendation
1 – 2	Acceptable	1	No action required
3 – 4	Investigate further	2	Change may be needed
5 – 6	Investigate and change soon	3	Change soon
7	Very high risk	4	Change immediately

Fig 7 – Action level according to the score of RULA

4. QEC – Quick Exposure Checklist

QEC (Quick Exposure Checklist) is an observational ergonomic assessment method used to evaluate workers' exposure to physical risk factors associated with work-related musculoskeletal disorders. It assesses different body regions, particularly the back, shoulder/arm, wrist/hand, and neck, while considering factors associated with the task. The assessment produces scores for individual body regions as well as an overall exposure level, allowing the researcher to identify which parts of the body are exposed to greater ergonomic stress.

A simple ergonomic assessment workflow

Step 1 – Observe the task Understand what the worker actually does.

Step 2 – Identify awkward postures Look for bending, twisting, reaching, squatting, excessive wrist deviation and static positions.

Step 3 – Record exposure Determine how frequently and for how long the posture is maintained.

Step 4 – Select an assessment method OWAS, RULA, REBA or QEC depending on the task.

Step 5 – Determine risk level Calculate the score and identify the body regions requiring attention.

Step 6 – Redesign the task Modify tools, equipment, working height, posture, work-rest schedule or method.

Conclusion

Posture stress is an important but often overlooked occupational hazard, particularly in physically demanding activities such as agriculture. Prolonged bending, squatting, twisting, repetitive movements and insufficient rest can place continuous stress on muscles, joints and the spine, gradually increasing the risk of work-related musculoskeletal disorders. The evidence from agricultural workers shows that awkward postures can contribute substantially to discomfort, particularly in the lower back, hip, shoulders, wrists, neck and knees. Ergonomic assessment methods such as OWAS, RULA, REBA and QEC provide practical tools for identifying risky postures and determining the urgency of corrective action which makes us understand why a posture is stressful and how the work can be redesigned. Improvements in tool and machinery design, working height, work-rest schedules, task organization, mechanization and worker training can help reduce unnecessary physical strain. Ultimately, good ergonomics means designing the workplace, tools and machines around the capabilities and limitations of the human body. A safer posture is not only about reducing pain; it can also improve comfort, reduce fatigue and support sustainable productivity.

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Soil Nematodes as Bioindicators of Soil Health and Ecosystem Functioning

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Abstract

Soil health depends on living organisms as much as on chemistry and structure. Nematodes are especially useful indicators because they occupy several levels of the soil food web and respond quickly to change. Their feeding groups reflect decomposition, nutrient release, food-web complexity and crop stress, and indices such as the Maturity, Enrichment, Structure and Channel Index turn community data into statements about disturbance and resource supply. Nematode communities respond to organic amendments, residue retention, crop diversification and reduced tillage, but they must be interpreted alongside other soil measurements.

Keywords: Nematode, soil health, decomposition, crop diversification, organic amendments.

Introduction

Soil health is the capacity of a soil to function as a living system that sustains plant productivity, regulates water and nutrient cycling and supports biodiversity (Doran & Zeiss, 2000; Karlen et al., 1997). Routine tests of organic carbon, pH, bulk density and nutrients describe the soil at the time of sampling but say little about how well its biology is working, which is why biological indicators are attracting interest. Nematodes are unsegmented roundworms found in nearly every soil, feeding on bacteria, fungi, plant roots, protozoa, algae and other nematodes (Yeates et al., 1993). Because their feeding groups respond differently to disturbance and food supply, the make-up of a nematode community reveals what is happening in the soil (Bongers & Ferris, 1999; Neher, 2001). This article explains how nematodes are used as indicators, how the main indices are read, and where their limits lie.

Functional Groups of Soil Nematodes

Soil nematodes are grouped by diet into bacterivores, fungivores, plant parasites, omnivores and predators (Yeates et al., 1993), and body form, especially the structure of the mouth, is closely linked to feeding habit and ecological role (Bongers & Bongers, 1998). Bacterivores belong to the bacterial decomposition channel and increase when easily decomposed organic material stimulates bacterial growth, while fungivores belong to the fungal channel, which is associated with slower breakdown of resistant material. Plant parasites feed on roots and, at high numbers, reduce crop growth and yield, so they signal risk rather than health. Predators and omnivores sit higher in the food web; many have long life cycles and low reproductive rates and decline under disturbance, so their presence suggests a food web that has developed without repeated disruption (Bongers, 1990; Ferris et al., 2001).

Nematodes as Indicators of Soil Health

Nematodes suit this role because they occur in almost every soil, cover a wide range of feeding habits and life strategies, can be extracted with simple methods and can be identified without culturing (Bongers & Ferris, 1999; Neher, 2001). Intensive tillage, heavy pesticide use, monocropping and low organic-matter return change nematode abundance and community make-up, whereas organic amendments, residue retention, cover cropping, crop diversification and reduced tillage push communities the other way (Freckman & Ettema, 1993). A mix of trophic groups that includes omnivores and predators usually indicates a well-developed food web, while dominance by a few fast-reproducing, disturbance-tolerant taxa signals stress. Many nematodes complete a generation in a few weeks, so a sample mostly shows recent conditions, with slow-growing groups adding information about longer-term stability.

Nematodes and Food-Web Functioning

Nematodes act at more than one level of the soil food web. Bacterivores and fungivores consume microbial biomass and, because microbes hold more nitrogen than these grazers need, release the surplus as ammonium that

plants and microbes can use, while predators and omnivores keep the lower groups in check (Ferris et al., 2004; Ferris, 2010a). When fresh residues are added, the extra carbon lets microbes grow, bacterivores or fungivores then increase, and higher trophic levels may follow, so a rise in one group can point to a change in microbial activity or decomposition pathway. Metabolic footprints, which combine the abundance and body size of each group, estimate carbon use and energy flow through the nematode fauna (Ferris, 2010b). Nematodes are thus active members of the processes they indicate.

Nematode-Based Ecological Indices

Most work now relies on indices that give ecological meaning to the taxa found. These rest on the colonizer–persister (c–p) scale of 1 to 5: colonizers (c–p 1–2) reproduce quickly, tolerate disturbance and respond rapidly to food, whereas persisters (c–p 4–5) grow slowly and are sensitive to disturbance (Bongers, 1990; Bongers & Bongers, 1998; Neher & Darby, 2006). The Maturity Index (MI) is the weighted mean c–p value of free-living nematodes; low values indicate an opportunist-dominated, disturbed or enriched soil, and higher values a more stable system, while under nutrient-rich conditions MI falls and the Plant Parasite Index rises (Bongers et al., 1997). The Enrichment Index (EI) measures the share of opportunistic bacterivores and fungivores and shows a response to readily available resources (Ferris & Bongers, 2006), the Structure Index (SI) reflects persistent groups such as omnivores and predators and indicates a well-connected food web, and the Channel Index (CI) shows whether decomposition runs mainly through bacterial or fungal pathways (Ferris et al., 2001). EI and SI plotted together on a food-web diagram place soils in broad conditions such as disturbed, enriched, maturing or degraded. The indices have limits: they are applied unevenly, agricultural systems dominate the literature and some taxa do not behave as their c–p value predicts (Du Preez et al., 2022). Recent reviews trace their development (Somasekhar & Chavan, 2024), and a combined Nematode Soil Health index has been proposed, though it needs testing on more datasets (Ghaderi et al., 2025).

Relevance to Sustainable Agriculture

Farmyard manure, compost, crop residues and green manures supply carbon and nutrients that stimulate microbial communities and reshape the food web, and nematode groups respond accordingly. In California organic vegetable systems, Ferris et al. (2012) examined how the nematode assemblage was structured, and soil management can be designed to favour bacterivores and fungivores and the nitrogen mineralization they provide (Ferris et al., 2004). Conservation agriculture, reduced tillage, rotation and cover cropping improve habitat and food supply in the same way. Sampling before and after a change of practice, and over several seasons, shows whether soil biology is shifting, and reveals changes in decomposition, resource supply and food-web structure that chemical analysis alone would miss.

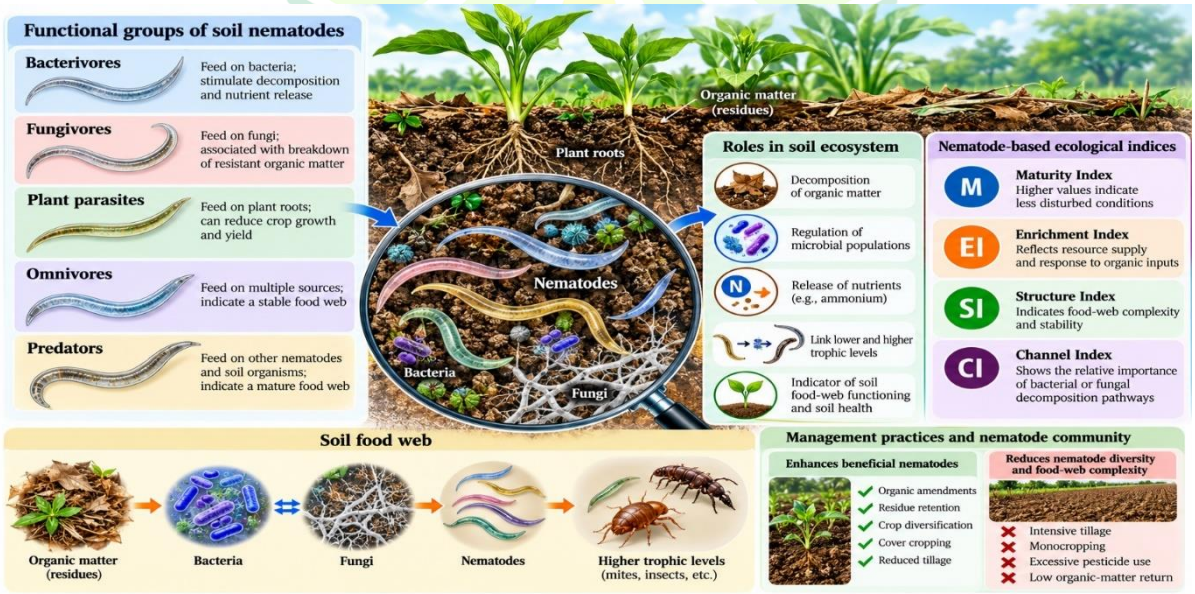


Fig. 1. Role of soil nematodes in soil health and food-web functioning

Limitations and Considerations

Nematodes should not be the only indicator. Community composition varies with soil texture, moisture, temperature, crop, season, organic matter and sampling depth, so the same index value can mean different things in different ecosystems (Neher et al., 2005); samples should be compared with others from the same soil type, crop and season, or with a reference site. Plant parasites need separate interpretation, since a higher count may threaten the crop rather than signal improvement. Many species look alike and morphological identification takes training and time, although molecular techniques are likely to improve speed and consistency (Du Preez et al., 2022). For a full picture, nematode data are best combined with organic carbon, microbial biomass, enzyme activities, aggregate stability, nutrients, respiration and physical properties.

Conclusion

Nematodes link microbes, plant roots, decomposers and higher consumers, and their community structure reflects resource supply, decomposition, nutrient cycling and disturbance. The Maturity, Enrichment, Structure and Channel indices turn species lists into statements about food-web function and are sensitive enough to test whether sustainable practices are working. With careful interpretation, local reference values and support from other soil measurements, nematode communities can make soil-health assessment more complete, and advances in molecular identification should make them easier to use.

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The tiny thieves in your grain: how science is protecting our food after harvest?

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Imagine working hard for months- sowing the seeds, watering the crop, protecting it from pests and weather and finally filling sacks with golden grain. You would think the struggle is over. But for millions of farmers, a second battle is only beginning. Inside those sacks, tiny insects may already be quietly eating the grain, filling it with dust and webbing, and ruining months of hard work.

This battle does not happen in the field. It happens in the godown, the kitchen shelf, the warehouse and the grain silo. And today, science is offering some remarkable new weapons to fight it from bags that suffocate insects without any chemical, to technology that can switch off the genes, pests need to survive.

How much food are we really losing?

Here is a surprising fact: of all the food grain lost after harvest in the world, insects are responsible for the biggest share about 41%. Rats and mice account for around 18%, birds for 9%, and dampness and moisture for another 7%. Scientists have recorded more than 600 kinds of beetles, 70 kinds of moths and over 350 kinds of tiny mites that attack stored grain.

What does this mean in simple terms? For every 100 bags of grain stored, several bags worth of grain are lost or spoiled before they can be eaten or sold. These insects do not just eat the grain, they leave behind droppings, shed skins, dust and mould, making the remaining grain unfit for use. For a farmer, this is income lost. For a nation, this is food security threatened.

Who are these tiny thieves?

Stored grain pests generally fall into two groups:

Type of pest	What it does	Examples you may have seen
Grain borers and weevils (primary pests)	Attack whole, healthy grains. They bore holes into the grain and eat it from inside, leaving behind empty shells and powder	Rice weevil, maize weevil, lesser grain borer, grain moth
Flour beetles and moth larvae (secondary pests)	Attack broken grain, flour and grain dust. They follow the borers and make the damage worse	Red flour beetle, Indian meal moth, saw-toothed grain beetle



Damaged grains

Have you ever opened an old bag of rice and found it full of powder, or noticed small holes in grains, or seen tiny webs in flour? That is the work of these pests. Rats, mice, birds and mites add to the problem by eating the grain, spoiling it with their droppings, and letting fungus grow.

How did our grandparents fight them?

Long before modern science, farmers developed clever habits that are still useful today:

- Dry the grain well in the sun before storing it. Dry grain keeps insects away far better than damp grain.
- Store grain in clean bags and clean rooms, with no cracks in walls or floors where pests can hide.
- Mix neem seed powder with the grain- an age-old, safe remedy that still works.
- Keep the storage area dry, airy and rat-proof, and check the grain regularly.

When insects did attack, the usual remedy was fumigation- placing chemical tablets that release poisonous gas inside the storage, in an airtight room, for about five days. This method is powerful, but it has serious drawbacks. The gas is highly poisonous to humans and animals. It works poorly in cold or humid weather. Insects are now developing resistance to it, meaning the same tablets no longer kill them. And one common fumigant, methyl bromide, is now banned in many countries because it damages the ozone layer that protects our planet.

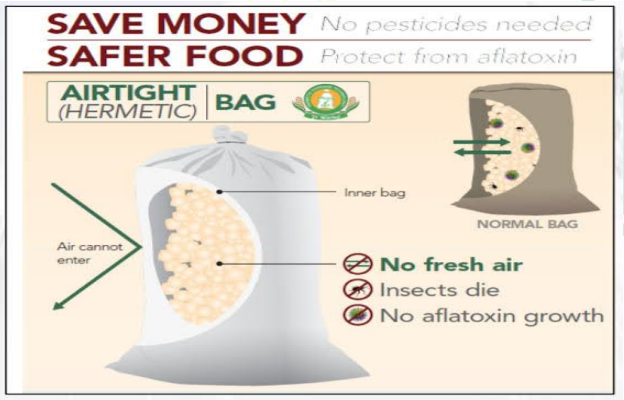
So the question became: can we protect grain without filling it with poison? The answer, happily, is yes.

The wonder of airtight storage: let pests suffocate in their own breath

One of the smartest modern inventions is also one of the simplest- the airtight storage bag.

Think of it like this: every living creature, including insects, needs to breathe. When grain and the insects inside it are sealed in a completely airtight bag, the insects use up the oxygen and release carbon dioxide. Within days, the oxygen level drops so low that the insects can no longer survive. They suffocate without a single drop of chemical being used.

Special multi-layer plastic bags, popularly known as **PICS bags**, were developed for exactly this purpose. A farmer can place grain in the inner bag, tie it tightly, place it inside the outer bag, tie that too and the grain stays safe for months. Metal silos and large sealed plastic cocoons work the same way for bigger quantities. Scientists have even developed large storage chambers where air is pumped out to create a vacuum, the insects die both from lack of air and from drying out.



Hermetic Bags for storage

This method is safe, leaves no chemical traces, does not allow insects to develop resistance, and even stops mould growth. For a small farmer, the bag pays for itself many times over in saved grain.

Fighting insects with heat, sound and light-like energy

Scientists have discovered several clever physical methods that kill pests without touching the grain with chemicals:

Method	In simple words, how it works
Ozone treatment	Ozone is a special form of oxygen with strong germ-killing power. It destroys the breathing system of insects and mould, then turns back into ordinary oxygen leaving no harmful residue
Irradiation	The grain is exposed to controlled rays (like those used in hospitals to sterilise equipment). The rays damage the insects DNA, so they either die immediately or become unable to reproduce
Microwave / radiofrequency heating	Special waves heat the insects hiding inside the grain faster than the grain itself, the insects are cooked while the grain stays unharmed
Sound wave detection	Tiny microphones placed in grain can 'hear' insects feeding inside! Each pest makes its own signature sound, so infestations can be detected early without even opening the bag
Controlled air storage	The air inside storage is changed, oxygen reduced or carbon dioxide increased- so insects slowly run out of breath
Cold plasma	A 'cool' form of charged gas, created by electricity, damages the cells and genes of insects and moulds at normal temperature. It sounds like science fiction, but it works

Many of these methods are especially valuable for grains meant for babies food, organic products or export, where even small chemical residues are unacceptable.

Earth powder and other gentle weapons

Not every effective weapon is a poison. Diatomaceous earth- a fine powder made from the fossilised remains of ancient algae, works purely by physical action. When an insect crawls over it, the microscopic sharp particles scratch its protective outer skin. The insect loses moisture and dries out. To us it is harmless dust; to the insect it is a desert. This powder is safe for humans, leaves no dangerous residue and works against weevils, flour beetles and grain borers.

The invisible world of nanoparticles

Nanotechnology works at a scale thousands of times smaller than a grain of sand. Extremely tiny particles of silver, copper, zinc and other materials can pass into an insect's body and disturb its breathing, digestion and growth. Scientists can also pack natural oils from plants like neem inside nano-sized capsules, so the protective effect is released slowly over a long time- meaning fewer applications and less waste. Because these tiny particles attack pests in completely new ways, insects cannot easily develop resistance against them.

Enlisting nature's own soldiers

Instead of chemicals, why not use living organisms that eat or infect the pests?

- A natural soil bacterium called Bt (*Bacillus thuringiensis*) produces proteins that are poisonous to insects but safe for humans. Scientists are now developing stronger strains of this friendly bacterium.
- Fungi such as *Beauveria bassiana* act like a 'green mould infection' for insects-the spores stick to the pest's body, grow into it, and kill it. New and improved versions of these fungi are being created so they work faster and last longer on grain.

These biological methods are like hiring an army that works silently around the clock and leaves no poison behind.

Gene editing: the most futuristic weapon of all

The newest frontier in pest control is happening at the level of genes- the instruction manuals inside every living cell.

Scientists today can use a remarkable tool called CRISPR, often described as 'molecular scissors', to cut and edit the DNA of pests with great precision. By disrupting the genes that insects need for survival or reproduction, it is possible to create pest populations that gradually die out or fail to multiply. A recent breakthrough even allows these scissors to be delivered by simple injection into adult insects, making the technology much easier to use on many different pest species.

There is also RNA interference, or RNAi- a method in which the pest is fed special molecules that 'silence' its essential genes, as if switching off a light. The insect stops growing and reproducing. The beauty of this approach is that it is designed to affect only the target pest, leaving friendly insects and other animals untouched.

How do scientists even know which insect is hiding in the grain? Just like every product in a supermarket has its own barcode, every insect species has its own DNA barcode. A quick laboratory test can identify the pest even from a single egg or larva and multiple pests can be identified in a single test. Knowing exactly which enemy you are facing is half the battle won.

The storage room that thinks for itself

The grain godowns of the future will be smart. Small sensors placed inside storage silos can continuously measure temperature, moisture and the gases released by insects. If conditions start favouring pests, an automatic alert is sent to the farmer's phone or the system itself switches on ventilation to fix the problem. Artificial intelligence can study past data and predict pest outbreaks before they happen. Drones and robots can inspect huge warehouses and apply treatment exactly where needed. What once depended on luck and guesswork now depends on information.

What can you and I do today?

You do not need a laboratory or expensive equipment to protect grain. Whether you are a farmer with sacks of paddy or a homemaker with a tin of rice, these simple habits make a big difference:

1. Dry the grain thoroughly before storage, damp grain is an open invitation to insects and fungus.
2. Store in clean, dry, airtight containers, and clean the storage area regularly.

3. Check your grain every few weeks. Look for holes in grains, fine powder, webs or a musty smell - these are early warning signs.
4. Avoid mixing chemical insecticides with grain meant for eating, it is dangerous and illegal.
5. Where possible, use airtight bags or sealed containers, they protect grain for months without any chemical.
6. Remember: one insect allowed to live today becomes hundreds next month.

Old ways versus new ways

The old way	The new way
Repeated chemical fumigation	Airtight storage that kills pests without chemicals
Insects develop resistance to chemicals	Many different methods make resistance difficult
Risk of poison residues in grain	Little or no residue, safer for food
Some chemicals harm the environment	Environment-friendly alternatives
Checking grain by eye, occasionally	Sensors and alerts that monitor day and night
Kills pests today, but they return	Prevents infestation for the long term

The bigger lesson

The fight against stored grain pests teaches us something important: protecting food is as important as producing it. A country can grow record harvests, but if a tenth of that grain is eaten by insects in storage, the effort is wasted. The good news is that solutions now exist for every level from a poor farmer using an airtight bag, to a warehouse using sensors and smart technology. The gentlest solutions are often the smartest: deny the insect air, water, food or the genes it needs and it defeats itself.

Look before you lock the godown!

The next time you see a sack of grain being stored, remember - the harvest is not over, it has simply moved to its second battlefield. Dry it well, seal it tight, and check it often. The reward of a whole season's hard work deserves nothing less.

"The best protection for grain begins the day it leaves the field."

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Spaying and Neutering: More Than Just Birth Control

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Beyond the standard six-month appointment: How modern science reveals a complex balance of health risks, lifelong benefits, and breed-specific trade-offs for your dog.

The Six-Month Standard Under the Microscope

For decades, welcoming a new puppy home came with an almost mandatory instruction: schedule spay or neuter surgery at exactly six months. It was presented as a win-win routine procedure that prevented unwanted litters while automatically protecting your dog against future health problems. But is the decision really that simple?

Veterinary medical evidence presents a far more nuanced story. While gonadectomy (the surgical removal of ovaries or testicles) undeniably protects against specific diseases, it also alters a complex endocrine system. Removing sex hormones before a dog reaches physical maturity shifts lifelong risks for bone development, joint stability, immune response, and even certain aggressive cancers.

KEY TAKEAWAY

There is no universal 'right age' to spay or neuter every dog. The decision requires balancing breed-specific cancer risks, orthopedic vulnerabilities, and reproductive health goals.

Male Dogs: Weighing Protection Against Hidden Risks

Neutering male dogs is widely advocated as a preventive health measure, but the medical evidence shows a delicate balance of benefits and drawbacks.

What Neutering Protects Against

Testicular Cancer Elimination: Neutering eliminates the risk of testicular tumors. However, testicular tumors carry a low metastasis rate (6–14%) and a 90%+ cure rate, resulting in less than a 1% overall mortality risk in intact males.

Non-Cancerous Prostate Care: Neutering effectively prevents Benign Prostatic Hyperplasia (BPH), which affects over 80% of intact males over age 5, and shrinks an enlarged prostate quickly if performed later in life.

The Surprising Downsides

- Quadrupled Prostate Cancer Risk: Contrary to popular belief, neutered males face a 4-fold higher risk of aggressive ductal/urothelial prostate cancer compared to intact males, suggesting intact hormones play a protective role in the prostate environment.
- Bone Cancer (Osteosarcoma): In medium-to-large breeds like Rottweilers, males neutered before one year of age experience a 3.8-fold higher risk of osteosarcoma, raising their lifetime risk of this aggressive bone cancer to 28.4%.
- Endocrine & Metabolic Impacts: Neutered males face a 3-fold increase in hypothyroidism and a 3-fold increase in obesity, which triggers secondary joint problems and pancreatitis.

Female Dogs: A High-Stakes Balancing Act

For female dogs, spaying involves profound health trade-offs, where major life-saving benefits must be weighed against significant late-onset conditions.

The Essential Health Benefits

- Mammary Tumor Reduction: Mammary tumors account for 53% of all malignant tumors in intact females. Spaying dramatically slashes this risk depending on timing: experiencing zero estrus cycles reduces relative risk to 0.5%, one cycle to 8%, and spaying before 30 months reduces relative risk to 6% compared to intact females.
- Eradicating Pyometra: Pyometra—a severe, life-threatening uterine infection—affects roughly 23% of intact females by 10 years of age and carries a 4% mortality rate. Spaying nearly eradicates this condition.

The Long-Term Risks of Spaying

- Hemangiosarcoma Exposure: Spayed females face a 5-times higher risk of cardiac hemangiosarcoma and a 2.2-times higher risk of splenic hemangiosarcoma. This vascular cancer is a leading cause of sudden death in popular breeds like Golden Retrievers, Boxers, and German Shepherds.
- Urinary Incontinence & UTIs: Between 4% and 20% of spayed females develop urinary 'spay incontinence' (compared to 0.3% in intact females). Spayed females also have a 3- to 4-fold higher risk of persistent or recurring urinary tract infections.

The Science of Growth Plates & Joint Health

Why does age at sterilization matter so much? The answer lies in how the skeleton grows. Sex hormones (estrogen and testosterone) provide the crucial chemical signal that tells long bone growth plates to close and stop lengthening. When a dog is spayed or neutered before physical maturity (typically 12 to 18 months depending on size), growth plate closure is delayed. Bones continue growing beyond their natural design, resulting in elongated limbs, altered joint lever angles, and abnormal alignment.

Clinical consequences of early gonadectomy include:

- Cranial Cruciate Ligament (CCL) Ruptures: Sterilized dogs face a doubled risk of tearing their CCL (the canine equivalent of the ACL), driven by altered knee joint angles and increased weight.
- Hip Dysplasia: Dogs spayed or neutered before 5.5 months of age show a 70% increased risk of developing hip dysplasia compared to those sterilized later.

5. Quick Reference: Health Risks vs. Benefits

Health Category	Confirmed Benefits	Health Risks
Cancers & Tumors	➢ Eliminates testicular cancer (<1% mortality) ➢ Prevents mammary cancer (0.5% risk if spayed before 1st estrus)	➢ 3.8x osteosarcoma in early-neutered males ➢ 4x prostate cancer in neutered males ➢ >5x cardiac hemangiosarcoma in spayed females
Reproductive & Urogenital	➢ Eradicates pyometra (23% risk in intact females) ➢ Prevents benign enlarged prostate (BPH)	➢ 4–20% spay incontinence in females ➢ 3–4x higher persistent UTIs in females ➢ Recessed vulva if spayed before puberty
Orthopedics & Joints	➢ Reduces roaming and sexual behavior-related injuries	➢ 2x cranial cruciate ligament (CCL) ruptures ➢ 70% increase in hip dysplasia if spayed/neutered before 5.5 months
Metabolic & Endocrine	➢ Slighter lower perianal fistula risk	➢ 3x risk of hypothyroidism ➢ 1.6–3x risk of obesity
Immune System	➢ Removes ovarian/uterine tumors (rare, <0.5%)	➢ 27–30% higher risk of adverse vaccine reactions (hives, allergic shock) in small/toy breeds

Smart Questions for Your Veterinarian

When discussing spay or neuter options with your veterinary team, skip the blanket timeline and ask targeted questions tailored to your dog:

Q: "What are the specific cancer and orthopedic risks for my dog's breed?"

Q: "When do growth plates typically close for a dog of this size and adult weight?"

Q: "If keeping my female dog intact through her first estrus, what signs of pyometra should I monitor?"

Q: "Are non-surgical or hormone-sparing alternatives (such as vasectomy or ovary-sparing spay) appropriate options?"

The Bottom Line

Deciding when—or whether—to spay or neuter your dog is one of the most important healthcare choices you will make. By replacing one-size-fits-all mandates with personalized, breed-conscious medical planning, dog owners can optimize their companion's lifelong health, joint integrity, and vitality.

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Income generation through custom hiring of tractor operated combine harvester in Jehanabad

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1. Farmer Profile



- Name of Farmer: Kaushlendra Kumar
- Father's Name: Late Vinda Singh
- Village: Waina
- Block: Modanganj
- District: Jehanabad
- Educational Qualification: Intermediate
- Age: 45 Years
- Farmers Categories (Marginal/Small/Big): Semi Medium
- Major Farming System: Rice-Wheat-Green Gram

2. Farmer Situation Analysis

Sri Kaushlendra Kumar is a progressive farmer of village Waina, Block- Modanganj, Jehanabad district. Sri Kumar has passed Matriculation in Year 1993 and awarded 10+2 certificate in year 1995 from S.S. College, Jehanabad. He has 7 acres of cultivable land. Rice, wheat cropping system is prominent farming system in his village. As like, he cultivates Rice in Kharif season and Wheat as major crop during Rabi season as well as Green Gram during Summer Season. After death of his father in year 2000, he was facing livelihood problem andwhole responsibility came on his shoulder. So, he involved himself in farming and thus having experience of 25 years in farming. But initially, Sri Kumar started cultivation of crops with traditional farming method and he was facing financial scarcity due to low profit from crop cultivation. One of the major causes was non-timeliness in farming operations and crisis of labour for different farm operations. Harvesting was one of the most important such operation in which sickle was usedfor crop harvesting that requires a large number of labourers and too much time. This traditional practice of harvestingcaused delay in harvesting of Rice resulting delay in sowing of wheat and otherRabi crops. Another problem in his village was high moisture condition in the paddy field which causes delay in harvesting and old harvester was unable to perform harvesting operation in that high moisture condition.

3. Association with Krishi Vigyan Kendra

Sri Kaushlendra Kumar was facing livelihood problem after death of his father. He is a hard-working farmer, showing keen interest in use of machines in farming. He came in contact with KVK, Gandhar, Jehanabad in year 2009 and got training in various aspects of scientific crop cultivation. He purchased a tractor (MF1035) in year 2018 for timely field operation and after performing his own field work; he used this tractor to plough the field of other fellow farmers on custom hiring basis and started income generation from this venture. However, this income was small initially, he got seasonal income of Rs. 168000/ during Kharif and Rs. 240000/- during Rabi season, thus anannual total income of Rs. 408000/-.

In the meantime, KVK Jehanabad introduced climate resilient agriculture programme in his village duringyear 2020 in whichdemonstration on use of improved farm implements like zero tillage for wheat, lentil, chickpea, mustard sowing during Rabi season, use of DSR machine for direct seeding of rice, use of raised bed planter for maize sowing, use of combine harvester for Rice, Wheat harvesting was conducted on farmers field.Due to his keen interest and guidance by KVK, Jehanabad, he got expertise in operation of these modern farm machineries.

4. Innovative Technology/Practice Adopted or Developed

Earlier, he was having income of Rs.120000/- from crop cultivation and Rs. 408000/- from custom hiring of his tractor for ploughing operation. In year 2025, he purchased tractor driven (4 wheel, Mahindra) combine harvester (Standard S-731) that is capable of harvesting crops in high moisture condition also. Sri Kaushlendra Kumar started providing this combine harvester to the other farmers of his village on hiring basis. In the season Kharif 2025, he earned Rs. 384,000/- by harvesting rice crop in high moisture condition, Rs. 168000/- from harvesting of Garma rice whereas during Rabi season 2025, he gained Rs. 288000/ fromharvesting of Wheat crop and Rs. 60000/- from Mustard harvesting. Annual income of Sri Kaushlendra Kumar from custom hiring of tractor operated combine harvester during year 2025-26 reached to Rs. 900000/-.

5. Economic Impact

Particular	Before the Intervention (only tractor hiring)	After the Intervention, (tractor &harvester hiring)
Unit Running /operational Cost (Rs.)	180400	553410
Gross Income (Rs.)	408000	1428000
Net Income (Rs.)	227600	874590
Benefit-Cost Ratio	2.26	2.58

Due to custom hiring of this harvester, he got a jump in his net annual income by Rs. 646990/- as compared to tractor hiring only (Rs. 227600) whereas B:C ratio increased from 2.26 to 2.58.

6. Social Impact and Farmer-to-Farmer Extension

The success of the custom hiring of combine harvester had a positive influence beyond the beneficiary farmers. Sri Kaushlendra Kumar expressed satisfaction with the performance ofcustom hiring of combine harvester machine. He observed better harvesting practice with improved profitability as well as ease in harvesting of Rice crop as compared to traditional harvester machine.

The successful operationof the harvester also generated interest among neighbouring farmers. The performance of the machine encouraged farmers in the surrounding area and he has suggested using this machine to young fellow farmers in his village and adjoining villages also. This farmer has emerged as a local entrepreneur through which rural youth can gain income and perform the harvesting work on time. He also trained the rural youthsand tells them about its utility and employment opportunitiesas well asto observe the performance of the machine in field conditions.

7. Entrepreneurship and Employment Generation

It is being preferred by fellow farmers also because of harvester's capability to harvest the crop in high moisture condition. This venture facilitated the farmers inadvancement in time for early Wheat sowing by zero tillage technology. Even it reducedcost of cultivation and nullifies the chances of paddy straw burning. Net annual turnover from custom hiring of this combine harvester has been compounded as Rs. 874590/-.

8. Awards, Recognition and Media Coverage

He has participated in Kisan Mela at BAU, Sabour, as well as district level Krishi Yantrikaran Mela, agricultural exhibitions and trainings on use of various technologies at Krishi Vigyan Kendra, Jehanabad including five days training on "Enhancement in water productivity for improvement in livelihood through agriculture" (04-10 Sept. 2009), organized at KVK, Jehanabad by ICAR-RCER, Patna.

He has uploaded 4-5 related videos in you tube for further expansion and to popularise the combine harvester machine among other farmers.

The performance of custom hiring activity by Sri Kaushlendra Kumar helped farmers of his village as well as neighbouring village farmers to harvest Rice, Wheat and Mustard crop timely. Specially, this harvester easily harvested Rice crop even in high moisture condition existing in some patches of this region.

9. Future Vision

Shri Kaushlendra Kumar encourages the mechanized harvesting of Rice, Wheat and Mustard crop using tractor driven combine harvester as demonstrated earlier by Krishi Vigyan Kendra, Jehanabad. He is satisfied with the performance of this harvester and profitability obtained through its custom hiring. His future vision is to maintain higherincome through timely operation of improved farm implements. Sri Kaushlendra Kumar is interested to expand this expertise. He wants to continue sharing his experience with young fellow farmers in his village and

adjoining areas so that the benefits of improved farm machineries can be expanded across the Rice-Wheat growing areas of Jehanabad district.He want to use this machine on a largerarea to get increased income from custom hiring of this harvester and he also planned to purchase and use new farm machines like straw reaper machine for collection of paddy straw, M.B. Plough for deep summer ploughing, bund former for strengthening of field bunds so thatdifferent field operations can be performed easily and timely alongwith enhancement in income generationin future.

10. Message to Fellow Farmers

He shares his knowledge and experience with other farmers and suggests this tractor operated combine harvester forPaddy harvesting in high moisture condition so that Wheat sowing can be done timely. On the other hand, this machine is capable of generating handsome income for livelihood improvement of rural youths. In his words “I suggest this harvester machine to the rural youths for income generation activity by adopting farm mechanization. I thank KVK Jehanabad for providing technical guidance, promoting the farmers to continuous learning the advanced technologies and motivation towards adoption of improved farm technologies.”








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Outstanding women farmer using advanced machinery in farming

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Farmer Profile

Smt. Indu Kumari
Vill. - Heridih, Panchayat- Sumera,
Block-Makhdumpur, Jehanabad, Bihar

1. **Crops:** Paddy, Wheat, Chickpea, Lentil, Mushroom
2. **Area:** 1.0 acre
3. **Technical Guidance: Krishi Vigyan Kendra, Jehanabad**
4. **Financial performance**

Crop/technology/Enterprise	Yield (q/ha)	Gross cost (Rs. /ha)	Gross Return (Rs. /ha)	Net Return (Rs. /ha)	B:C Ratio
Paady	41.5	41400	98313.5	56913.5	2.37
Wheat	39.5	38600	102366	63766	2.65
Lentil	17.75	26800	99400	72600	3.71
Chickpea	20.25	28200	108100	79900	3.83
Mushroom	400 bags	60000	190000	130000	3.16

She gets net annual income of Rs. 273180/ha from crop production. Besides this, Smt. Indu Kumari produces 9.5 quintal of button mushroom with a net annual income of Rs. 130000/-.

5. **Agricultural practices and farm machinery adopted:** Smt. Indu Kumar is progressive farm women. She uses Direct Paddy Seeder for sowing of paddy seed, Dibbler for sowing of Chickpea, lentil seedand zero tillage technology in wheat cultivation. She uses mini seed grader machine for processing of paddy and wheat seed which is capable of processing 1.5 quintal paddy or wheat seed per hour. She is also involved in Mushroom cultivation (Button) with 400 bags from which she getsproduction of 9.5 quintal mushroom. Mrs. Indu is not only using advance machinery in farming but she is also involved in organic cultivation of vegetables in which Vijamrit, Jeevaamrit, Amrit Pani, Agniastra etc. is used.
6. **Leadership and community impact:** Smt. Indu Kumari is adopting advanced agricultural technologies and leading several Self-help groupscontaining 300 farmers and farm women.
7. **Innovation in Agriculture:** Use of Seed grader machine for processing of paddy and wheat seed produced by members of self-help group of farmers and farm women
8. **Market linkage:** Local market Tehta, Makhdumpur, Jehanabad
9. **Award and recognitions received**

Name of Award	Year	Occasion	Institution	Purpose
3rd Prize	2008	Foundation day of Jehanabad district	District Magistrate, Jehanabad	Women Empowerment
2nd Prize	2012	Bihar Shatabdi Year Utsav	Mahila Vikas Nigam, Patna	Nari Shakti Shatabdi Utsav
Consolation Prize	2017	Bihar Diwas Programme at Jehanabad	District Magistrate, Jehanabad	Swachhata Activity
Consolation prize	2018	Lohiya Swachh Bihar Abhiyan	BDO, Makhdumpur, Jehanabad	construction of 2 Soak pits under Swachhata activity
Aprajita Award	2018	Prabhat Khabar	Prabhat Khabar, Bihar	Women Empowerment
3rd Prize	2026	Entrepreneurship Conclave, Bodhgaya	Mahila Utthan Federation of India, Kolkata	Outstanding Entrepreneurial Excellence



Use of Mini Seed Grader Machine



Operation of Direct Paddy Seeder



Operation of Rotary Dibbler



Zero Tillage Wheat Cultivation



Use of Hand Sprayer



Picking of fresh Button Mushroom





Appreciation by Hon'ble Chief Minister, Govt. of Bihar and Honoured by Hon'ble MLA, Makhdumpur and Hon'ble DM, Jehanabad for women empowerment and entrepreneurial activities

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Ghost Fishing as a Source of Marine Pollution: Impacts on Marine Life and Fisheries

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Abstract

Abandoned, lost, or discarded fishing gear (ALDFG), commonly known as ghost gear, is a major concern in marine pollution. Made from durable materials such as nylon and polypropylene, lost nets, traps, and fishing lines can remain in the ocean for years and continue to capture marine organisms through a process known as ghost fishing. This gear can injure or kill fish, crustaceans, turtles, seabirds, and marine mammals. It can also damage coral reefs and seagrass beds, contribute to microplastic pollution, and cause economic losses to fisheries, tourism, and shipping. This article explores the causes and impacts of ghost fishing and highlights possible solutions, including fishing gear recovery, gear marking, biodegradable alternatives, and proper disposal practices.

Keywords: Ghost fishing, ALDFG, Marine pollution, Derelict fishing gear, Marine biodiversity

Introduction

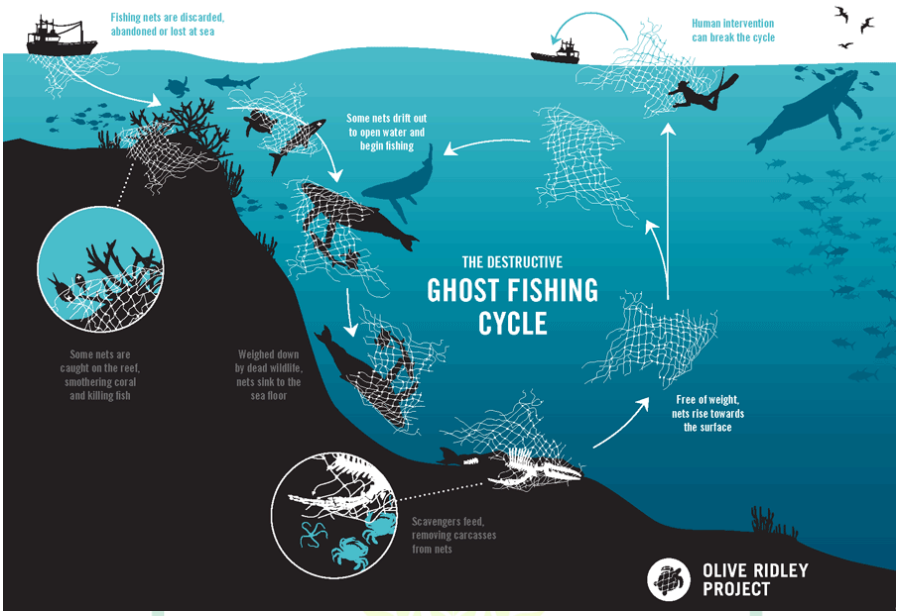
Fishing gear is often lost, abandoned, or discarded in seas, oceans, and other waterways, creating marine debris known as abandoned, lost, or discarded fishing gear (ALDFG) (Lively & Good, 2019). Lost fishing gear and gear fragments are among the most hazardous types of marine debris pollution. Lost gillnets and traps can remain intact for over a decade and continue to catch marine organisms (Laist, 1996). There is growing concern about the increasing amount of plastic waste, particularly lost fishing gear, that is washing up along coastlines around the world. During both legal and illegal fishing operations, fishing gear may be abandoned, accidentally lost, or intentionally discarded into the marine environment. Such gear is called 'Abandoned, Lost or Discarded Fishing Gear' (ALDFG). Fishing gear is often made from non-biodegradable materials such as polyamide (PA). When fishing gear is lost in the ocean, it can have long-lasting impacts, including marine litter, microplastic production, leaching of chemicals, and ghost fishing due to its durability (Wataniyakun et al., 2025). One of the most common problems associated with ghost fishing is the entanglement of seals, seabirds, and turtles, which are reported to be caught in small fragments of trawl nets, gillnets, and monofilament lines (Laist, 1996). Besides causing entanglement and death to marine species, ALDFG can continue to kill organisms even after the gear has been lost or discarded and contribute to ghost fishing (Wataniyakun et al., 2025).

Studies have estimated that ghost fishing results in losses of up to 30% of commercial species catches, but it also poses a significant threat to non-target species (Laist, 1996). Studies assessing the scale of this problem have reported impacts at both local and global levels. Research has estimated that, in South Korea, 11,436 tonnes of traps and 38,535 tonnes of gillnets are abandoned annually (Koziol et al., 2022). The continued loss of marine organisms caused by abandoned, lost, or discarded fishing gear can negatively affect both coastal communities and the wider marine environment. Globally, each year, about 1.82% of fishing gear is lost at sea. Loss rates vary by gear type: 3.57% of trawl nets, 3.33% of longline mainlines, 2.86% of hooks, 1.51% of purse seine nets, 0.81% of gillnets, and 0.74% of pots and traps are lost. In total, about 25 million pots and traps and nearly 14 billion hooks are lost every year (Richardson et al., 2022).

Ghost Fishing

Fishing nets, traps, lines, and other equipment that fishermen discard at sea are known as ghost gear, also commonly referred to as ghost nets. It remains functional in the water and causes the mortality of aquatic organisms without human control. The phenomenon was first recognized by capture fisheries scientists in the mid-1970s (Matsuoka et al., 2005). The term 'ghost fishing' was first documented in 1978 and has subsequently been defined by the FAO (Wataniyakun et al., 2025). The lost gear acts as a passive fishing device, continuing to

capture marine organisms such as fish, sea turtles, marine mammals, seabirds, and crustaceans within its operating range (Voma et al., 2026).



Credit: OLIVE RIDLEY PROJECT

Scale of the Problem

According to a study, it has been estimated that 1.15 to 2.41 million tonnes of plastic enter the ocean each year (Koziol et al., 2022). More than half of the plastic is less dense than water. This indicates that most of the plastic remains in the upper layers of the ocean rather than reaching the seabed. Depending on the material or size, this type of floating plastic can be differentiated. The most frequently found plastics include polyethylene (PE) and polypropylene (PP). Other classification systems categorize Great Pacific Garbage Patch (GPGP) debris based on size or general type. About 92% of its mass consists of debris larger than 5 mm, of which at least 46% is made up of fishing nets (Koziol et al., 2022). More than 950 animal species worldwide have been reported to suffer from entanglement in or ingestion of marine litter, posing a significant threat to their survival and conservation (Gunasekaran et al., 2024). Every year, approximately 640,000 tonnes of fishing gear enter marine environments. Studies estimate that this contributes almost 10% of total marine litter. Therefore, ghost fishing is an important cause of marine pollution and biodiversity decline (Voma et al., 2026). Ghost fishing gear results from both human activities and environmental conditions. Accidental gear loss is also the most common in areas with intensive fishing activity, particularly where trawls, gillnets, traps, and pots are used.

Impact on Marine Life

Ghost fishing can have serious consequences for marine ecosystems and the services they provide. Small fragments of lost fishing gear, especially trawl nets, gillnets, and monofilament lines, are commonly involved in entanglement cases (Laist, 1996). When ALDFG remains in the water for an adequate period of time, sessile organisms may accumulate on it. This process is called 'biofouling' (Koziol et al., 2022). Lost traps and pots are also one of the main problems in the world's oceans and seas. They are used to catch a wide range of organisms, including crustaceans such as crab and lobster, octopus, whelk, cuttlefish, and fish. Baited traps can attract both target and non-target organisms. Once organisms enter traps or pots, they can serve as a new attractant in a process called self-baiting. Fishermen estimate that lost mesh pots can continue ghost fishing for 4–10 years. After accounting for escapement, an estimated 10,395–41,646 crabs die in these lost pots each year (Laist, 1996). The overall effect of ghost fishing by traps and pots can last from days to years. However, its effectiveness usually decreases over time as the gear becomes damaged, fouled, or buried, allowing trapped organisms to escape and preventing new animals from entering. The effectiveness also varies depending on the gear and species involved.

Impact on Fisheries and Economy

The study estimated that ghost fishing of commercial stocks is equal to 5–30% of annual landing levels. These estimates consider only ghost fishing by gear lost within the respective fishery, such as lobster mortality in lost lobster pots. One study estimated that annual Dungeness crab losses accounted for 4.5% of harvest value, which is equivalent to USD 744,296. Globally, removing derelict pots and traps at less than 10% shows a recovery of USD 831 million. Marine debris also affects tourism, with its direct economic impact estimated at USD 6.41 billion in 2015, which is 59.2% of the total damage caused by derelict plastic. Particularly when weather conditions are bad, propeller entanglement can lead to reduced stability and steering ability. Ghost fishing gear also damages critical coastal habitats, including seagrass beds, coral reefs, and mangroves. Marine debris, including lost fishing gear, can disrupt ship navigation by blocking water intakes, entangling propellers, and causing collisions with floating objects, resulting in economic losses when vessels must change their routes to avoid these hazards. This can be particularly significant in areas with heavy marine traffic (Koziol et al., 2022).

Management and Reduction of Ghost Fishing

Removing lost fishing gear is an important measure for reducing ghost fishing. More than 10,000 ghost nets have been collected over 10 years in Australia. The program also worked with Aboriginal artists to turn ghost nets into art, providing an alternative to burning or disposing of them in landfills. Derelict crab traps were collected in Louisiana, USA, in 2012 and 2013, with about 3,607 traps collected (Lively & Good, 2019). Cleanup and recovery efforts can be limited in scope. Another solution is the creation of bio-based fishing gear to reduce plastic waste in the ocean. Some of the popular bio-based plastics available on the market are polylactic acid (PLA), polyhydroxyalkanoate (PHA), and polybutylene succinate (PBS). They are used as substitutes for polypropylene (PP), polyester (PET), and polystyrene (PS). The Food and Agriculture Organization (FAO) provides the Voluntary Guidelines on the Marking of Fishing Gear to improve gear tracking, reduce gear loss, and support sustainable fisheries management. The guidelines provide a framework for countries to establish effective monitoring and reporting systems (Voma et al., 2026).

Conclusion

Ghost fishing is one of the important threats to marine environments. It kills organisms, destroys their habitats, disturbs natural and ecological systems, and causes microplastic pollution. Although the overall impact of derelict fishing gear and ghost fishing has not yet been fully assessed, available evidence shows that the issue is significant and cannot be overlooked. Assessing and reducing ghost fishing is important for the future of capture fisheries, as the resources lost through ghost fishing could instead support human consumption. Effective gear-return programs can also reduce the ecological damage caused by abandoned, lost, or discarded fishing gear.

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Water-Based PCR Detection of Aquaculture Pathogens for Early Disease Detection

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Abstract

Disease is the largest single source of loss in finfish and shrimp farming, and most of that loss accumulates before clinical signs appear. Conventional molecular diagnosis relies on tissue from sacrificed or biopsied animals, which is invasive and statistically weak when infection prevalence is low. Water-based detection takes the opposite route: pathogen nucleic acids shed into the culture environment as environmental DNA and RNA (eDNA/eRNA) are captured from a water sample and amplified by polymerase chain reaction (PCR). This article outlines the rationale, workflow, assay options, and field evidence for water-based PCR surveillance, drawing on work with white spot syndrome virus (WSSV) in shrimp ponds and tilapia tilapinevirus (TiLV) in tilapia systems. It examines the sampling, concentration, and extraction steps that govern sensitivity, and the limit of a water positive, which reports a genetic target rather than a viable, infectious agent. The approach works best not as a replacement for tissue diagnosis but as a repeatable, non-lethal early-warning layer.

Keywords: Environmental DNA; qPCR; aquaculture biosecurity; early disease detection; white spot syndrome virus; tilapia tilapinevirus; non-invasive surveillance

Introduction

Aquaculture now supplies more aquatic animal food than capture fisheries, and disease is the principal brake on its productivity. In intensive shrimp and tilapia systems, an outbreak can move from first infection to mass mortality within a week, so a diagnostic method's value depends less on its analytical elegance than on how early it produces an actionable signal.

The established molecular workflow samples the animal: pleopods, gills, hepatopancreas, or whole postlarvae are pooled, nucleic acids extracted, and a pathogen-specific PCR run. This is diagnostically decisive and underpins official certification, but it has three structural weaknesses. It destroys or stresses stock; it requires that the sampled animals actually carry the pathogen, improbable when prevalence is far below one per cent in a pond holding hundreds of thousands of animals; and being labour-intensive, it is rarely repeated often enough to catch the start of an epizootic.

Water-based PCR treats the culture water as an integrating sample. Every animal continuously sheds cells, mucus, faeces, and virions, and infected animals shed pathogen nucleic acid with them, so a litre of pond water carries a diluted molecular signature of the whole population rather than of a few individuals. Reviews of eDNA methods in freshwater aquaculture argue that this property, with non-lethal sampling, suits routine biosecurity monitoring [1].

Why Water Rather Than Tissue

The statistical case is the strongest. Detecting a pathogen at 0.5 per cent prevalence with 95 per cent confidence requires several hundred individually tested animals, an impossible weekly burden. A water sample need not find an infected animal; it needs only to capture enough shed target molecules to exceed the assay's detection limit, and because shedding begins during subclinical infection, the signal can precede visible disease.

Water sampling is also cheap, repeatable, and applicable where tissue sampling is impractical: broodstock ponds, hatchery tanks holding larvae too small to biopsy, quarantine units, and the inlet channels that form a farm's main biosecurity boundary. Screening intake water before it reaches production is a preventive function tissue testing cannot provide. Monitoring can also be quantitative: filtering the same volume by the same protocol at fixed intervals yields a time series of copy numbers, and a rising trend is more informative than a single positive.

From Pond Water to a PCR Result

Sampling design comes first. Target molecules concentrate near cages, feeding areas, aerator wakes, outlets, and the sediment-water interface, and are diluted elsewhere. Replicate samples from fixed points, taken at a consistent

time of day in sterile containers, make results comparable between visits; contamination control begins here, because one contaminated bottle can produce a false positive that drives a costly decision.

Concentration usually limits sensitivity, since target concentrations in pond water are very low. Membrane filtration is the common choice, with pore size traded against clogging in turbid water; alternatives include tangential flow ultrafiltration, used to process large volumes of shrimp pond water for WSSV detection [2], and chemical flocculation. Iron flocculation with probe-based reverse-transcription qPCR recovered about sixteen per cent of spiked TiLV from water while remaining cheap enough for routine use [3]: recovery need not be high if it is consistent and quantified.

Extraction must cope with inhibitors. Humic acids, polysaccharides, tannins, and metal ions co-purify with nucleic acids and suppress the polymerase, producing false negatives indistinguishable from true absence, so kits designed for environmental matrices are standard. Because eDNA, and especially eRNA, degrades quickly, filters should be preserved immediately in lysis buffer or ethanol, or frozen.

Assays validated on tissue cannot be assumed to work on water; detection limit, efficiency, and specificity must be re-established in the environmental matrix. A defensible run includes a no-template control, a positive control, an extraction blank, and an internal amplification control to show that inhibition was absent.



Choice of PCR Format

Conventional endpoint PCR is inexpensive and adequate for presence-absence screening, and has been used to detect eDNA of major shrimp pathogens in water and sediment. Nested PCR raises sensitivity for low-load WSSV detection but sharply increases contamination risk. Probe-based quantitative PCR (qPCR) is the practical reference standard because it is quantitative and closed-tube; for RNA viruses such as TiLV, the reverse-transcription variant is required. Multiplex assays screen several targets at once, digital PCR gives absolute quantification with better tolerance of inhibitors, and isothermal chemistries such as LAMP, though not PCR, move testing to the pond bank.

Evidence From Field Studies

The shrimp literature is the most developed. WSSV has been detected by PCR in filtered fractions of shrimp farm water, and the same study showed that the filtered material remained infectious to Penaeus vannamei, linking the molecular signal to transmission risk [4]. The virus has since been recovered from zooplankton and seston, indicating that plankton and detritus act as in-pond reservoirs [5], and reviews treat water as a central WSSV transmission route [6]. In finfish, TiLV work in Thailand established that pond water supports non-invasive routine detection and quantification after a low-cost concentration step [3].

Interpreting a Positive Result

A water PCR positive means a sequence attributable to the pathogen was present in the sample. It does not establish that the agent was viable, infectious, or causing disease; free DNA persists after the organism dies, and detection can arise from carriers, incidental fauna, or inlet water. A negative does not prove absence either, since shedding may fall below the detection limit or amplification may have been inhibited. The workable stance is therefore tiered. Water PCR is the screening layer, run frequently at fixed points; a positive, or a rising quantitative trend, triggers targeted tissue sampling and confirmatory testing under recognised protocols such as the WOAH Manual of Diagnostic Tests for Aquatic Animals [7], alongside immediate measures such as suspending water

exchange and isolating the affected unit. Every result should be logged with water temperature, salinity, stocking density, and recent management events, since a copy number is interpretable only against that context.

Limitations

Standardisation is the largest gap: sampling volumes, filters, concentration methods, and extraction kits vary between studies, so thresholds do not transfer between farms. The relationship between copies per litre and infection prevalence has been quantified for few pathogen-host combinations, matrix inhibition remains a routine error source, and cost and cold-chain logistics restrict access for smallholders.

Conclusion

Water-based PCR shifts surveillance from reacting to sick animals towards monitoring the environment they share. Its advantages follow from the sample itself: non-lethal collection, population-level integration, high-frequency repeatability, applicability to hatcheries and intake water, and quantitative trend data. Work on WSSV in shrimp ponds, and TiLV in tilapia systems shows the approach is field-deployable, provided concentration and extraction are optimised for water and assays are validated in that matrix rather than borrowed from tissue protocols. Its limits are equally clear, since a positive indicates a genetic target rather than infectious disease. Used as the screening tier of a biosecurity system, it provides what farmers most need and current practice least offers: warning early enough to act.

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The 110-Week Layer: Genetic Advancements and Recalibrated Husbandry

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ABSTRACT

The commercial egg industry is transitioning from traditional 72-week cycles to extended 100-110week lifecycles without molting, targeting an unprecedented milestone of 500 first-quality eggs per hen housed. This shift reduces pullet depreciation costs and lowers the sector's carbon footprint by 10% to 12%. Achieving these metrics requires leveraging multi-trait genomic selection alongside precise field management. Genetically, modern white strains are selected for enhanced persistency of lay (maintaining >80% production at week 100) and superior medullary bone mineral density. Unlocking this latent potential requires significant husbandry adaptations. Pullet rearing must prioritize gizzard volume development via structural fiber training and skeletal architecture optimization prior to week 12. Photoperiod stimulation must be delayed until a uniform flock threshold of 1,400 to 1,450 grams is achieved. Post 70 weeks, nutritional strategies must pivot toward organ preservation. These demands shifting diets to 70% to 80% coarse limestone fractions (2.0 to 4.0 mm) to protect structural bone reserves during nighttime shell calcification, alongside aggressive fortification with lipotropic agents to prevent Fatty Liver Haemorrhagic Syndrome (FLHS). Ultimately, synchronized management of this extended lifecycle establishes a new efficiency benchmark for commercial poultry producers and veterinarians.

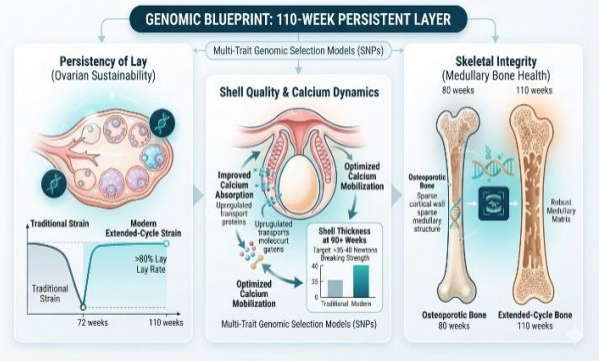
1. INTRODUCTION

For decades, the commercial egg industry operated on a rigid economic calculus flock depletion and replacement occurred at approximately 72 to 80 weeks of age. Beyond this window, a sharp physiological cliff emerged, characterized by a steep decline in the persistency of lay, deteriorating shell integrity and an exponential rise in internal skeletal depletion. Producers were forced to accept these boundaries, balancing the high capital depreciation of rearing a replacement pullet against the diminishing returns of an aging flock. Today, advances in commercial genomics have completely rewritten this paradigm. The industry is actively transitioning to a 100-110week production cycle without molting, targeting an unprecedented benchmark of 500 first-quality eggs per hen housed. This structural shift fundamentally recalibrates farm economics. By extending the productive life of the layer flock by 30 weeks, producers can spread fixed pullet rearing costs across a much larger volume of marketable egg mass. Achieving this milestone, however, requires a precise understanding of the genetic mechanisms that prevent the bird's biological machinery from breaking down.

2. THE GENETIC BREAKTHROUGHS BEHIND THE EXTENSION

2.1 Persistency of Lay (Ovarian Sustainability)

Historically, the late-stage production drop was caused by the natural follicular atresia and hormonal exhaustion of the avian ovary. Genetic selection has smoothed out this curve by prioritizing the ovarian follicular hierarchy. Modern white lines maintain a highly stable, sequential release of mature ova late into their life cycle. Genetically improved persistency ensures that the rate of decline post-peak is kept under 0.5% per week, allowing flocks at 100 weeks to consistently maintain lay rates well above 80%.



2.2 Shell Quality and Calcium Dynamics at 90+ Weeks

An aging hen faces a double jeopardy her eggs naturally grow larger (increasing the surface area that requires coating), while her intestinal tract becomes less efficient at absorbing dietary calcium. Left unmanaged, this

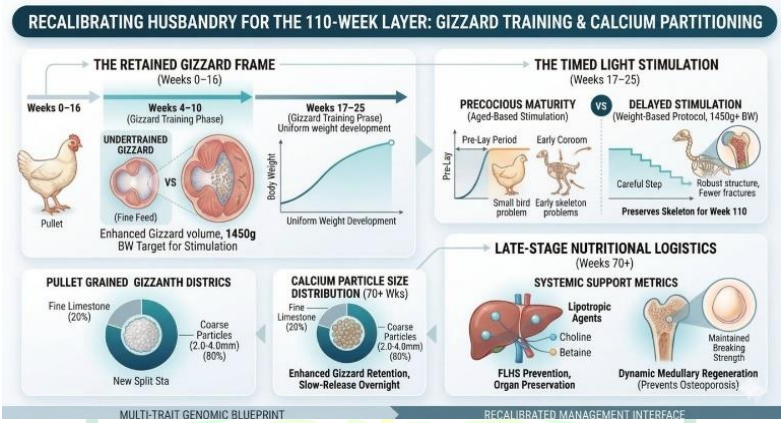
results in thin shells, micro-cracks and elevated downgrades. Genetics solved this by improving the expression of calcium-binding proteins in the intestinal mucosa and optimizing the circadian rhythm of the shell gland (uterus). Selection models now track shell breaking strength and shell elasticity at advanced ages, ensuring the hen can efficiently mobilize and deposit 2 to 2.2 grams of calcium per egg, even past day 700 of life.

2.3 Skeletal Architecture and Medullary Bone Health

A layer hen draws up to 40% of the calcium required for shell formation directly from her skeletal reserves-specifically the medullary bone-during the dark period when she is not feeding. In unimproved lines, this continuous resorption leads to progressive structural osteoporosis, cage fatigue and spontaneous fractures. Modern genetic selection directly evaluates bone mineral density (BMD) using non-invasive imaging and family lines. By selecting for a highly dynamic, structurally sound medullary bone matrix that rapidly regenerates during non-shell-forming hours, geneticists have engineered a bird that sustains structural integrity up to 110 weeks without sacrificing her own structural frame.

3. MANAGEMENT SHIFTS RECALIBRATING HUSBANDRY FOR THE 110-WEEK LAYER

Unlocking a 500-egg genetic potential requires a complete departure from historical management manuals. A bird engineered to lay past 700 days of age demands a proactive, multi-phasic husbandry strategy. If a producer treats a long-life flock with a traditional 72-week playbook, the bird's biological system will fail long before she reaches her genetic target.



3.1 Pre-Lay Structural Architecture (Weeks 0 to 16)

The foundation of a 110-week lifecycle is built entirely during the pullet rearing phase, where the primary objective shifts away from rapid weight gain toward the deliberate development of skeletal frame uniformity and gizzard capacity. To optimize gizzard training, introducing coarse insoluble grit alongside high-fiber structural components like sunflower or oat hulls between weeks 4 and 10 significantly expands gizzard volume. This anatomical enhancement ensures the hen possesses the necessary feed intake capacity late in life, enabling her to ingest the massive volumes of feed required to sustain both her body mass and extended egg output. Simultaneously, the flock must achieve critical skeletal milestones early, as a replacement pullet deposits over 90% of her total structural bone mineral content by week 12. This narrow developmental window requires veterinarians and barn managers to closely monitor shank and keel bone development. If the structural skeleton remains underdeveloped by week 16, the bird will permanently lack the medullary bone volume necessary to sustain continuous calcium mobilization at week 90 and beyond, triggering early-onset cage fatigue and shell degradation.

3.2 Photoperiod Manipulation and Sexual Maturity

Because precocious maturity remains the ultimate enemy of late-stage persistency, stimulating a flock to lay too early will permanently stunt their skeletal frames, yielding a high incidence of oviduct prolapse and early-onset shell degradation. To mitigate this risk, modern white lines must never receive light stimulation based on chronological age alone instead, producers must delay light step-ups until the flock achieves a uniform weight threshold of 1,400 to 1,450 grams, which typically occurs around 17 to 18 weeks of age. Furthermore, a strict step-down lighting program during the initial weeks of life is absolutely critical to keep the pullets calm and

prevent premature activation of the hypothalamus-pituitary-gonadal axis, ensuring the birds mature in lockstep with their structural capacity.

3.3 Late-Stage Nutritional Logistics & Particle Size Distribution

As the flock passes 70 weeks of age, the nutritional strategy must pivot from driving maximum production performance to prioritizing long-term organ preservation, specifically targeting gastrointestinal health and the metabolic footprint of the liver. To safeguard eggshell integrity during this late-stage plateau, the ratio of fine to coarse limestone must be progressively altered as the hen ages. Past 70 weeks, 70% to 80% of the dietary calcium should be supplied exclusively as coarse particles measuring between 2.0 and 4.0 mm. These larger fractions reside significantly longer in the gizzard, dissolving slowly overnight to provide a continuous, slow-release stream of calcium that directly supplies the shell gland during the dark period, thereby preventing the bird from drastically mining her own structural bone reserves. Simultaneously, systemic metabolic support is non-negotiable, as the liver of a 100-week hen filters enormous quantities of lipids for continuous yolk synthesis. To mitigate the risk of Fatty Liver Haemorrhagic Syndrome (FLHS) and ensure prolonged liver function, late-stage diets must be aggressively fortified with lipotropic agents, including choline chloride, betaine and methionine, alongside elevated concentrations of vitamins E and C. Finally, replacing traditional inorganic zinc, manganese and copper oxides with highly bioavailable organic trace mineral chelates significantly enhances the structural matrix of the eggshell membrane, directly reducing the incidence of micro-cracks and subsequent downgrades at the packing station.

4. THE TRIPLE WIN SUSTAINABILITY, WELFARE AND FARM MARGINS

The transition to a 110-week cycle represents an alignment of environmental sustainability, animal welfare standards and economic efficiency.

Metric Impact	72-Week Production Cycle	110-Week Production Cycle
Pullet Rearing Overhead	High (Requires frequent replacement inputs)	Low (Amortized over extra 30-40 weeks)
Feed Conversion Ratio (FCR)	2.10 - 2.15 kg feed per kg egg	1.95 - 2.02 kg feed per kg egg
Carbon Footprint Drop	Baseline	**10% to 12% reduction** in total emissions
Flock Welfare Profile	Standard (Interrupted by depletion/molt)	High (Extended, continuous liveability)

5. ENVIRONMENTAL FOOTPRINT REDUCTION

From an ecological standpoint, the extended lifecycle functions as an efficient resource optimizer. Rearing a pullet requires massive amounts of water, energy and high-protein feed without any immediate egg output. By extending the commercial lifespan of a single hen from 72 to 110 weeks, the total number of replacement pullets needed per year drops significantly. This optimization reduces the global poultry sector's environmental footprint, yielding a 10% drop in carbon emissions and significantly lower nitrogen and phosphorus output per dozen eggs produced.

6. THE FINANCIAL MATRIX

Pullet depreciation is generally the second-largest cost center on a commercial egg farm, surpassed only by feed. When a producer spreads the upfront purchase and rearing cost of a pullet over 500 eggs instead of 320 eggs, the cost of production per dozen eggs drops by an estimated 7% to 9%. These savings drastically improve profit margins, allowing commercial producers to hedge against volatile global grain and energy markets.

7. CONCLUSION

The 110-week persistent layer is no longer an experimental project it is the current global benchmark for commercial white bird systems. By using precise genomic markers, breeding companies have engineered a resilient bird capable of sustaining high lay rates and pristine shell structural integrity well past two years of life. However, genetics only provides the blueprint. The long-term success of this extended lifecycle relies entirely on the precision of farm managers and veterinarians. Through advanced gizzard training, tailored late-stage calcium partitioning and focused hepatic support, the industry is successfully producing clean, high-quality protein with fewer resources than ever before. As selection models refine these traits further, the industry is already looking ahead to the next logical milestone: a safe, predictable, and sustainable 120-week laying cycle.

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EL NINO EFFECTS ON MAJOR FRUIT CROPS

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The El Nino climate phenomenon significantly disrupts fruit crop cultivation in India, primarily driven by erratic monsoon rainfall, prolonged heatwaves, and severe groundwater depletion. Because horticultural crops are highly sensitive to sudden thermal and moisture fluctuations, changes in the microclimate lead to physiological stresses that severely diminish fruit yield, market quality, and farmer profitability.

The primary impacts of El Nino on major Indian fruit crops manifest across distinct lifecycle phases and geographical zones:

1. Physiological Damage and Crop-Specific Stress

Mango (The Hardest Hit)

Indias prized mango belts (across Andhra Pradesh, Maharashtra, Tamil Nadu, Telangana, and Karnataka) suffer heavily from erratic winter-to-spring temperature transitions. Extreme spring heat waves trigger premature flowering, massive flower drop, and fruit shedding. Compounding this, sunburn and localized acidic heat reactions cause smaller fruit sizes, drastically reducing the yield of premium varieties like Benesan, Alphonso, Dasehari, Kesar, Imam Pasand etc.

Banana

Insufficient monsoonal rainfall and dipping groundwater tables drastically limit water availability for this highly moisture-reliant crop. This directly stunts bunch size and restricts proper fruit development.

Citrus & Papaya

Severe water shortages combined with rapid moisture evaporation from the soil lead to restricted nutritional uptake, causing sunscald, smaller fruit dimensions, and overall degraded fruit quality

2. High Outbreaks of Pests and Diseases

The intense dry heat followed by sudden, unseasonal spells of rainfall creates a perfect breeding ground for destructive horticultural pests. Populations of sucking insects like thrips, aphids, mites, and whiteflies spike rapidly. Warm winter anomalies also heighten the risks of aggressive fungal infections and widespread infestation, requiring farmers to increase chemical inputs and monitor fields more frequently.

3. Regional Vulnerabilities

Southern & Western India (Andhra Pradesh, Maharashtra, Tamil Nadu, Karnataka)

Suffers from extreme thermal stress, borewell failures, and delayed river water releases (e.g., Cauvery water constraints), which actively choke irrigation channels for fruit orchards.

North & Northeast India

While mild dry cold conditions can occasionally benefit early flowering stages for temperate fruits like litchis, peaches, and plums, prolonged drought and rising heat fast-track premature fruit ripening, dragging down overall weight and commercial volume.

4. Economic Fallouts

As fruit and plantation farming yields decline due to these lingering climate disruptions, local markets face a sharp contraction in supply. Driven by strong domestic demand during festival seasons, the prices of essential commodities like banana stems, mango leaves, and premium fresh fruits spike heavily, contributing to broader food inflation across urban centers.

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Transforming Rural Women into Public Transport Contributors: The Changing Role of Women SHGs in Telangana

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Introduction

For anyone travelling along the roads of Telangana, it has become a familiar sight to see Telangana State - Road Transport Corporation (TGS-RTC) buses carrying inscriptions acknowledging a particular Mandal Samakhya (MS), a block/mandal level federation of women Self-Help Groups (SHGs). This naturally raises an intriguing question on how rural women, who often have limited economic resources, have been able to support such a large public-sector undertaking like RTC? Behind these inscriptions lies an inspiring story of rural women, who volunteered themselves, started with small savings, pursued and through their collective effort and with Government support, gradually established themselves and rose to the level where they can contribute to the public sector units like RTC.

The SHG movement in combined Andhra Pradesh (AP) started as early as 1980s with the launch of the Development of Women and Children in Rural Areas (DWCRA) in 1982. This started collective thrift and credit practices among rural women (Ramesh 2007). Later formation of Society for Elimination of Rural Poverty (SERP) in 2000 resulted in the large-scale expansion of SHGs across the state (Government of Andhra Pradesh, 2019; Soumya & Kumar, 2025). SHG groups provide participating women with various financial and non-financial benefits including mobilization of savings, accessing institutional credit, building social capital, gaining confidence, obtaining economic and technological exposure, and sustaining their livelihoods by diversifying their income sources (Jayashree and Reddy, 2016; Mishra *et al.,* 2018 & Atieno *et al*., 2024). Thus, SHGs became important avenues for the personal development and empowerment of rural women (Soumya & Kumar, 2025).
To enhance the voice and bargaining power of these poor women, SERP followed the principle of federating SHGs at higher levels; Village Organization (VO), Mandal Samakhya (MS) and Zilla Samakhya (ZS) at village, block and district levels respectively (Shylendra, 2021). These federations are registered under Mutually Aided Co-operative Societies (MACS) Act, 1995 (Ramesh, 2007). Subsequently, these federations developed their own source of income and employed regular staff that enhanced their financial, managerial and operational efficiency (Shylendra, 2021 & Yellaswamy, 2025).

Mahila Shakti programme

The Telangana state Government further implemented Mahila Shakti programme with an aim of wealth creation and to economically empower rural women (Government of Telangana, 2026). Under this programme, the SHG federations are encouraged to undertake larger and varied economic activities. One such initiative under the programme is the provision of buses by the SHG federations, especially MS, to the TGS-RTC on a hiring basis. The MS purchases bus through the state Government's financial support of around ₹30 lakhs along with their own contribution of about ₹6 lakhs and earns regular income of about ₹69,000 per month from hiring (The Hindu, 7 July 2025).

Traditionally, SHGs have been recognised for promoting savings, improving access to credit and supporting small livelihood activities among rural women. The emerging journey of SHG federations, where they became an important contributor of TGS-RTC signifies a broader transformation. Through collective investment in buses, these federations are moving beyond conventional thrift and credit activities towards productive asset ownership, enterprise management and engagement with a major public-sector institution. This initiative opens up new

possibilities for strengthening the economic role of rural women and diversifying the income sources of their institutions.

Conclusion

The partnership between SHG federations and TGS-RTC represents a promising evolution in the institutional journey of rural women in Telangana. It demonstrates how collective institutions, when supported by appropriate public investment and formal institutional linkages, can explore economic opportunities beyond their conventional activities. The long-term success of this model will depend on financial viability, transparent management and sustained institutional support. If these conditions are met, the buses bearing the names of women's federations may come to symbolise more than financial assistance: they may represent rural women's growing role in managing productive assets, generating institutional income and participating in the wider economy.

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Organic Farming and Water Security: A Review of Soil Health, Productivity and Groundwater Implications

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Abstract

Agriculture accounts for the largest share of global freshwater withdrawals, while groundwater depletion threatens the reliability of irrigation in many regions. Organic farming is often promoted for its soil and environmental benefits, but its contribution to water security is less certain. This structured narrative review examines evidence on soil water retention, crop water productivity, nutrient losses to groundwater and irrigation-related energy use. Literature from Scopus, Web of Science, Google Scholar and FAO's AGRIS database was considered, with emphasis on comparative studies, meta-analyses and reviews. Findings indicate that organic management often improves soil organic carbon, aggregation and infiltration, potentially increasing soil water retention. However, effects on yield and water productivity vary by crop, climate, rotation and nutrient management. Nutrient losses may decline per unit of land, although poorly timed applications of manure or compost can still cause leaching. Direct measurements linking organic practices to reduced irrigation demand or aquifer depletion remain limited. Organic farming should therefore be viewed as one component of an integrated water-management strategy, alongside efficient irrigation, appropriate crop selection, soil-moisture monitoring and support during conversion. Long-term comparative trials in semi-arid and irrigated settings are needed to establish water outcomes more directly.

Keywords: Organic farming; soil water retention; water productivity; groundwater conservation; nutrient leaching; sustainable agriculture

1. Introduction

Agriculture is the largest user of freshwater globally. The Food and Agriculture Organization has estimated that irrigated agriculture accounts for roughly 70 per cent of global freshwater withdrawals, with higher shares in some arid countries (FAO, 2011). As surface-water supplies become constrained, groundwater pumping has expanded in many agricultural regions, sometimes beyond natural recharge. Satellite-based research has documented substantial groundwater storage losses, including in India (Rodell, Velicogna and Famiglietti, 2009; Richey et al., 2015).

Organic farming restricts or excludes synthetic fertilisers and pesticides and relies on practices such as crop rotation, organic amendments and biological pest regulation. Research has documented benefits for soil quality and biodiversity (Mäder et al., 2002; Tuomisto et al., 2012), but water-related outcomes are less consistent. Increased soil organic matter can improve infiltration and water retention, while lower yields in some systems may offset field-level gains. Likewise, reduced use of soluble nitrogen may lower nitrate leaching, but nutrients from manure and compost can be lost when their release is not synchronised with crop demand.

This review synthesises evidence on organic management and soil water retention, water productivity, nutrient-related water quality and economic viability. It also identifies the conditions under which organic practices may contribute to groundwater and wider water security.

2. Literature Review

2.1 Soil organic matter and water-holding capacity

Soil organic matter supports aggregate stability, pore development and the retention of plant-available water. Lal (2004) described soil carbon sequestration as offering co-benefits for water retention, infiltration and drought

resilience. A global meta-analysis by Gattinger et al. (2012) found higher topsoil carbon stocks under organic farming than under conventional management, although the magnitude varied by climate, soil and management. The long-running Swiss DOK trial also reported improved soil fertility, microbial biomass and soil structure in organic plots (Mäder et al., 2002). These changes provide a plausible pathway to better soil-water relations, but direct measurements of soil-water storage and crop water use remain less common than measurements of soil properties.

2.2 Yield and water productivity

Comparisons of organic and conventional yields show variation across crops and production systems. Seufert, Ramankutty and Foley (2012) found that organic yields were generally lower on average, with the gap influenced by crop type and management and reduced in some cases by rotations and nitrogen-fixing legumes. In contrast, Pretty et al. (2006) reported yield gains from resource-conserving practices in several developing-country contexts. Water productivity—the amount of marketable output per unit of water consumed—can therefore improve only when any reduction in irrigation use is not outweighed by yield losses. It is an important indicator in water-scarce settings, yet has rarely been measured directly and consistently in organic systems (Rosegrant, Ringler and Zhu, 2009).

2.3 Nutrient management and water quality

Agricultural nitrate leaching can contaminate groundwater, particularly when nitrogen supply exceeds crop uptake or excessive irrigation carries nutrients below the root zone. Tuomisto et al. (2012) found that organic farming generally had lower nutrient-related impacts per unit of land area, while impacts per unit of product were more variable because of yield differences. Legume rotations, manure and compost can supply nutrients gradually, but release rates depend on temperature, moisture and management. Nutrient losses can still occur if organic amendments are applied in excess or before periods when crops can use the released nitrogen.

2.4 Energy and economic considerations

Where irrigation water is pumped from aquifers, the volume applied influences energy use and pumping costs. Organic farms may use fewer purchased inputs, but their energy requirements depend on mechanisation and cropping pattern. Conversion can involve temporary yield reductions, additional labour, certification expenses and uncertain market access; price premiums are not always immediate (Pretty et al., 2006). These constraints matter because farmers who rely heavily on groundwater may have limited capacity to absorb transition-period income losses.

Overall, the literature suggests that organic management can improve soil organic matter and related physical properties, but yield effects are context-specific and water-quality benefits depend on nutrient management. Evidence is insufficient to assume that improved soil properties automatically translate into lower irrigation withdrawals or aquifer recovery.

3. Methodology

A structured narrative review was undertaken to make the search and selection process more transparent while allowing synthesis of studies with different designs and outcome measures. The review drew on Scopus, Web of Science Core Collection, Google Scholar and the FAO AGRIS database. Search terms combined organic farming, organic agriculture and agroecological practices with soil water retention, water productivity, irrigation, groundwater, aquifers, water-use efficiency and nitrate leaching. Searches focused on English-language peer-reviewed articles, review papers and authoritative reports, with seminal earlier publications retained where foundational.

Studies were included when they compared organic or organic-principle management with conventional management under comparable conditions, or provided systematic evidence on organic farming and at least one water-related outcome. Marketing-only studies, studies without a comparator and purely theoretical models without field validation were excluded. Reference lists of key reviews were also screened. Information extracted included study location and climate, crop system, duration of organic management, water outcomes and reported direction of effects. Study quality was appraised qualitatively, considering comparability, duration, direct versus inferred water measurements and reporting of uncertainty. PRISMA reporting principles were followed where applicable, adapted for narrative synthesis.

The method has limitations. Google Scholar searches are difficult to reproduce exactly, English-only selection may omit relevant regional research, and narrative synthesis cannot generate pooled effect sizes. The scarcity of direct water-budget measurements also means that some conclusions rely on soil properties and related indicators rather than measured changes in water use.

4. Results and Discussion

4.1 Soil water retention

Across the reviewed evidence, organic management was commonly associated with higher topsoil organic carbon, improved aggregation and greater porosity (Gattinger et al., 2012; Mäder et al., 2002). These properties are associated with improved infiltration and water-holding capacity. Evidence is stronger for changes in topsoil properties than for effects on deeper soil layers, irrigation demand or aquifer recharge. The relationship between improved soil structure and reduced water application is therefore plausible but not yet firmly established across multi-season field trials.

4.2 Yield and water productivity

Yield responses were variable, with average organic yields often lower than conventional yields but differences depending on crop, rotation, nutrient availability and the conventional system used for comparison (Seufert et al., 2012). Resource-conserving practices have produced positive results in some developing-country settings (Pretty et al., 2006). For water security, yield per unit of water is often more informative than yield per hectare alone. If organic management lowers irrigation requirements while maintaining acceptable yields, water productivity may improve. If yield losses are large, reduced irrigation alone may not improve productivity. The limited number of direct comparative measurements prevents a universal conclusion.

4.3 Nutrient losses and water quality

The evidence indicates lower nutrient-related impacts per unit of land in many organic systems, but the outcome per unit of product is less consistent (Tuomisto et al., 2012). Organic nutrient sources can reduce dependence on soluble mineral fertilisers, but poorly timed or excessive applications can still result in leaching. Soil testing, balanced nutrient plans and extension advice are needed to match nutrient release with crop demand and reduce risks to groundwater.

4.4 Economic transition and adoption

Conversion may involve lower yields, extra labour, certification costs and limited access to premium markets. These barriers can discourage smallholders and farmers dependent on groundwater for their livelihoods. Transitional assistance, group certification, market linkages and public procurement may reduce some barriers. Economic viability is not separate from environmental performance: farmers need sufficient support to maintain practices long enough for soil-related benefits to develop.

4.5 Conditions for water-security benefits

Organic farming is most likely to contribute to water security when soil organic matter is built over time, irrigation is scheduled according to soil and crop needs, and yield losses are limited through suitable rotations and nutrient management. Improved water retention does not necessarily reduce irrigation if farmers continue using fixed schedules. Organic soil management should therefore be combined with soil-moisture monitoring, efficient irrigation and locally appropriate crop choices. The evidence base remains geographically uneven, with fewer studies in semi-arid irrigated regions where groundwater depletion is acute. Future research should measure soil-water storage, irrigation volumes, evapotranspiration, yields and water productivity together over multiple seasons.

5. Conclusion

Organic farming can support water security through improved soil organic matter, soil structure and potentially lower nutrient losses per unit of land. Nevertheless, it is not a universal or automatic solution to groundwater depletion. Yield responses vary, water productivity is rarely measured directly, and benefits depend on appropriate nutrient management and changes in irrigation practice. Organic farming should be promoted as part of an integrated strategy that includes efficient irrigation, crop selection, soil-moisture-informed scheduling, extension support and equitable access to markets and certification. Long-term comparative studies in semi-arid

and irrigated systems are needed to determine whether soil-level improvements translate into measurable reductions in water use and groundwater stress.

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The Future of Agriculture: Smart Technologies for Sustainable Farming

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Introduction: Farming at a Turning Point

Agriculture is entering a period of rapid change. Farmers must produce safe, nutritious food for a growing population while facing increasingly uncertain rainfall, rising input costs, pressure on land and water, and the need to protect soil health. At the same time, many farming communities face labour shortages and fluctuating market prices. These challenges cannot be addressed by increasing the use of land, water, fertilizers and pesticides alone. Agriculture needs to become more productive, precise and sustainable.

Modern technology offers practical tools to support this transition. Drones, sensors, hydroponics, agricultural robots, smart irrigation, precision nutrient management and digital marketing are changing how crops are monitored, cultivated and sold. These innovations do not replace farmers' knowledge; they can strengthen it by providing timely information and helping farmers make better-informed decisions. The future of agriculture will depend on combining scientific knowledge, local experience and appropriate technology.

1. Agricultural Drones: Eyes in the Sky

Agricultural drones, also known as unmanned aerial vehicles (UAVs), can help farmers observe fields quickly and identify problems that may be difficult to detect from the ground. Equipped with suitable cameras or sensors, drones can capture images of crop growth, reveal uneven crop development, and help locate areas affected by water stress, nutrient deficiency, pests or diseases. Some drones are also designed for the application of approved crop-protection products or other agricultural inputs, subject to local regulations and label requirements.

Compared with walking through every part of a large field, drone-based surveys can cover an area in less time. The information collected can guide targeted field inspections and help farmers decide where further sampling or treatment is needed. Applying inputs only where justified may reduce wastage and unnecessary exposure, improve operational efficiency and lower some labour demands. However, drones require trained operators, appropriate equipment, safe operating practices and compliance with applicable aviation and pesticide rules. They are most effective when their observations are checked against field conditions rather than treated as a substitute for agronomic judgment.

2. Hydroponics: Growing Crops Without Field Soil

Hydroponics is a method of growing plants without conventional field soil. Plant roots receive water and essential nutrients through a carefully managed nutrient solution, sometimes with the support of an inert growing medium. Hydroponic systems are commonly used in greenhouses and other controlled environments, where growers can manage nutrient concentration, water supply, temperature, humidity and light more closely than in open fields.

Leafy vegetables and herbs, including lettuce, coriander and some other short-duration crops, can be suitable for hydroponic production. Certain systems can also support crops such as tomatoes and cucumbers when their specific requirements are met. Because water and nutrients can be delivered directly to the root zone and, in recirculating systems, reused, hydroponics can use water efficiently and reduce nutrient losses. A controlled environment may also make crop monitoring and production scheduling easier.

Hydroponics is not automatically inexpensive or suitable for every farmer. Initial investment, electricity, water quality, nutrient management, disease prevention and technical skill all influence success. It should therefore be selected according to local demand, available infrastructure and a realistic business plan. Rather than

replacing all field agriculture, hydroponics can complement conventional farming, particularly where land is limited or high-value crops have a reliable market.

3. Smart Crop Monitoring: Turning Data into Decisions

Smart crop monitoring uses information from field sensors, weather stations, cameras, satellite imagery and drones to assess crop and soil conditions. Depending on the equipment available, farmers may track soil moisture, temperature, humidity, crop growth, pest symptoms and other indicators. Digital platforms can combine these observations to help identify emerging problems and determine where closer inspection is needed.

For example, if a section of a field shows signs of poor growth, a farmer can inspect that area and test whether the cause is inadequate moisture, nutrient deficiency, disease, compaction or another factor. If soil or plant testing confirms a nutrient shortage, corrective action can be directed to the affected area instead of applying the same quantity across the entire field. Similarly, weather information and field observations can help farmers plan irrigation and crop-protection activities more carefully.

The value of smart monitoring depends on data quality and interpretation. Sensors need correct placement, calibration and maintenance, while automated alerts should be checked against actual field conditions. Digital tools work best when they provide understandable recommendations that farmers can act on—not simply large amounts of data.

4. Agricultural Robotics: Supporting Farm Operations

Agricultural robots are machines designed to carry out specific farm operations with limited or, in some cases, substantial human control. Depending on the design, they may assist with sowing, transplanting, inter-row cultivation, spraying, crop inspection, harvesting or material movement. Camera systems, sensors, positioning technology and software can help a robot identify crop rows and navigate a field. Some machines are operated remotely, while others can follow programmed routes or perform defined tasks autonomously in suitable conditions.

Weed management is one promising application. A robot equipped with cameras and image-recognition software may distinguish crop rows from weeds and mechanically remove weeds near the crop. Some systems can target individual weeds rather than treating the entire field, potentially reducing herbicide use where the technology is accurate and appropriate. Mechanical weeding can also reduce dependence on repeated manual operations, although performance depends on crop spacing, soil conditions, weed species and the growth stage of the crop.

Robotics can help address labour-intensive tasks, but equipment costs, repair facilities, battery life, field layout and operator training remain important considerations. For many smallholders, shared machinery, custom-hiring centres and farmer-producer organisations may offer more practical access than individual ownership.

5. Smart Irrigation: Giving Crops Water When They Need It

Water is essential for crop growth, but both shortage and over-irrigation can reduce productivity. Smart irrigation combines soil-moisture sensors, weather information, automated valves or pumps, and digital controls to improve the timing and quantity of irrigation. A sensor can indicate when moisture in the root zone falls below a selected threshold. The system can then alert the farmer or activate irrigation, depending on its design and settings.

When properly planned, smart irrigation can help avoid unnecessary watering, reduce pumping time and improve the use of available water. Remote monitoring through a mobile phone may be especially useful for farmers managing several plots or irrigation units. Drip and sprinkler systems can be combined with monitoring tools to deliver water more efficiently, provided that equipment is maintained and irrigation schedules reflect the crop, soil and weather.

Automation alone does not guarantee water savings. Sensors must be installed at suitable depths and locations, and the system must be checked for leaks, blocked emitters and faulty readings. Farmers should also consider the cost of equipment, power availability and the reliability of mobile connectivity. The objective is not simply to irrigate automatically, but to supply the right amount of water at the right time.

6. Precision Fertilizer Application: The Right Nutrient, in the Right Place

Fertilizers support crop growth, but excessive or poorly timed application can increase production costs and contribute to nutrient losses and environmental pollution. Precision nutrient management aims to supply crops

with the nutrients they need, in appropriate amounts and at suitable stages of growth. Soil testing, crop observations, nutrient recommendations, sensors and digital field maps can help farmers understand differences within a field.

Where reliable information indicates a nutrient deficiency, farmers can consider a targeted application rather than treating every part of the field identically. Variable-rate equipment, fertigation systems and properly designed sensor-based controls may support more precise delivery. These approaches can improve input-use efficiency and reduce avoidable labour and wastage. Nevertheless, sensors do not always measure all nutrients directly; recommendations should be based on validated methods and, where appropriate, soil or plant analysis. Technology should complement balanced nutrient management, including suitable fertilizer sources, correct timing, proper placement, organic matter management and attention to soil health. The goal is not to eliminate fertilizer use, but to avoid both deficiency and excess while maintaining yield and protecting the environment.

7. Smart Marketing: Connecting Farmers with Buyers

Producing a good crop is only one part of a successful farming business. Farmers also need timely information about prices, quality requirements, demand, transport and potential buyers. Digital marketing tools—including mobile applications, online marketplaces, farmer-producer organisations, messaging platforms and social media—can help farmers share information about available produce and connect with traders, retailers, processors, institutions or consumers.

Direct communication can help farmers learn what buyers are looking for, coordinate harvest and delivery, and explore opportunities for grading, sorting, packaging or selling collectively. Digital records and advance orders may also improve planning and reduce the risk of unsold produce. For perishable commodities, however, market access must be supported by suitable storage, transport, quality assurance and dependable payment arrangements.

Farmers should verify buyers, compare prices and commissions, understand delivery conditions, and use secure payment practices. Digital marketing is not a guarantee of higher prices, but it can widen the range of available options and improve farmers' access to market information.

Making Technology Work for Farmers

No single technology will solve every agricultural challenge. A tool that is suitable for a large commercial farm may not be affordable or practical for a smallholder. Before investing, farmers should assess the local problem, expected benefit, operating cost, maintenance requirements, training needs and availability of technical support. Demonstrations, farmer field schools, agricultural universities, extension agencies, cooperatives and custom-hiring services can help farmers evaluate technologies before adopting them.

Reliable internet access, local-language interfaces, data privacy, repair services and access to finance also influence adoption. Public institutions and private companies can support farmers by providing transparent information, practical training and after-sales service. Technology providers should design systems for real farm conditions, including small and fragmented holdings, variable connectivity and diverse cropping systems.

Most importantly, digital tools should support—not displace—the farmer's knowledge of soil, weather, crop varieties and local farming practices. The strongest results are likely when technology is integrated with sound agronomy, locally adapted research and responsible resource management.

Conclusion: A More Productive and Sustainable Future

The future of agriculture will be shaped by how effectively farmers combine traditional experience with scientific innovation. Drones can improve field observation, hydroponics can provide an alternative production system for selected crops, smart monitoring can identify problems earlier, and agricultural robots can support labour-intensive operations. Smart irrigation and precision nutrient management can improve the use of water and fertilizers, while digital marketing can create additional routes to buyers.

These technologies are not magic solutions, and their benefits depend on correct use, affordability, reliable information and local suitability. When chosen carefully, they can help farmers reduce avoidable losses, make better-informed decisions and protect valuable natural resources. The real measure of agricultural innovation is not how advanced a machine appears, but whether it improves farm livelihoods while sustaining soil, water,

biodiversity and food quality. A future-ready agricultural sector will therefore be technology-enabled, farmer-centred and environmentally responsible.

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Phomopsis Blight and Fruit Rot of Brinjal Caused by *Phomopsis vexans*: Biology, Epidemiology and Management Strategies

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Abstract

Brinjal or eggplant (*Solanum melongena L.*) is an important vegetable crop that is grown in many tropical and subtropical areas, especially in India. A major problem for brinjal is Phomopsis blight and fruit rot caused by *Phomopsis vexans.* This disease is one of the damaging causing large losses in yield and quality. *Phomopsis vexans* infects leaves, stems, fruits and seeds leading to blight symptoms rotting fruit and lowering market value. When the weather is humid and warm the disease can cause up to a 70 percent loss. *Phomopsis vexans* survives on seeds, fallen plant parts and in the soil making it hard to control. This review covers the biology, classification, symptoms, life cycle, spread and interaction between host and *Phomopsis vexans*. It also focuses on control methods such as cultural practices, chemical fungicides, biological control agents, seed treatments and the use of resistant varieties. Eco-friendly options like *Trichoderma viride Pseudomonas fluorescens*, plant extracts, nanoparticles and induced resistance are discussed as alternatives. A combined approach that mixes preventive and eco-friendly tactics is needed to lower disease severity and keep brinjal production sustainable.

Keywords: Brinjal, *Phomopsis vexans,* Chemical fungicides, biological control agents, Nanoparticles

1. Introduction

Brinjal or eggplant (*Solanum melongena L.*) is one of the important vegetable crops in the family Solanaceae. Brinjal or eggplant is grown widely in subtropical regions around the world (Harish *et al*., 2011). India is one of the producers of brinjal. In India brinjal is grown extensively in states such as West Bengal, Bihar, Gujarat, Maharashtra, Andhra Pradesh and Uttar Pradesh (Anonymous, 2014). Brinjal is prized for its yield, adaptability and nutritional value. Brinjal plays a role in India's vegetable economy (Harish *et al*., 2011; Anonymous, 2014). South Asia alone contributes 50 percent of the world's brinjal production showing its global importance as a vegetable crop (Harish *et al*., 2011).

Brinjal can be attacked by diseases from fungi, bacteria, viruses, nematodes and mycoplasma. These diseases can severely reduce growth and yield (Islam *et al*., 2010). Key brinjal diseases include damping off bacterial wilt, leaf *Fusarium wilt, Alternaria* leaf spot*, Cercospora* leaf spot and Phomopsis blight and fruit rot (Rangaswamy and Mahadevan 2002). Among them Phomopsis blight and fruit rot caused by *Phomopsis vexans* (Sacc. & Syd.) Harter is one of the damaging. *Phomopsis vexans* attacks every above-ground part of the plant leaves, stems, fruits and seeds (Islam *et al*., 2010).

Phomopsis blight and fruit rot has become a danger for brinjal growers because Phomopsis blight and fruit rot causes large losses in yield and quality (Hossain *et al*., 2013). The first report of the disease was in Gujarat, India in 1914. Since then, Phomopsis blight and fruit rot has spread to brinjal-growing areas (Hossain *et al*. 2013). Typical yield losses are 15 to 20 percent. In severe cases losses can reach 70 percent when conditions are ideal (Hossain *et al*. 2013). Phomopsis blight and fruit rot also lowers market value and fruit quality by 20 to 30 percent, which is important for farmers and traders (Jain and Bhatnagar 1985). *Phomopsis vexans* infects fruits during the stages of growth and the damage worsens during harvesting and marketing (Srinivas *et al*., 2005).

This review. Summarizes what is known about brinjal the main diseases that affect brinjal and the economic impact of Phomopsis blight and fruit rot. It also highlights advances in controlling Phomopsis blight and fruit rot with fungicides, biocontrol agents and plant extracts to promote sustainable brinjal production (Srinivas *et al*., 2005; Islam and Meah 2011; Das *et al*. 2014).

2. Taxonomy and Nomenclature of *Phomopsis vexans*

- **Kingdom:** Fungi
- **Phylum:** Ascomycota
- **Class:** Sordariomycetes
- **Order:** Diaporthales
- **Family:** Diaporthaceae
- **Genus:** *Phomopsis*
- **Species:** *Phomopsis vexans* (Sacc. & Syd.) Harter

Synonyms

- *Phoma vexans* Sacc. & Syd.
- *Phoma solani* Halst.
- Sexual stage: *Diaporthe vexans*

Halsted first described the pathogen in 1892. Named it Phoma solani. Later Saccardo and Sydow changed the name to Phoma vexans. Then Harter moved it to the genus Phomopsis. Called it *Phomopsis vexans* (Walker, 1952). Singh in 1992 also reported that the perfect or sexual stage of *Phomopsis vexans* is *Diaporthe vexans*.

3. Distribution and Economic Importance of *Phomopsis vexans*

Phomopsis vexans the cause of Phomopsis blight and fruit rot of brinjal is found in eggplant-growing areas worldwide especially in tropical and subtropical places. *Phomopsis vexans* is common in nations such as India, Bangladesh, Pakistan, China and the Philippines where brinjal is grown a lot (Harish *et al*., 2011). *Phomopsis vexans* has also been found in African countries and other humid regions that favor fungal growth. In India *Phomopsis vexans* was first seen in Gujarat in 1914. Later spread to other brinjal-growing states (Hossain *et al*. 2013). Bangladesh is also a hotspot for *Phomopsis vexans*, where many different isolates of *Phomopsis vexans* have been reported from various agro-ecological zones (Islam *et al*., 2010).

Phomopsis vexans causes Phomopsis blight and fruit rot. This disease is regarded as one of the most destructive diseases of brinjal because *Phomopsis vexans* attacks leaves, stems, fruits and seeds and this leads to severe crop losses (Islam *et al*., 2010). Under field conditions yield losses from *Phomopsis vexans* generally range from 15-20% but when conditions are favorable and infection is severe losses may reach up to 70% (Hossain *et al*. 2013). Several researchers have also reported that *Phomopsis vexans* can reduce both yield and quality substantially during the kharif season and under humid conditions (Sugha *et al*., 2002).

The disease has an impact on fruit quality and market value. Infected brinjal fruits develop lesions rot quickly and become unfit for consumption and sale. *Phomopsis vexans* infection usually worsens during harvesting, transportation and storage causing post-harvest losses (Srinivas *et al*., 2005). Jain and Bhatnagar (1985) reported that *Phomopsis vexans* may reduce the market value and quality of fruits by 20-30%. Thus, *Phomopsis vexans* poses an economic threat to brinjal cultivation and has a big effect on the income of farmers and vegetable traders.

4. Symptoms of Phomopsis Blight and Fruit Rot of Brinjal

Leaf Symptoms

The disease first shows up on leaves as brown spots that are round or irregular. These spots grow larger when conditions are good. The spots often have rings that look like a target board. When leaves are heavily infected *Phomopsis vexans* makes them blight, dry. They may fall early which cuts down the plant's ability to photosynthesize (Singh, 1992). *Phomopsis vexans* may also make pycnidia on leaves. These pycnidia are black fruiting bodies that sit inside the lesions (Islam *et al*., 2010).

Stem and Twig Infection

On stems and twigs *Phomopsis vexans* makes long brown to lesions that can later turn into cankers. In cases *Phomopsis vexans* can cause girdling of the stem, which dries and kills branches and young shoots. Stem infection by *Phomopsis vexans* weakens the plant. Can lead to poor flowering and fruit setting (Rangaswamy and Mahadevan 2002). Pycnidia are commonly formed on stem tissues and appear as small black dots scattered over the lesion surface (Singh, 1992).

Fruit Symptoms

Fruit infection by *Phomopsis vexans* is the damaging part of the disease. At first pale, sunken soft spots appear on the fruit surface. As *Phomopsis vexans* spreads these spots grow fast turn brown to brown and eventually cover

much of the fruit. Infected brinjal fruits. Become unmarketable (Hossain *et al*., 2013). Under conditions many black pycnidia form on the affected fruit surface in concentric patterns which are the hallmark of Phomopsis fruit rot (Islam *et al*., 2010). The disease gets worse during harvesting, transport and storage causing post-harvest losses (Srinivas *et al*., 2005).

5. Pathogen Biology and Morphology of *Phomopsis vexans*

Mycelium Characteristics

Phomopsis vexans grows as whitish to white mycelium on Potato Dextrose Agar (PDA). The colonies may look compact, thick and sometimes fluffy with rings that depend on the isolate and growth conditions (Islam *et al*., 2010). Some isolates show embedded growth while others make fluffy colonies with loose mycelial texture. *Phomopsis vexans* shows a lot of variation in colony colour, texture and spore production, among isolates taken from agro-ecological regions (Islam *et al*., 2010).

Pycnidia Structure

The pathogen forms pycnidia as fruiting bodies on infected plant tissues and on artificial media. Pycnidia are globose to irregular in shape, black in colour. Are embedded within host tissues. According to Singh (1992) pycnidia on leaves measure about 60-200 µm in diameter while pycnidia on fruits are comparatively larger measuring 120-350 µm. Pycnidia possess an ostiole through which spores are released. Studies on Bangladeshi isolates reported size ranging from 216.96-589.86 µm in length and 101.7-637.32 µm in breadth depending upon isolate groups (Islam *et al*., 2010). Pycnidia may be densely or sparsely distributed on the culture media and infected tissues.

Conidia (Alpha and Beta Spores) The fungus produces two types of conidia, alpha (α) conidia and beta (β) conidia. Alpha conidia are hyaline single-cellled, sub-cylindrical and measure about 5-9 × 2-2.9 µm in size (Singh, 1992). These conidia are mainly responsible for infection. For spreading the disease. Beta conidia, called stylospores are filiform, curved, hyaline and aseptate. Beta conidia measure 20-30 × 0.5-1.0 µm and generally do not germinate (Singh, 1992). Islam *et al*. (2010) Reported that α-conidia ranged from 4.6-7.36 µm in length while β-conidia ranged from 22.08-55.2 µm among isolates.

Growth Conditions The fungus grows under warm and humid environmental conditions which favour disease development. Optimum growth of *P. Vexans* occurs around °C on PDA medium (Islam *et al*., 2010). High humidity, frequent rainfall and moderate temperature during the kharif season promote infection, sporulation and spread of *P. Vexans* (Sugha *et al*., 2002). The disease becomes particularly severe during fruit development and during post-harvest handling under moist conditions (Srinivas *et al*., 2005).

6. Disease Cycle and Epidemiology of *Phomopsis vexans*

Survival of the Pathogen

Survival of the Pathogen *Phomopsis vexans* survives in seeds, crop debris and soil for extended periods and is the main source of inoculum for the next crop season. *Phomopsis vexans* remains viable in plant parts such as infected stems, fruits and fallen debris left in the field (Islam and Meah 2011). The fungus also persists internally and externally on seeds making the disease mainly seed-borne (Islam and Meah 2011). Infected crop residues in soil further help *Phomopsis vexans* to survive between growing seasons and to start infections when environmental conditions are favourable (Rangaswamy and Mahadevan 2002).

Primary Inoculum The primary inoculum mainly comes from seeds and diseased crop residues. Seed-borne infection plays a role in passing the disease from one season to the next (Islam and Meah 2011). Infected seedlings that grow from seeds develop leaf blight and stem lesions at early growth stages and these later become sources of secondary inoculum. Pycnidia that form on infected tissues release conidia that start infections in the field (Singh, 1992).

Secondary Spread Secondary spread of the disease mainly happens through rain splash, irrigation water and wind-borne dispersal of conidia. During humid and rainy weather spores ooze out from pycnidia in a mass and splash onto healthy leaves stems and fruits (Sugha *et al*., 2002). Wind-driven rain and mechanical injuries during cultivation and harvesting also help the pathogen spread quickly inside the crop canopy. Fruit infection becomes severe during harvesting, transport and storage when conditions are moist (Srinivas *et al*., 2005).

Favorable Environmental Conditions Warm and humid environmental conditions favour the development of Phomopsis blight and fruit rot. The optimum temperature for growth and infection of *P. Vexans* is between 25–30 °C (Islam *et al*., 2010). High relative humidity above 85 % and continuous rainfall help germination, infection and spread of *P. Vexans* (Sugha *et al*., 2002). A dense crop canopy, poor aeration and long leaf wetness further increase disease severity. The disease is usually more severe during the kharif season and, in areas that receive rains and have high atmospheric moisture.

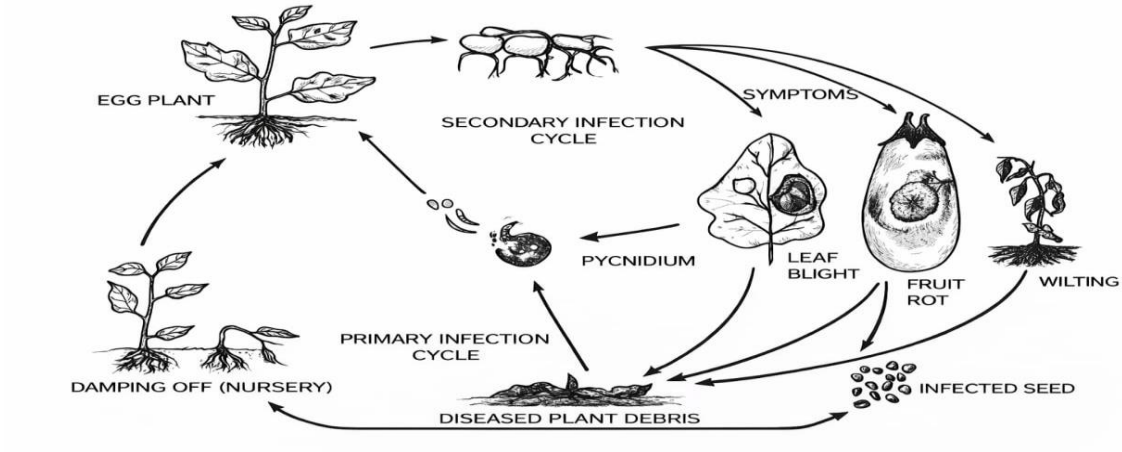


Fig. 1. life cycle of *Phomopsis vexanx* of brinjal

7. Host Pathogen Interaction:

The pathogen *Phomopsis vexans* infects plants through wounds, natural openings and direct penetration of epidermal tissues. The fungus first colonises leaves, stems and fruits. Then spreads quickly when conditions are humid. Pycnidia that form on infected tissues release conidia that germinate and penetrate host cells causing tissue discoloration, necrosis and fruit rot (Singh, 1992).

During infection *Phomopsis vexans* produces enzymes that break down cell walls and toxic chemicals that help it destroy host tissues and spread. Enzymes such as pectinase, cellulase and polygalacturonase dissolve plant cell walls causing fruits to soften and rot (Sugha *et al*., 2002). The production of these enzymes makes the disease more severe and spreads quickly inside plant tissues.

When *Phomopsis vexans* attacks, brinjal plants activate defense mechanisms. Brinjal plants produce compounds, phytoalexins and defense-related enzymes that limit fungal growth. Higher activity of enzymes such as peroxidase, polyphenol oxidase and ammonia lyase is linked to resistance against *Phomopsis vexans* infection (Islam and Meah 2011). Phenolic compounds strengthen cell walls and stop *Phomopsis vexans* development, which lowers disease progression.

The interaction between *Phomopsis vexans* and brinjal is decided by the balance between *Phomopsis vexans* virulence factors and brinjal defense responses. When the environment is favorable *Phomopsis vexans* defeats resistance and causes severe blight and fruit rot.

8. Detection and Diagnosis of *Phomopsis vexans*

Visual Diagnosis

Phomopsis blight and fruit rot on brinjal can first be identified by field symptoms. Infected brinjal leaves show brown spots with concentric rings. Brinjal stems have cankers and dieback. Brinjal fruits have sunken lesions that grow and rot completely. Tiny black pycnidia arranged in patterns on brinjal tissues are a typical sign of *Phomopsis vexans* (Singh, 1992). Severe fruit infection makes shrivel and become unmarketable especially when the weather is humid (Hossain *et al*. 2013).



Fig. 2. Symptoms of *Phomopsis vexans*

Microscopy:

Microscopic examination is often used to confirm the presence of *Phomopsis vexans*. Brinjal tissues are checked for pycnidia and conidia. *Phomopsis vexans* forms round pycnidia inside brinjal tissues. Two types of spores are seen: alpha (α) conidia, which're clear, single-cell and slightly cylindrical and beta (β) conidia, which are thread-like and curved (Singh, 1992). Measuring pycnidia and conidia under the microscope allows identification of *Phomopsis vexans* isolates (Islam *et al*., 2010).

Molecular Methods (PCR-Based Detection)

Molecular techniques give accurate detection of *Phomopsis vexans*. Polymerase Chain Reaction (PCR) methods that use primers are widely used to identify *Phomopsis vexans* in infected brinjal tissues and seeds. Studies in Bangladesh showed that different *Phomopsis vexans* isolates from brinjal areas have genetic differences (Islam *et al*., 2004a). PCR and DNA-based methods are very sensitive and helpful for detection, seed health checks and epidemiology. These methods are more reliable than symptom-based diagnosis especially when *Phomopsis vexans* is hidden.

9. Integrated Disease Management of *Phomopsis vexans:*

Table: Integrated Disease Management of *Phomopsis vexans*

Management Component	**Practices/ Treatments**	**Details and Importance**
1. Cultural Practices	Use of disease-free seeds	Healthy and certified seeds reduce primary seed-borne inoculum of *Phomopsis vexans* (Islam and Meah, 2011).
	Crop rotation	Rotation with non-solanaceous crops helps reduce survival of the pathogen in soil and crop debris.
	Field sanitation	Removal and destruction of infected plant debris and fruits minimize carryover of inoculum (Rangaswamy and Mahadevan, 2002).
	Wider spacing	Proper spacing improves aeration and reduces humidity within crop canopy, thereby lowering disease incidence.
2. Chemical Control	Carbendazim	Carbendazim effectively reduces leaf blight and fruit rot incidence when applied as foliar spray (Sugha *et al*., 2002).
	Mancozeb	Mancozeb is widely recommended as a protective fungicide against Phomopsis disease in brinjal.
	Copper oxychloride	Copper-based fungicides help suppress fungal growth and reduce spread of infection under field conditions.
3. Biological Control	*Trichoderma viride*	*Trichoderma* species antagonize the pathogen through competition, antibiosis and mycoparasitism, reducing disease severity.
	Pseudomonas fluorescens	This beneficial rhizobacterium suppresses pathogen growth and induces systemic resistance in brinjal plants.
4. Host Resistance	Resistant/tolerant varieties	Cultivation of tolerant varieties is an economical and eco-friendly approach, though highly resistant varieties are limited. Some local cultivars show moderate tolerance to *P. vexans*.
5. Seed Treatment	Hot water treatment	Hot water treatment of seeds helps eliminate externally and internally seed-borne inoculum.
	Fungicide seed dressing	Seed treatment with fungicides such as Carbendazim or Thiram reduces seed-borne infection and improves seedling health (Islam and Meah, 2011).
6.Emerging Approaches	Nanoparticles (Zn, Cu-based)	Zinc and copper nanoparticles exhibit antifungal activity and are being explored for eco-friendly disease management.
	Plant extracts	Botanical extracts such as neem, garlic and eucalyptus possess antifungal properties against *P. vexans*.
	Induced resistance (SAR, ISR)	Activation of systemic acquired resistance (SAR) and induced systemic resistance (ISR) enhances host defense through increased production of phenolics and defense enzymes.

10. Conclusion:

Phomopsis blight and fruit rot from *Phomopsis vexans* is a destructive disease of brinjal. It attacks leaves, stems, fruits and seeds causing quality and quantity losses. The disease spreads across brinjal regions and can cut yield by 20 to 70 percent when conditions are right (Hossain *et al*. 2013). Besides yield the disease also drags down fruit quality and market value leading to big economic losses, for farmers and traders.

Because the pathogen is seed-borne and lives in crop debris and soil the disease management approach must be. Effective. Using disease- seeds rotating crops cleaning fields and spacing plants properly can lower the disease incidence. Chemical fungicides like Carbendazim, Mancozeb and copper oxychloride can suppress the disease when used carefully. Biological control agents, for example Trichoderma and Pseudomonas fluorescens give eco-friendly alternatives and help keep disease management sustainable. Treating seeds and growing tolerant varieties also cut down the inoculum and slow the disease spread. Future disease management should focus on sustainable methods, such, as developing resistant cultivars using plant extracts, nanoparticles and boosting systemic resistance.

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Plant Molecular Farming: Green Biomanufacturing for the Future

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Introduction

Plant molecular farming (PMF), also known as molecular pharming, is an emerging biotechnology approach in which plants or plant cells are used as biological production platforms for recombinant proteins and other high-value molecules. Instead of relying only on conventional microbial or mammalian bioreactors, PMF uses the biological capacity of plants to synthesize, fold, assemble and accumulate complex products. The field has developed over several decades, while modern PMF increasingly uses transient expression systems, particularly in Nicotiana benthamiana, to obtain products rapidly. Recent research is also expanding the host portfolio toward alternative platforms such as duckweed and controlled plant-cell systems. PMF is gaining renewed attention because biomanufacturing must become more scalable, economical and sustainable while meeting demand for therapeutic proteins, vaccines, food ingredients and industrial enzymes. Recent reviews describe PMF as a potential platform for decentralized and sustainable biomanufacturing, while highlighting the importance of process integration, product quality, containment and downstream purification. The field is therefore moving from proof-of-concept expression toward integrated production systems that connect molecular design, cultivation, extraction and purification. The recent literature also emphasizes diversification of host plants. Duckweeds, for example, are fast-growing aquatic monocots with promising biomass productivity and genetic resources. Their use may help reduce some concerns associated with using terrestrial crops as production hosts, although large-scale controlled cultivation and transformation efficiency remain important challenges.

Importance of Plant Molecular Farming

1. Cost-Effective Production: Plants can provide a comparatively economical biological platform because they use light, water and nutrients to generate biomass, reducing dependence on expensive fermentation infrastructure for selected applications.

2. Rapid Production: Transient expression systems can produce recombinant proteins within a relatively short production cycle, supporting rapid response to changing demand and emerging biological threats.

3. Production of Complex Proteins: Plant cells can synthesize and assemble many recombinant proteins, including multimeric proteins and antibodies, while providing post-translational processing capabilities that are useful for biopharmaceutical applications.

4. Scalable Biomass-Based Manufacturing: Plants can be cultivated in controlled environments and, depending on the host and product, offer opportunities to increase production capacity through cultivation scale or stacked systems.

5. Product Diversification: PMF is no longer restricted to pharmaceuticals; current research considers vaccines, enzymes, food proteins, nutritional compounds, biomaterials and other high-value products.

6. Alternative Host Platforms: Duckweeds and plant-cell cultures are being investigated to overcome limitations associated with conventional terrestrial hosts and to enable more controlled production.

7. Sustainable and Decentralized Biomanufacturing: Recent work positions PMF as a possible component of future bioeconomies, particularly where local or distributed production of high-value molecules is advantageous.

Mechanism of Plant Molecular Farming

Plant molecular farming (PMF) begins with the selection and molecular design of a gene encoding the desired product. The gene of interest is introduced into a suitable plant expression system through either stable transformation or transient expression. In transient expression systems, engineered genetic material is delivered

into plant tissues, commonly through Agrobacterium-mediated transformation or related approaches. The introduced genetic sequence is subsequently transcribed and translated by plant cells, resulting in the production of the recombinant protein.

Following expression, the target molecule accumulates in the selected plant tissue or, in some systems, is directed toward secretion or a specific cellular compartment. The plant biomass is then harvested and subjected to downstream processing. These operations may include extraction, clarification, concentration, purification, and quality assessment. The final product is characterized based on its identity, purity, biological activity, stability, and other application-specific quality attributes.

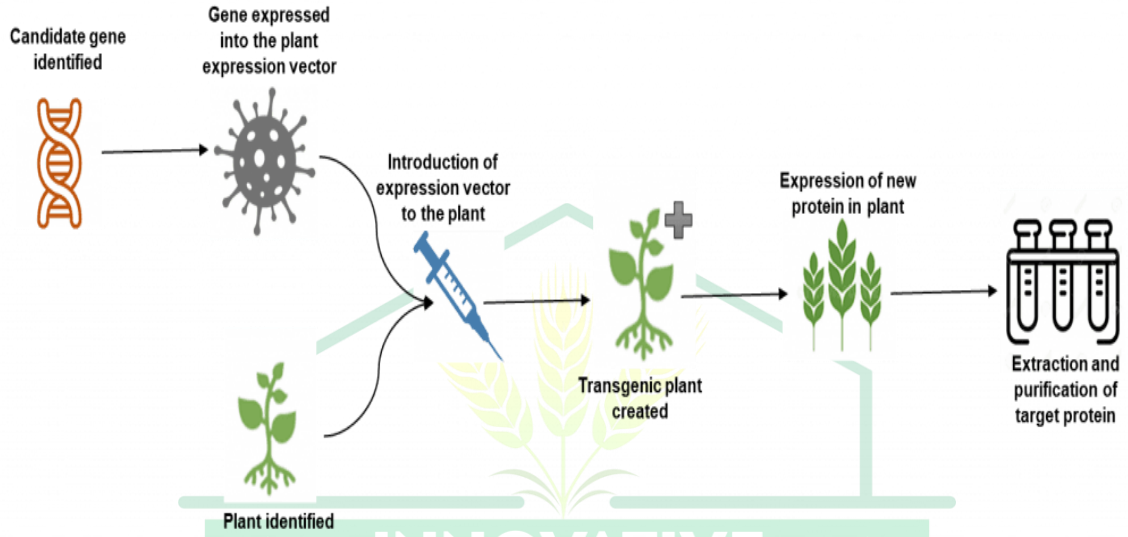


Fig. 1. General workflow of plant molecular farming, from target-gene design and host selection to expression, harvesting and purification.

Applications of Plant Molecular Farming

Plant molecular farming has applications across healthcare, food and nutrition, and industrial biotechnology. In healthcare, plants are used as production platforms for therapeutic proteins, monoclonal antibodies, vaccine antigens, and other biologically active molecules. PMF is also being explored for the production of food and nutrition-related proteins, including proteins with potential functional and nutritional benefits. In industrial biotechnology, plants can serve as production systems for enzymes and other high-value recombinant products. These diverse applications demonstrate the versatility of PMF and highlight the importance of evaluating the technology not only in terms of protein yield, but also product functionality, safety, production cost, downstream purification requirements, scalability, and environmental sustainability.

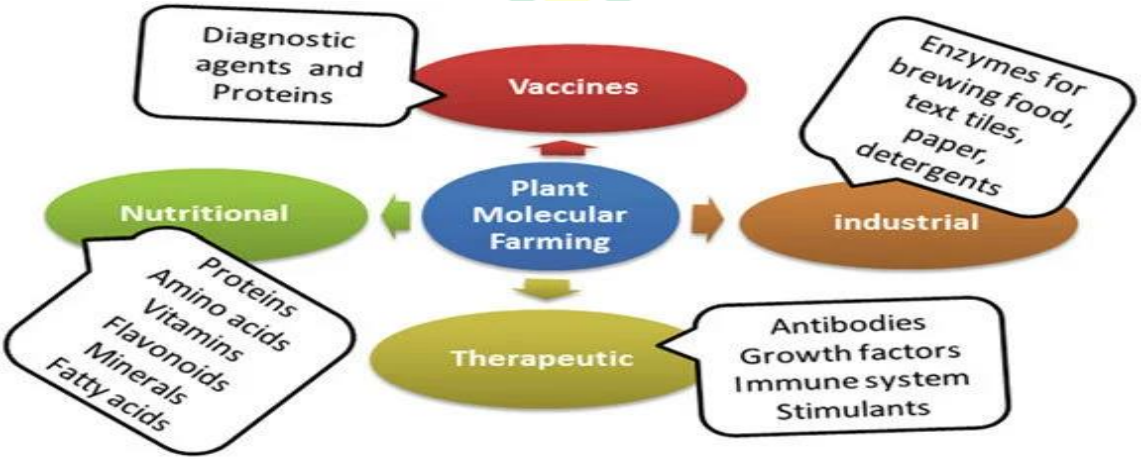


Fig. 2. Major application areas of plant molecular farming across healthcare, food, and industry.

Modern Milestones in Plant Molecular Farming

The commercial viability of Plant Molecular Farming (PMF) as an alternative to microbial and mammalian cell fermentation is demonstrated across three primary sectors:

- **Human Therapeutics and Biopharmaceuticals**

The landmark regulatory benchmark for PMF remains Taliglucerase alfa (Elelyso), an enzyme replacement therapy produced via transgenic carrot cell suspension (Daucus carota). Its 2012 US FDA approval validated plant platforms as safe, scalable bioreactors free from human pathogen cross-contamination. Furthermore, transient expression systems utilizing Nicotiana benthamiana demonstrated rapid-response capabilities by yielding clinical-grade Virus-Like Particle (VLP) vaccine candidates within four to six weeks of genome sequencing during pandemic outbreaks.

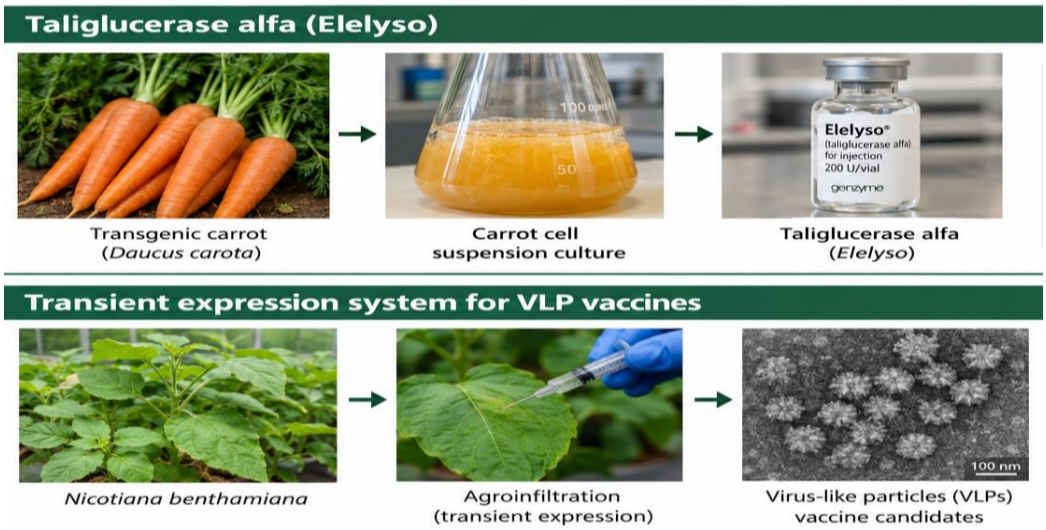


Fig. 3. Plant-based production of human therapeutics and biopharmaceuticals using transgenic carrot cell culture and transient expression in Nicotiana benthamiana.

- **Recombinant Food Proteins and AgTech Applications**

Recent advancements in seed-specific transformation have enabled field-scale expression of functional animal proteins. Moolec Science achieved stable integration in Glycine max (soybean), accumulating porcine muscle proteins up to 26% of total soluble seed protein. Similarly, host-system optimizations in Solanum tuberosum (potato) and oilseeds are targeting recombinant bovine caseins, addressing the functional requirements (e.g., micelle formation and heat-melt capabilities) lacking in native plant proteins.

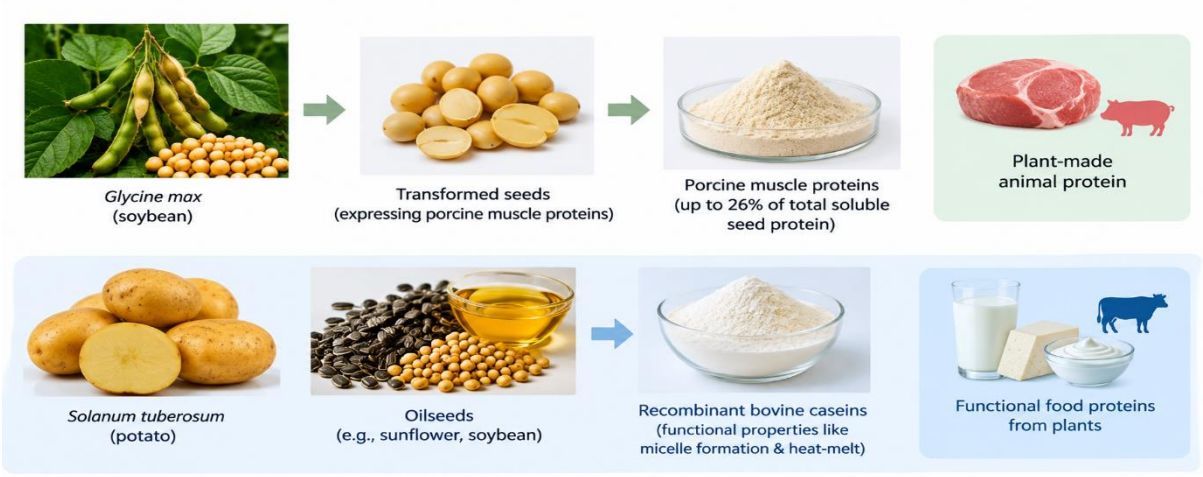


Fig. 4. Recombinant production of animal proteins in plants for food and agricultural applications.

Bioprocess Inputs and Growth Factors

To lower upstream costs in cellular agriculture, transgenic cereal crop platforms, such as Hordeum vulgare (barley), have been commercialized by entities like ORF Genetics to express human growth factors (e.g., FGF, EGF). Seed-based accumulation avoids expensive stainless-steel bioreactor capital expenditure (CapEx) while yielding cost-effective, serum-free media components for tissue engineering.

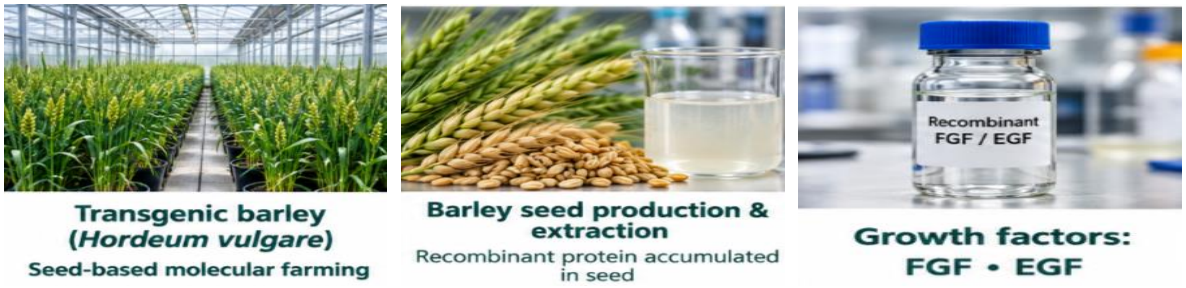


Fig. 5. Transgenic barley for recombinant FGF/EGF production and scalable serum-free media.

Future Perspectives

Future research in plant molecular farming should focus on improving product yield, consistency, quality, and scalability through advanced genetic engineering and optimized cultivation strategies. The development of alternative plant hosts, including Nicotiana benthamiana and duckweed, may provide efficient platforms for producing complex biopharmaceuticals. Particular attention should be given to engineering plant-specific post-translational modifications, improving downstream purification, and integrating automated cultivation and bioprocessing technologies. Furthermore, combining molecular engineering with process optimization, biosafety assessment, techno-economic analysis, and sustainable production approaches will be important for large-scale commercialization. Continued advances in regulatory frameworks and product characterization are also expected to support the broader adoption of plant-derived therapeutics, vaccines, and other high-value bioproducts.

Conclusion

Plant molecular farming (PMF) has evolved from an experimental approach into a promising platform for the production of high-value recombinant proteins and other biomolecules. By combining genetic engineering with plant-based production systems, PMF offers significant opportunities in pharmaceuticals, vaccines, nutrition, and industrial biotechnology. Recent advances highlight the importance of improving expression efficiency, diversifying host platforms, simplifying downstream processing, strengthening quality control, and achieving economically and environmentally sustainable production at scale.

Continued developments in plant synthetic biology, molecular engineering, controlled cultivation, and bioprocessing are expected to enhance the efficiency and reliability of PMF and enable it to complement established microbial and mammalian production systems. Emerging platforms such as duckweed, together with integrated and decentralized biomanufacturing strategies, further expand the potential of PMF to contribute to future healthcare, food security, and the bioeconomy.

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Editing the code of life in Rice: How CRISPR-Cas9 is revolutionizing crop improvement

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Introduction

Rice (*Oryza sativa* L.) serves as the primary staple food for more than half of the world's population. With global demographics projecting a population near 10 billion by 2050, the demand for rice production is intensifying. However, modern agriculture faces compounding environmental and economic pressures, including climate change, shifting weather patterns, shrinking arable land, freshwater scarcity, and escalating pest and disease outbreaks. To sustain global food security, conventional plant breeding methods while historically foundational are increasingly limited by long development cycles and linkage drag. CRISPR-Cas9 genome editing has emerged as a transformative molecular tool that enables precise, site-specific targeted modifications within the rice genome, compressing crop improvement timelines from decades down to a few years.

The Molecular Mechanism: How CRISPR-Cas9 works

Originally adapted from the adaptive immune mechanism of bacteria, the CRISPR-Cas9 system operates as molecular scissors designed to locate and edit specific genomic sequences (Liu *et al*., 2021). The system consists of two core functional elements:

- **Guide RNA (gRNA):** A synthetic RNA sequence custom-designed to complement and hybridize with a specific ~20-nucleotide target sequence in the host plant genome.
- **Cas9 Endonuclease:** A protein enzyme guided by the gRNA to create double-strand breaks (DSBs) at precise target locations adjacent to a protospacer adjacent motif (PAM).

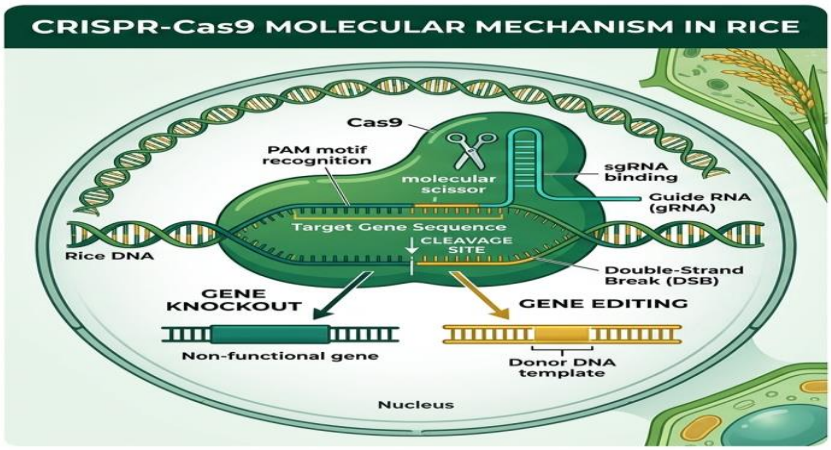


Figure 1: Molecular mechanism of CRISPR-Cas9 genome editing in rice cell nucleus showing gRNA targeting, Cas9 cleavage, and repair outcomes (Gene Knockout vs. Precision Gene Editing).

Once a double-strand break is generated, the plant's endogenous DNA repair mechanisms are triggered via either Non-Homologous End Joining (NHEJ) or Homology-Directed Repair (HDR). Researchers exploit the error-prone NHEJ pathway to induce small insertions or deletions (indels) that cause frame-shift mutations, successfully generating gene knockouts to study or eliminate undesirable traits (Park *et al*., 2022).

Major Applications in Rice Crop Improvement

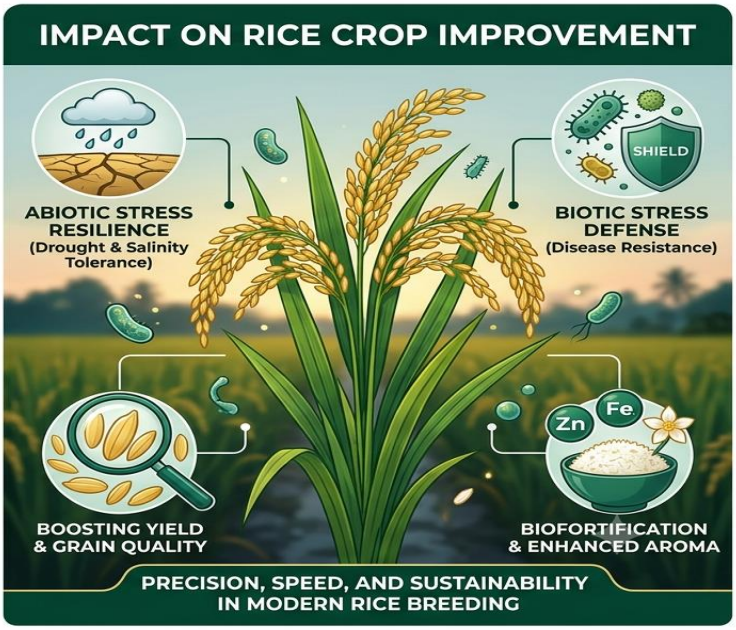


Figure 2: Major agricultural applications of CRISPR-Cas9 in rice crop improvement, including abiotic stress resilience, biotic disease defense, yield enhancement, and grain biofortification.

1. Enhancing Grain Yield and Quality Architecture

Grain yield is a polygenic trait regulated by grain weight, panicle structure, tiller number, and grain dimensions.

- **Grain Weight and Dimensions:** Targeting negative regulatory genes such as *GW2*, *GW5*, and *TGW6* via CRISPR-Cas9 knockout strategies has demonstrated marked increases in thousand-grain weight and overall seed size (Zhang *et al*., 2025; Rengasamy *et al*., 2024).
- **Aroma and Grain Flavor:** The volatile compound 2-acetyl-1-pyrroline (2-AP) provides the characteristic fragrance in premium Basmati and Jasmine rice varieties, regulated by the BADH2 gene. Targeted knocking out of BADH2 using CRISPR-Cas9 converts non-aromatic elite rice lines into fragrant cultivars without sacrificing agronomic performance (Imran et al., 2023).

2. Developing Abiotic Stress Resilience

Extreme environmental conditions driven by climate change necessitate the rapid development of stress-tolerant crop varieties.

- **Salinity Resistance:** Soil salinization severely restricts rice productivity in coastal and irrigated regions. CRISPR-Cas9-mediated knockout of negative regulators like the transcription factor *OsbHLH024* enhances salt tolerance by modifying ion transporter expression and reactive oxygen species (ROS) scavenging (Alam *et al*., 2022).
- **Drought Resilience:** Targeted modifications of senescence-associated genes (*OsSAP*) and stomatal density regulators allow edited plants to reduce transpirational water loss and maintain photosynthetic capacity during periods of severe drought (Park *et al*., 2022).

3. Biotic Stress Defense and Disease Resistance

Phytopathogens cause substantial annual yield losses in global rice production.

- **Bacterial Blight (*Xanthomonas oryzae* pv. *oryzae*):** Pathogens exploit host *OsSWEET* sucrose transporter genes to fuel infection. Editing promoter regions or coding sequences of susceptibility genes such as

OsSWEET14 blocks pathogen access to nutrients, conferring durable bacterial blight resistance without triggering yield penalties (Zeng *et al*., 2020).

- **Rice Blast (*Magnaporthe oryzae*):** Knockout of negative defense regulators, such as the ethylene-responsive factor gene *OsERF922*, significantly increases host resistance against rice blast fungal infection through enhanced immune signaling pathways (Wang *et al*., 2016).

4. Biofortification and Food Safety

Improving the nutritional profile and biosafety of rice grains directly addresses public health challenges such as micronutrient deficiencies and heavy metal toxicity.

- **Heavy Metal Uptake Reduction:** Cultivation in industrial soils can lead to toxic cadmium accumulation in grains. Specific CRISPR-Cas9 knockout of the heavy metal transporter gene OsNramp5 prevents cadmium transport into the grain while leaving plant productivity and essential nutrient transport intact (Tang *et al*., 2017).
- **Nutritional Enhancement:** Disrupting phytic acid biosynthesis pathways via targeted gene editing decreases phytate content, increasing the bioavailability of essential dietary minerals like iron and zinc in polished rice grains (Liu *et al*., 2021).

Advantages Over Conventional Transgenic Breeding (GMOs)

Compared with traditional Genetically Modified Organism (GMO) development, which involves random genomic insertion of foreign recombinant DNA, CRISPR-Cas9 offers key technical and regulatory distinctions:

- **Transgene-Free Lines (SDN-1):** The CRISPR-Cas9 transgene construct can be segregated out through standard genetic crosses in subsequent T1 or T2 generations, yielding null-segregant, non-transgenic edited lines carrying only precise, endogenous genomic edits (Park *et al*., 2022).
- **Streamlined Regulatory Protocols:** Global regulatory agencies including those in the United States, Japan, India, Australia, and multiple South American countries increasingly classify transgene-free SDN-1 (Site-Directed Nuclease-1) edited crops as non-GMO, exempting them from onerous regulatory burdens and accelerating field commercialization.

Scientific Challenges and Emerging Technologies

Despite its broad utility, full implementation of CRISPR-Cas9 faces minor technical hurdles:

- **Off-Target Effects:** Unintended cleavage at non-target genomic sites with sequence homology remains a concern, prompting the adoption of high-fidelity Cas9 variants and optimized gRNA design algorithms.
- **Multiplex Editing:** Simultaneous manipulation of multiple complex polygenic traits requires multi-gRNA cassette expressions, which are being refined to optimize editing efficiency across diverse gene targets (Zhang *et al*., 2025; Rengasamy *et al*., 2024).

Advanced genome editing variants such as base editing (enabling targeted single-nucleotide conversions without DSBs) and prime editing (allowing direct search-and-replace edits) are further expanding the precision and scope of rice trait engineering.

Conclusion

CRISPR-Cas9 genome editing represents a paradigm shift in plant biotechnology, moving crop improvement from stochastic selection to precise genomic design. By enabling simultaneous improvements in yield potential, biotic and abiotic resilience, nutritional value, and food safety, CRISPR technology serves as a critical driver for sustainable rice production and global food security.

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Why Do Fruits Change Colour When They Ripen?

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Introduction

Have you ever wondered why a green mango gradually turns yellow, why a tomato changes from green to bright red, or why a strawberry develops its attractive crimson colour? These familiar transformations reveal a remarkable biological process taking place inside the fruit. Ripening involves coordinated changes in colour, texture, taste, aroma and nutritional composition. Naturally occurring pigments are broken down, newly produced or accumulated in different cellular structures, while plant hormones help coordinate the process.

Understanding these changes is useful beyond satisfying curiosity. Farmers and horticulturists rely on signs of maturity to decide when to harvest, handle and market fruits. Consumers use colour as one clue when choosing produce. Yet colour alone does not always guarantee sweetness or ideal eating quality.

Why Are Young Fruits Usually Green?

Many developing fruits are green because their tissues contain chlorophyll, the pigment that gives leaves their colour and absorbs light for photosynthesis. Young tomatoes, mangoes and bananas commonly contain chlorophyll in their outer tissues.

During ripening, enzymes dismantle chlorophyll molecules in a process called degreening. Pigments previously hidden by the green colour may then become visible, while additional pigments may be synthesized. A banana peel, for example, changes from green to yellow largely as chlorophyll declines and yellow carotenoids become more apparent. Not all ripe fruits lose their green colour: some apple cultivars and other fruits remain green at edible maturity. Genetics matters as much as the passage of time.

The Three Main Pigment Groups

Chlorophyll produces the familiar green appearance of many immature fruits. Its breakdown can reveal other pigments, but loss of greenness should not be confused with complete ripeness.

Carotenoids contribute yellow, orange and red shades. Beta-carotene helps produce orange-yellow colours in mangoes and papayas; lycopene is largely responsible for the red colour of ripe tomatoes; and xanthophylls contribute yellow coloration in several fruits. As tomatoes ripen, green chloroplasts develop into pigment-storing chromoplasts, and lycopene accumulates. This is a well-studied example of ripening-related cell transformation.

Anthocyanins produce many red, purple and blue shades, particularly in strawberries, grapes and some apple skins. They belong to the flavonoid group and usually accumulate within vacuoles, the fluid-filled compartments of plant cells. Their visible colour depends on chemical structure, concentration, cellular acidity and interactions with other substances. Fruit colour is therefore determined by the mixture and location of pigments, not by one universal ripening dye.

How Plant Hormones Control Ripening

Fruits do not change colour at random. Developmental signals activate genes and enzymes that regulate pigment formation and breakdown. Ethylene is one of the most influential signals. Although it is a gas, ethylene acts as a plant hormone and helps regulate ripening in bananas, mangoes, apples and tomatoes.

These are called climacteric fruits because they typically show a rise in respiration and ethylene production around ripening. Ethylene influences chlorophyll breakdown, pigment synthesis, softening, aroma production and changes in sugar and acid metabolism. It acts within a wider network of genes and hormones rather than operating as a solitary switch.

Strawberries and grapes are non-climacteric fruits: they do not show the same characteristic ethylene and respiration surge. In strawberries, the hormone abscisic acid (ABA) plays a prominent role in ripening and anthocyanin formation. Other hormones also contribute. Similar visible colour changes can thus arise from different biological regulatory systems.

The Journey from Green Tomato to Red Tomato

A young tomato contains chlorophyll and appears green. As it reaches physiological maturity, the first patches of non-green colour appear at the breaker stage. The fruit then passes through turning, pink and red-ripe stages. Chlorophyll declines while carotenoid synthesis accelerates; lycopene becomes especially abundant in the flesh and skin.

Ethylene influences the expression of ripening genes and helps coordinate the transformation of chloroplasts into chromoplasts. This explains much of the characteristic colour change, but it is not a rule that all ripe tomatoes must be red. Yellow, orange and purple cultivars possess different pigment profiles owing to genetic variation. Colour is a product of both developmental stage and cultivar.

Why Do Fruits Become Sweeter and Softer?

Colour change is only one part of ripening. A green banana is generally firm and rich in starch, while a ripe banana is softer and sweeter. Enzymes convert stored starch into soluble sugars, altering flavour. In mangoes and other fruits, changes in sugars and organic acids also affect the balance between sweetness and sourness.

Meanwhile, enzymes modify pectin and other components of the cell wall, contributing to softening. Fruit aroma develops through changing production of volatile compounds. Although these processes are coordinated, they do not occur at exactly the same rate. A fruit may look attractively coloured before reaching its best flavour, which is why colour should not be the sole measure of quality.

Can Sunlight and Temperature Change Fruit Colour?

Light can influence pigment accumulation, especially anthocyanins. In red apple cultivars, exposed portions of the fruit may develop stronger pigmentation than heavily shaded areas. Temperature can also affect pigment metabolism. Excessive heat, for example, may interfere with normal lycopene accumulation in tomato and contribute to uneven red coloration.

These effects vary with crop, cultivar and stage of development. Water availability, nutrient balance and orchard management can also influence fruit appearance indirectly. This knowledge helps growers manage canopy conditions, select suitable varieties and interpret differences in colour without assuming that every pale fruit is immature.

Can Fruits Change Colour After Harvest?

Yes, provided the fruit was harvested at a suitable stage of maturity. Mature green bananas, tomatoes and mangoes can continue ripening after harvest. Their natural ethylene signalling continues, and commercial handlers may use carefully controlled ethylene exposure to achieve more uniform ripening.

Strawberries and grapes generally do not continue gaining sweetness or full eating quality after picking in the same way. They are therefore usually harvested much closer to consumption maturity. A mature green fruit may colour after harvest, but a fruit picked too early may never attain desirable flavour. Appropriate harvest maturity, storage temperature and careful handling remain essential.

Does Brighter Colour Mean Better Nutrition?

Fruit pigments can contribute to nutritional value. Beta-carotene is a precursor of vitamin A, while lycopene and anthocyanins have antioxidant properties demonstrated in chemical and laboratory studies. Their presence, however, does not establish that a darker or brighter fruit is necessarily healthier or that eating a specific pigment prevents disease.

Fruit quality also depends on fibre, vitamins, minerals and many other constituents. Variety, ripeness, storage and processing all affect composition. Eating a varied selection of fruits is more sensible than ranking every fruit by the intensity of its colour.

Why Might Colour Matter in Nature?

Brightly coloured fleshy fruits may attract animals that eat them and disperse their seeds. For some species, changes in appearance accompany the development of flavours and textures that make ripe fruits appealing to

seed dispersers. The relationship is not universal: animal vision, fruit chemistry, habitat and evolutionary history all influence the ecological role of colour. Still, fruit pigmentation provides a fascinating example of how plant development can interact with the surrounding environment.

Conclusion

A green mango turning yellow or a tomato becoming red is the visible result of coordinated biochemical changes. Chlorophyll disappears, carotenoids or anthocyanins may accumulate, and hormonal signals guide the process. Genes, sunlight and temperature help shape the final colours. For growers, this science supports better choices about maturity, harvesting and handling. For everyone else, it offers a new way to appreciate the fruit bowl: behind each colour is an intricate story of living cells at work.

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Seeds of the Future: Integrating Artificial Intelligence, Smart Seed Technology and Precision Phenotyping for Next-Generation Seed Systems

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Abstract

Seeds are the starting point of crop productivity, yet conventional quality assessment can be slow, labour-intensive and dependent on destructive sampling or subjective inspection. Artificial intelligence (AI), smart sensors and precision phenotyping offer ways to measure seed traits rapidly and consistently, including size, colour, damage, varietal identity and selected indicators associated with viability and vigour. This article synthesizes recent literature and seed-system guidance to explain these technologies, their uses and their limitations. Digital tools should strengthen-not replace validated germination, purity, health and certification procedures. Their greatest value will come from combining sensor data with reliable reference tests, biological understanding and field performance.

Introduction

A seed lot may look uniform but differ greatly in physiological quality. Standard germination testing estimates the capacity to produce normal seedlings under specified favourable conditions; seed vigour provides a broader indication of speed, uniformity and performance under less favourable conditions. Storage ageing, mechanical injury, infection and differences in maturity can reduce performance even when external appearance changes little. Seed enterprises must also assess large lots quickly and maintain traceable records. High-throughput phenotyping, the rapid measurement of many samples using sensors, combined with AI is emerging as a promising route to more objective seed inspection.

Approach and evidence base

This is a narrative review, not an original experiment. It synthesizes peer-reviewed reviews and selected studies on computer vision, spectroscopy, machine learning and seed-system development. No new samples were collected and no original accuracy estimate is claimed. Study characteristics below illustrate the scope of research, not a universal performance benchmark.

From seed images to intelligent decisions

Modern seed-quality assessment is moving beyond visual inspection towards rapid, non-destructive and data-driven evaluation. A digital workflow begins with representative sampling and controlled image acquisition; images are then segmented so that individual seeds can be measured consistently. Red-green-blue (RGB) and three-dimensional imaging can quantify length, width, shape, colour, surface texture and visible damage, while near-infrared (NIR) spectroscopy and hyperspectral imaging capture wavelength-dependent signals associated with seed composition and selected quality attributes. X-ray imaging can reveal some internal structures or damage that may not be visible externally. These measurements are converted into numerical features and analysed using machine-learning methods such as random forests and support-vector machines, or deep-learning models such as convolutional neural networks. Depending on the crop and training data, models may assist with seed classification, size grading, foreign-material detection, damage screening and prediction of selected quality traits. An image-based prediction is not automatically a direct measurement of viability or vigour: physiological claims must be calibrated and independently validated against standard germination and vigour tests, while seed-health and genetic-purity claims require appropriate specific tests. Robust models should be evaluated on

independent seed lots, harvest seasons and locations, with sample size, class balance, uncertainty and errors reported. When these safeguards are followed, image analytics can help prioritize samples for testing, improve consistency and support-but not replace-validated seed-quality decisions.

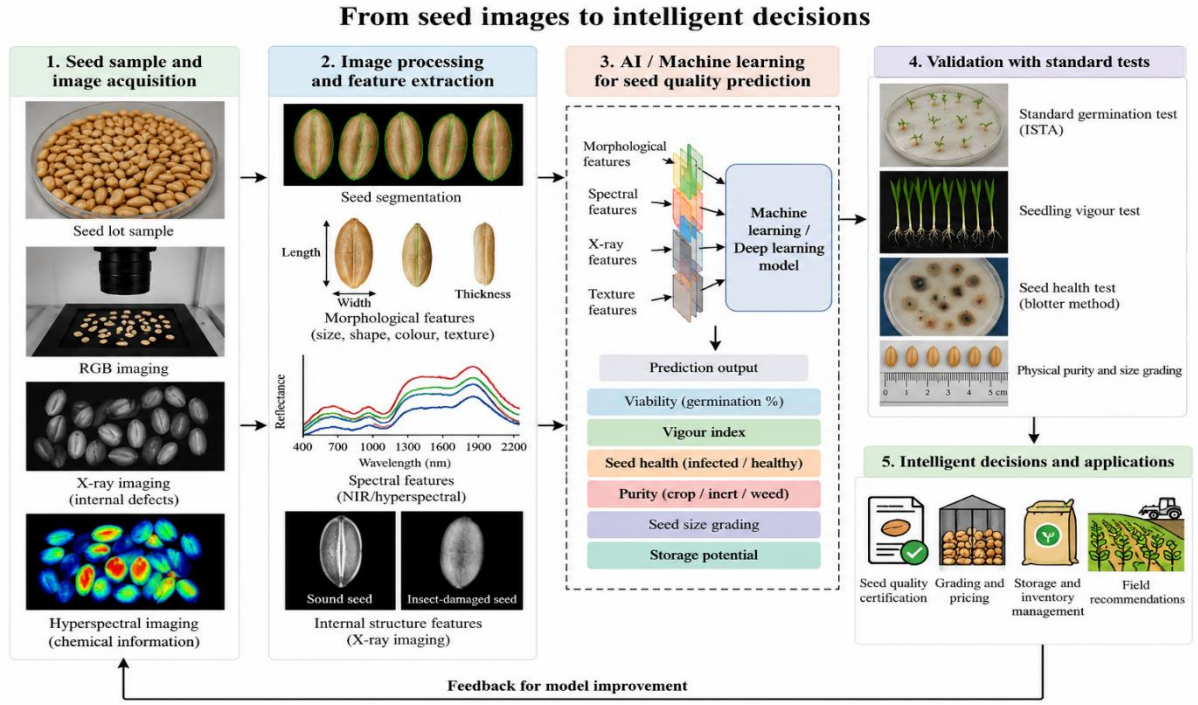


Figure 1. From seed images to intelligent decisions: integration of image acquisition, feature extraction, artificial intelligence, standard seed-quality validation and practical decision-making.

A practical workflow should also record metadata such as species, cultivar, seed-lot identity, harvest year, storage temperature and moisture content. These factors can influence both sensor signals and physiological quality. During model development, images from the same seed lot should not be randomly divided between training and test sets, because this can make performance appear better than it will be on a new lot. Instead, validation should hold out independent lots and, where possible, different seasons or locations. Researchers should report sensitivity, specificity, error rates and uncertainty alongside overall accuracy.

1. Computer vision and high-throughput phenotyping

A camera can capture seed length, width, shape, colour, surface texture and visible defects. Image-processing software separates individual seeds from the background; machine-learning classifiers can then group seeds or flag unusual samples. Three-dimensional imaging adds volume and shape information. Deep-learning methods can learn complex visual patterns, but performance depends on representative training images, consistent lighting, camera calibration and testing on lots not used during model development. A model trained on one cultivar, harvest year or imaging setup may fail when seed-coat colour, dust, background or moisture changes.

For seed laboratories, image-based systems can be useful for rapid counting, size grading, shape measurement, detection of broken or shrivelled seeds, and preliminary identification of contaminants. A well-designed imaging station requires stable illumination, a scale reference, a consistent camera distance and a background that contrasts with the seed. The system should be checked using manually verified samples and periodically recalibrated. Machine vision can reduce repetitive labour, but unusual or ambiguous samples should be flagged for expert review rather than automatically rejected.

2. Spectral sensing: looking beyond appearance

Near-infrared (NIR) spectroscopy measures how seed material interacts with near-infrared light and, when calibrated against reference laboratory measurements, can support predictions of moisture or composition. Hyperspectral imaging combines spatial images with information across many wavelengths, allowing models to associate spectral patterns with composition, ageing, damage or fungal symptoms. Fluorescence, Raman and X-

ray methods can provide complementary signals for specific questions. These methods are not interchangeable: sensor choice depends on crop, target trait, seed coat, throughput, cost and whether the required information is internal or external.

Spectral measurements are indirect: a model learns relationships between spectral patterns and reference measurements collected from representative samples. A calibration developed for one species, instrument or moisture range may not transfer reliably to another. External validation and periodic recalibration are therefore essential. Hyperspectral cameras collect many narrow wavelength bands and can be data-intensive, whereas multispectral systems use fewer selected bands and may be more practical for routine screening. The best instrument is the one that measures the target trait reliably at an acceptable cost and throughput—not necessarily the one that collects the most data.

3. Artificial intelligence and data fusion

Machine learning (ML) learns statistical relationships between input features and known outcomes. Random forests and support-vector machines can work with engineered image or spectral features, while convolutional neural networks learn features directly from images. Data fusion combines sources for example, image shape, NIR spectra, seed mass, storage history and germination-test results. This may capture more of the biology than any single sensor. However, apparent accuracy can be misleading if seeds from the same lot occur in both training and test sets. Validation should separate lots, seasons and, where possible, locations. Researchers should report sample size, class balance, sensitivity, specificity, uncertainty and independent validation not accuracy alone.

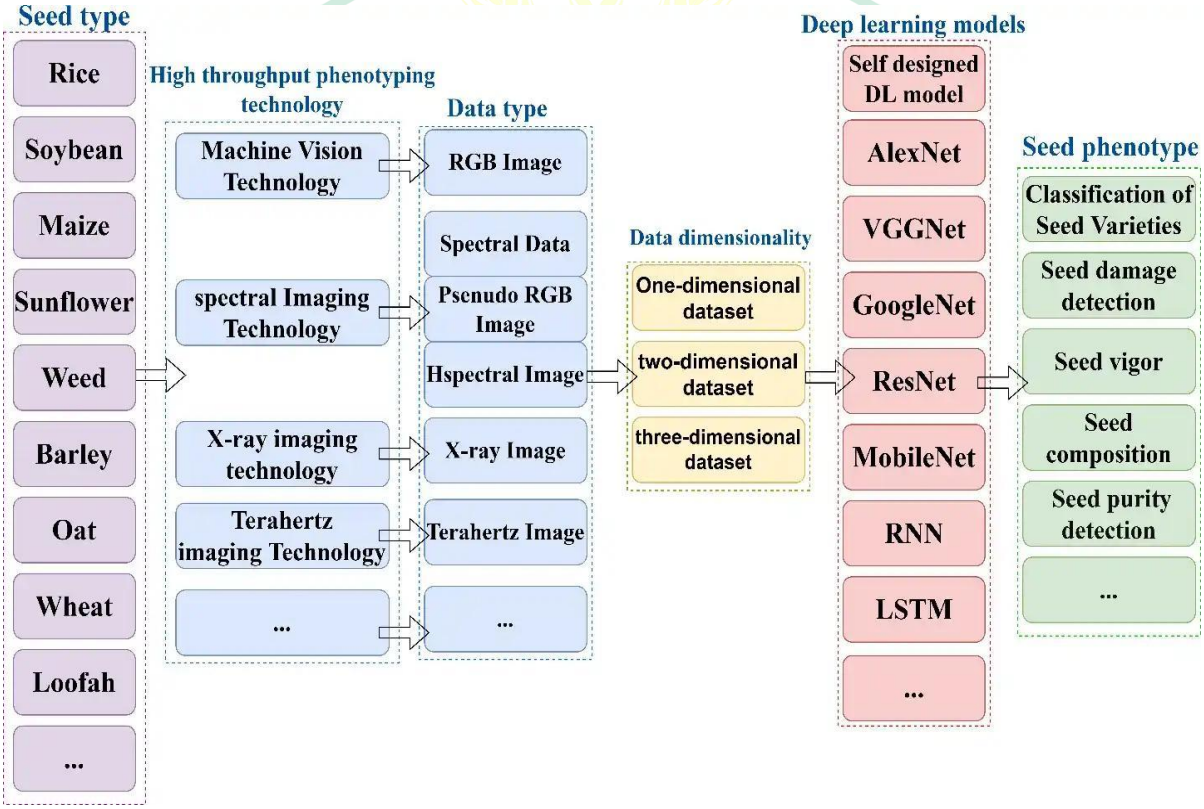


Figure 2. Precision seed phenotyping through multimodal data fusion and independent validation.

Before choosing a model, researchers should define the prediction task: classification (for example, identifying seed types), regression (estimating a continuous value), or anomaly detection (flagging samples unlike the training data). Simple models may be preferable when datasets are small or interpretability is important; deep-learning methods generally require more diverse, well-labelled examples. Data cleaning, balanced sampling, independent testing and transparent reporting are often as important as the algorithm itself. Explainable outputs such as highlighting image regions or identifying influential spectral bands-can help analysts judge whether a prediction is biologically plausible.

4. Smart seed systems: from testing to traceability

A smart seed system links seed-lot identity, quality records, storage conditions and movement through the supply chain. Barcode or quick-response (QR) codes can connect packages to digital records; sensors can monitor temperature and relative humidity in stores; dashboards can flag conditions that may accelerate deterioration. Digital traceability can support inventory management, but a code does not itself prove genetic purity or germination quality. Records must be linked to trustworthy sampling, laboratory results, chain-of-custody procedures and authorized certification. The Food and Agriculture Organization (FAO) emphasizes that effective seed systems require quality assurance, production, distribution and access not technology alone.

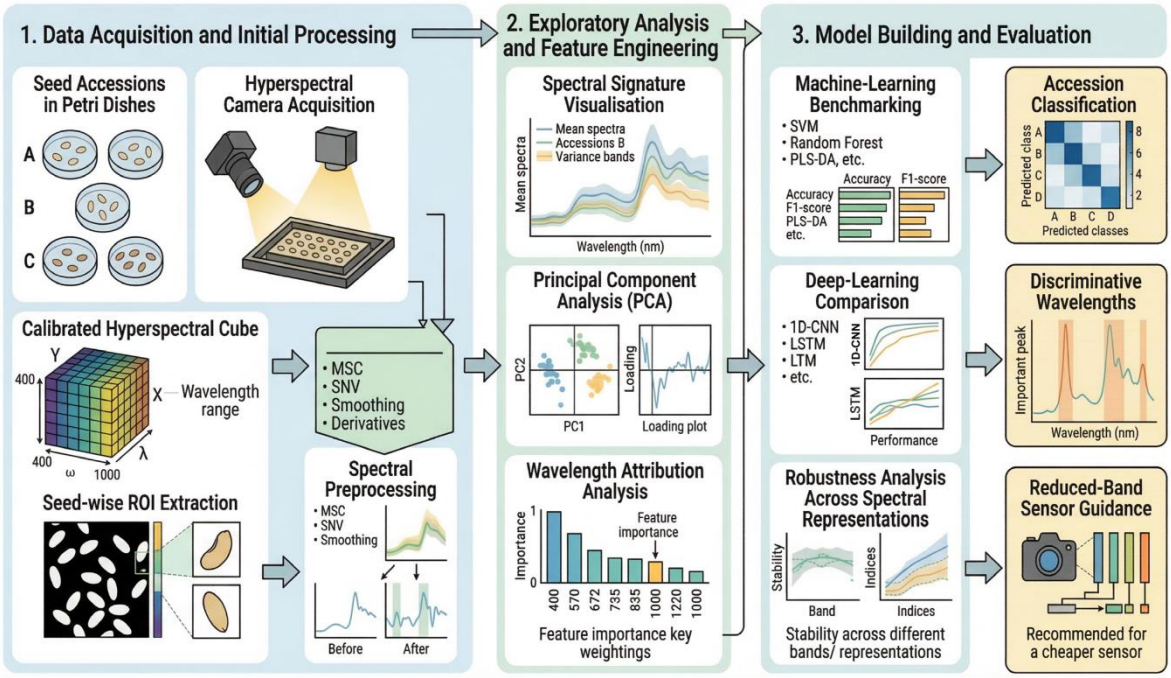


Figure 3. Next-generation intelligent seed systems integrating smart sensing, artificial intelligence, quality validation and digital traceability.

Digital traceability becomes more valuable when each record links a unique lot identifier with sampling date, test method, result, storage history, treatment and dispatch details. Temperature and relative-humidity logs can help identify storage conditions that may accelerate deterioration, but they do not directly measure viability. Inventory systems can use these records to support first-expiry-first-out stock rotation and to prioritize lots for retesting. Access controls, regular backups and clear responsibility for data entry are needed to keep records trustworthy.

What does the evidence show?

The evidence base is expanding, but results are crop- and task-specific. A 2025 review describes deep-learning applications in seed classification, grading, damage detection, cleanliness, composition prediction and vitality assessment. A 2025 study analysed 1,038 samples from five legume species using colour, physical traits and chemiluminescence-related features to investigate germination-potential classification. These examples show the value of combining diverse measurements; they should not be interpreted as a universal performance benchmark. Recent reviews describe rapid progress in machine vision, multispectral and hyperspectral imaging, and deep-learning approaches for seed classification, damage detection and selected quality predictions. However, studies use different species, sample sizes, instruments, reference tests and validation strategies, so reported performance should not be compared as if all experiments measured the same outcome. A model that distinguishes seed varieties accurately may not be suitable for predicting germination, vigour or seed-borne infection. The strongest evidence is obtained when predictions are tested on independent seed lots and compared with established laboratory or field methods.

Table 1. Examples of evidence and practical implications for next-generation seed systems

Evidence/ technology	Potential contribution	Important limitation
Deep-learning review (Jin et al., 2025)	Reviews classification, grading, damage, cleanliness, composition and vitality applications.	Review evidence does not validate every use for certification.
Hyperspectral imaging review (Zhang et al., 2019)	Combines spatial and spectral signals for quality, defect and selected physiological assessments.	Equipment and calibration may be costly; results are task-specific.
Legume study: 1,038 samples, five species (Griffo et al., 2025)	Explores germination-potential prediction using heterogeneous features.	Not a universal accuracy estimate; external validation is essential.
Digital lot records and storage sensors	Improve traceability, stock rotation and visibility of storage conditions.	Do not replace sampling, germination tests or official certification.

A roadmap for India

For Indian seed laboratories and universities, the practical pathway is staged. First, digitize routine records and standardize sample identification, imaging conditions and reference tests. Second, develop crop-specific models using representative lots across cultivars, seasons, storage histories and stress conditions. Third, validate models independently against germination, vigour, purity or health tests and field emergence. Fourth, evaluate cost per sample, maintenance, operator training and usability in public and private laboratories. Low-cost camera systems may suit physical grading, while spectral instruments may be justified for specialized testing. Shared datasets and inter-laboratory comparisons could reduce duplication and improve reliability.

Challenges and safeguards

AI can reproduce bias in training data, perform poorly on unfamiliar lots and produce confident but incorrect predictions. Seed quality is multidimensional: a clean, uniform-looking lot may still have low vigour, pathogens or varietal admixture. Sensor drift, dust, lighting, moisture and crop differences can change readings. Models should provide uncertainty flags and refer doubtful samples to trained analysts. Data ownership, cybersecurity and long-term instrument support also matter. Regulatory use requires transparent validation and alignment with applicable seed-testing and certification rules.

A further challenge is the difference between a model's statistical performance and its operational value. Even a reasonably accurate classifier may be unsuitable if false negatives allow poor-quality seed to pass, or if false positives lead to unnecessary rejection of viable seed. The acceptable error depends on the intended use and the consequences of a wrong decision. Screening tools should therefore include clear thresholds, uncertainty flags and procedures for confirmatory testing. Official certification and regulatory decisions must continue to follow applicable seed-testing rules and authorized procedures.

Conclusion

The future seed laboratory will likely combine conventional seed science with digital imaging, spectroscopy, AI and connected records. These technologies can help screen large volumes, identify samples needing closer inspection, improve storage decisions and make quality information more traceable. Their value depends not on algorithms alone, but on representative data, sound seed physiology, independent validation and affordable implementation. For M.Sc. students, the opportunity is to become bilingual in biology and data: understand germination and vigour first, then use sensors and AI to measure them more efficiently. The goal is not a black box, but a reliable, explainable and farmer-serving seed system.

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Millets: The Future Crops for Nutrition and Climate-Resilience Agriculture

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Abstract

Millets are a group of climate-resilient, nutrient-dense cereals that can play a vital role in sustainable agriculture and global food security. They are well-adapted to arid and semi-arid regions, requiring low water and nutrient inputs, and possess deep root systems that enhance soil health and reduce erosion. Millets provide high-quality proteins, dietary fiber, essential minerals, and bioactive compounds, making them valuable for addressing malnutrition and lifestyle-related health issues. Despite their potential, millet cultivation faces challenges including low yields, limited processing and storage infrastructure, fragmented markets, and low consumer awareness. Strengthening millet research, improving varieties, developing processing technologies, and implementing supportive policies are essential to integrate millets into mainstream food systems. Their adoption can enhance biodiversity, ecological sustainability, and dietary diversity, establishing millets as key crops for a resilient and sustainable food-secure future.

Keywords: Millets, Climate-resilient crops, Sustainable agriculture, Nutri-cereals, Food security, Biodiversity

Introduction

The global food system is facing growing challenges due to climate variability, water scarcity, and rising health concerns. Staple crops like rice and wheat, while vital for food security, consume large amounts of water and are increasingly affected by extreme weather. At the same time, malnutrition and lifestyle-related health issues remain widespread, highlighting the urgent need for crops that are both resilient and nutritious. Millets, small-seeded cereals traditionally grown in dry and semi-arid regions of Asia and Africa, offer a sustainable solution. Varieties such as pearl millet, finger millet, and foxtail millet are hardy, thrive in poor soils, and require minimal water. They are rich in dietary fiber, high-quality proteins, essential minerals, and bioactive compounds, earning them the title of **"nutri-cereals".** Integrating these grains into farming systems and diets can enhance climate resilience, improve nutrition, and promote sustainable agriculture

What Are Millets?

Millets are small-grained cereals cultivated for centuries in dry and semi-arid regions. Drought-tolerant and adaptable to marginal soils, they provide significant nutritional benefits, including fiber, proteins, and essential minerals.

Millets are broadly categorized into major and minor types:

- **Major millets:** Pearl millet (*Pennisetum glaucum*), finger millet (*Eleusine coracana*), and sorghum (*Sorghum bicolor*). These are widely grown and serve as staple foods in many areas.
- **Minor millets:** Foxtail millet (*Setaria italica*), proso millet (*Panicum miliaceum*), kodo millet (*Paspalum scrobiculatum*), little millet (*Panicum sumatrense*), and barnyard millet (*Echinochloa spp.*). These are cultivated locally in smaller quantities.

Nutritional Profile of Millets

Millets are nutrient-dense cereals that provide energy through complex carbohydrates and are rich in dietary fiber, B-complex vitamins, and essential minerals such as iron, magnesium, and phosphorus. Regular consumption can aid in the management of lifestyle-related disorders, including diabetes, cardiovascular diseases, and obesity. Naturally gluten-free, millets are suitable for individuals with celiac disease and gluten intolerance. They are also

a source of bioactive phytochemicals, particularly phenolic compounds, which exhibit antioxidant activity and reduce the risk of chronic diseases. With protein content comparable to major cereals and a higher proportion of essential amino acids, millets- especially finger millet, rich in iron and zinc are effective in addressing micronutrient deficiencies, particularly among women and children.

Table 1. Proximate composition of various millets (per 100 g)

Millet	Protein (g)	Fat (g)	Crude Fiber (g)	Carbohydrate (g)	Calcium (mg)	Phosphorus (mg)	Thiamine (mg)	Riboflavin (mg)
Sorghum	10.4	1.9	1.6	70.7	35.2	266	0.28	0.15
Pearl millet	11.6	5.0	1.2	67.0	35.0	339	0.30	1.40
Finger millet	7.3	1.3	3.6	72.6	34.8	250	0.40	0.60
Barnyard millet	6.2	2.2	9.8	55.0	18.3	280	0.33	4.20
Foxtail millet	12.3	4.3	8.0	63.2	31.0	300	0.60	1.60
Kodo millet	8.3	1.4	9.0	66.6	32.3	300	0.15	2.00
Proso millet	12.6	1.1	2.2	63.8	10.0	200	0.41	0.20
Little millet	7.7	4.7	7.6	60.9	17.0	220	0.30	0.09

Source: (Pandey *et al*., 2025)

Climate Resilience of Millets

Millets are hardy, climate-resilient crops ideally suited to arid and semi-arid regions due to their deep root systems that enable efficient use of soil moisture and reliable performance under low rainfall and drought conditions. Crops such as pearl millet and finger millet can sustain growth and grain formation even during moisture stress, while their ability to thrive in poor and problem soils is supported by efficient nutrient uptake and tolerance to salinity and soil acidity. Compared to major cereals like rice, wheat, and maize, millets require considerably less water and fertilizers, making them cost-effective and environmentally sustainable. Their natural resistance to several pests and diseases further reduces crop losses and dependence on chemical pesticides, positioning millets as a key component of climate-resilient and sustainable agricultural systems.

Table 2. Climate Resilience Characteristics of Millets

Climate Resilience Attribute	Explanation and Significance
Tolerance to moisture stress	Extensive root systems help millets draw water from deeper soil layers, enabling satisfactory crop performance even under limited rainfall.
Suitability to marginal soils	Millets grow successfully in low-fertility soils due to efficient use of available nutrients, including better utilization of limited phosphorus.
Low water requirement	These crops need much less irrigation than rice or wheat, making them ideal for dryland and water-limited farming systems.
Ability to withstand high temperatures	Millets remain productive under elevated temperatures, supporting cultivation in regions affected by increasing heat stress.
Inherent pest and disease tolerance	Natural resistance to several pests and diseases helps reduce crop damage and limits dependence on chemical plant protection measures.
Genetic diversity and adaptability	The wide range of millet species and varieties allows cultivation across diverse climatic zones, strengthening overall agricultural resilience.

Source: (Ashoka *et al*., 2023)

Challenges in Millet Production

Millets face low yields, poor market access, and climate risks. Limited processing, storage facilities, and consumer awareness reduce their demand. Policy neglect and fragmented markets further restrict growth. Addressing these issues is key to boosting millet production and consumption.

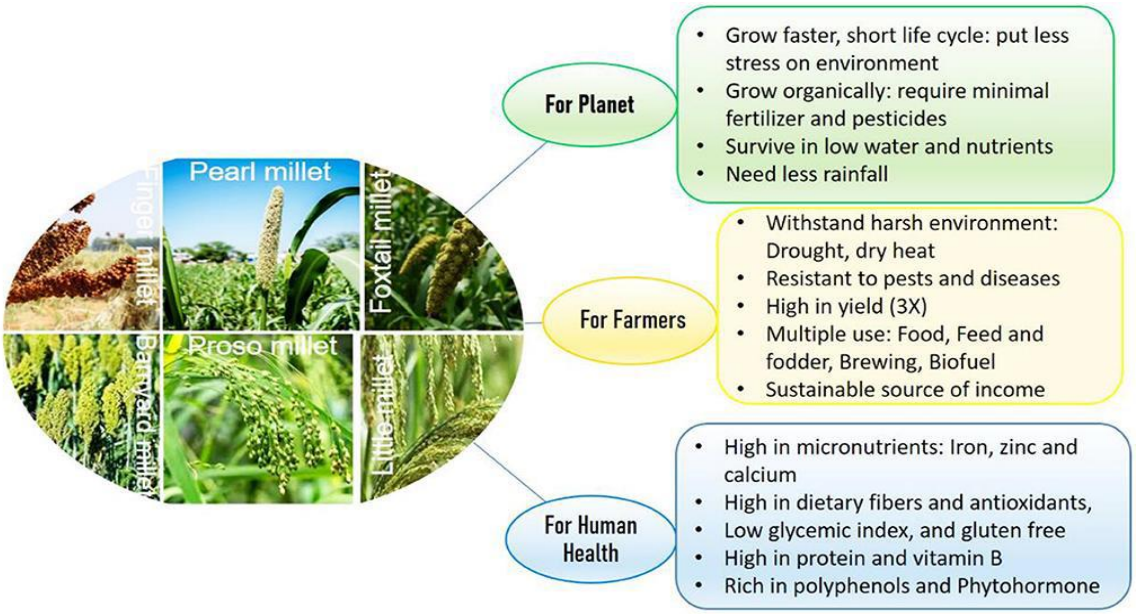


Figure 1: Unique properties of millets for climate smart agriculture, ensuring human health, food and nutritional security. [Source: (Rathinapriya *et al*., 2020)]

Future Scope of Millets

Millets are climate-resilient, low-input crops that improve soil health and support sustainable agriculture. Expanding awareness, policy support, processing infrastructure, and global markets can boost their cultivation and consumption, contributing to food and nutrition security.

Conclusion

Millets are a climate-resilient and nutrient-rich crop with immense potential to strengthen sustainable agriculture and global food security. Their adoption can enhance biodiversity, ecological sustainability, and dietary diversity. To fully realize this potential, efforts are needed in research, improved varieties, processing technologies, supportive policies, and awareness campaigns. Integrating millets into food systems represents a crucial step towards a sustainable, resilient, and food-secure future

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Future Horticulture: Integrating Artificial Intelligence, Precision Farming and Smart Technologies for Sustainable Fruit, Vegetable and Ornamental Production

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Abstract

Horticulture supplies fruits, vegetables, flowers, spices and other high-value products that support nutrition, livelihoods and agricultural diversification. Yet production faces pressure from water scarcity, heat stress, labour shortages, pest and disease outbreaks, variable product quality and postharvest losses. Artificial intelligence (AI), remote sensing, precision irrigation, protected cultivation, robotics and digital traceability can help growers make timely, site-specific decisions. This article explains these technologies in accessible language, outlines their applications across the horticultural value chain and highlights the need for crop-specific validation, affordability and sound horticultural knowledge. Technology is most useful when it complements-not replaces-careful observation, experimentation and skilled crop management.

Introduction

Horticultural crops often have high value per unit area and require careful management of growth stage, canopy, flowering, fruit set, maturity, quality and postharvest handling. Small errors in irrigation, nutrient supply, pollination or harvest timing can reduce marketable yield. Orchards, vegetable fields, nurseries and greenhouses also vary in soil, microclimate, cultivar and production system. Precision horticulture uses measurements and targeted management to respond to this variability. Digital tools can extend a grower's ability to observe plants and identify risks early, but recommendations must be interpreted through crop physiology and local conditions.

These requirements make horticulture a useful setting for precision agriculture: decisions can be linked to measurable outcomes such as fruit number, grade, firmness, soluble solids, flower quality, shelf life and water productivity. For example, the same irrigation schedule may not suit a young orchard, a fruiting tomato crop and a potted ornamental plant because their rooting volume, canopy demand and marketable traits differ. Digital tools are therefore most effective when they are designed around a clear crop-management question rather than adopted simply because the technology is new.

Approach and evidence base

This is a narrative overview of precision-agriculture concepts and emerging horticultural applications, not an original field experiment. Examples describe potential uses and implementation considerations. Benefits differ by crop, farm size, climate, sensor quality, connectivity and operator skills; local trials and economic evaluation are therefore essential before large-scale adoption.

The article emphasizes established principles and practical examples rather than claiming that every technology is commercially mature. Sensor readings should be compared with trusted measurements, and recommendations should be tested under local growing conditions. A useful evaluation records the crop and cultivar, growth stage, sensor position, calibration method, management action and outcome. This makes results easier to reproduce and helps students distinguish a promising prototype from a tool that is dependable for farm decisions.

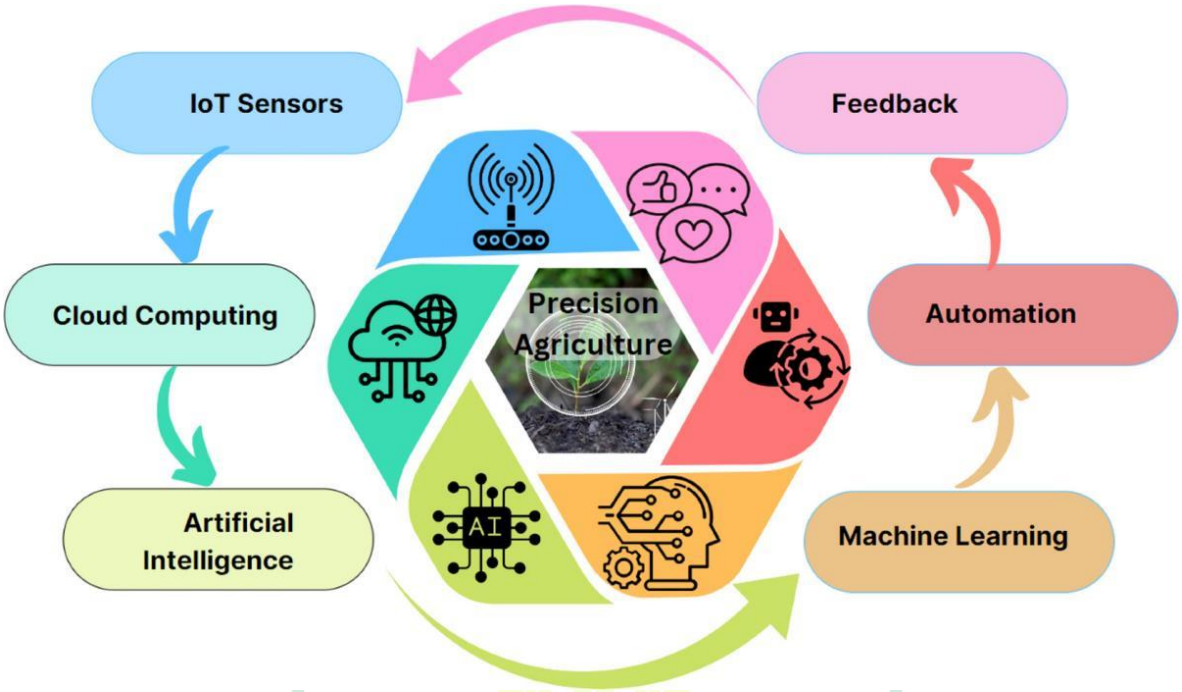


Figure 1. Smart Horticulture Decision Cycle

1. Artificial intelligence and computer vision

Computer vision uses cameras and algorithms to extract information from plant images. In orchards, image analysis can assist with fruit counting, canopy assessment, flower detection and estimation of maturity-related colour. In vegetable production, it can support weed recognition, disease-symptom screening, fruit grading and growth monitoring. Machine-learning models can combine images with weather, soil moisture, crop stage and management records to estimate risks or prioritize inspection. However, similar visual symptoms can result from disease, nutrient deficiency or water stress. Models should be tested on independent farms, cultivars and seasons, and suspected diseases should be confirmed when necessary.

Applications can be grouped into detection, measurement and prediction. Detection identifies objects or symptoms, such as flowers, fruits, weeds or discoloured leaves; measurement estimates traits such as fruit diameter, canopy cover or fruit count; prediction estimates a future outcome, such as harvest date or risk of quality loss. These are different tasks and require different reference data. For reliable fruit counting, for instance, the model must be tested when fruits overlap, leaves obscure the view, light changes or fruit colour resembles the background. Students should also learn to interpret false positives and false negatives, not just a headline accuracy score.

Drones and satellite imagery extend observation beyond individual plants. Repeated images can reveal canopy gaps, uneven growth, water-stress patterns and changes in crop cover, helping teams decide where to scout or sample. These images do not directly diagnose every nutrient deficiency or disease: soil background, shadows, canopy density and sensor type can alter the signal. For small farms, a shared drone service or freely available satellite data may be more practical than purchasing equipment. Images should be linked to ground observations and used to guide targeted inspection, not as a substitute for it.

2. Precision irrigation and fertigation

Soil-moisture sensors, weather stations, evapotranspiration estimates and crop-stage information can guide irrigation scheduling. Fertigation delivers dissolved nutrients through irrigation water, allowing applications to be adjusted to crop demand. Sensor-guided management may reduce unnecessary irrigation, nutrient leaching and energy use, but only when sensors are correctly installed, calibrated and interpreted. One sensor cannot represent an entire field when soil texture, slope, root depth or emitter performance varies. Combine readings with crop appearance, root-zone knowledge, water quality and periodic soil or plant analysis.

Scheduling should consider crop evapotranspiration, effective rainfall, soil water-holding capacity, rooting depth, crop coefficient and irrigation-system efficiency. In orchards, monitoring at more than one depth can help indicate whether water reaches the active root zone or is draining below it. In greenhouse substrates, the volume and frequency of irrigation may need to respond more quickly to radiation and plant size. Fertigation also requires attention to nutrient compatibility, solution pH and electrical conductivity, emitter uniformity and the risk of salt accumulation. Water-saving claims should be checked against yield and marketable quality, because reducing irrigation too far can cause smaller fruit, blossom-end rot in susceptible crops or uneven quality.

3. Protected cultivation and climate-smart production

Greenhouses, net houses and low tunnels can moderate temperature, wind, rainfall and pest exposure, enabling high-value production or better season control. Automated systems monitor temperature, relative humidity, light, carbon dioxide and substrate moisture, and may control ventilation, cooling or irrigation. Yet protected cultivation is not automatically sustainable: poorly designed structures can overheat, use substantial energy or accumulate salinity. Structure design, crop choice, ventilation, water availability, market access and operating costs should be assessed together. Climate-smart horticulture also includes mulching, soil organic matter management, tolerant cultivars, diversified planting and water harvesting.

Protected structures can extend production seasons, improve uniformity and protect high-value crops, but their performance depends on ventilation, shading, orientation, structure height, pest exclusion and local climate. Temperature and relative humidity together influence plant transpiration, pollen function and disease development; therefore, a single temperature reading may not describe the actual crop environment. In greenhouse tomatoes and cucumbers, for example, pollination, pruning, training and canopy ventilation remain important even when climate controls are automated. Before investment, growers should estimate capital cost, energy and water demand, labour, expected market price and the risk of crop failure.

Pollination and crop load are further examples where digital tools must be interpreted biologically. Flower-counting systems may help estimate flowering intensity, but fruit set also depends on pollinator activity, pollen viability, temperature and cultivar compatibility. In orchards and greenhouse crops, monitoring flowering and fruit set can support decisions on pollinator habitat, pruning or crop-load management. In ornamental production, image-based grading may assess flower number, stem length, colour uniformity and visible damage; however, grading standards vary by market and species. Automated measurements should therefore be checked against buyer specifications and trained human assessors.

4. Smart pest and disease management

Digital traps, weather-based disease-risk models, scouting applications and image-based alerts can help prioritize inspection. These tools work best within integrated pest management (IPM), which combines monitoring, cultural practices, resistant cultivars, biological control and carefully targeted pesticide use. An AI alert should trigger verification, not automatic spraying. Correct diagnosis, pest thresholds, pesticide labels, pollinator protection, resistance management and pre-harvest intervals remain essential.

An effective digital IPM workflow combines routine scouting with weather and crop-stage information, maps where problems occur, and prioritizes inspection of high-risk areas. Traps can monitor selected insects, while weather models may estimate conditions favourable for certain diseases; neither necessarily confirms the presence of a pest or pathogen. Good practice includes maintaining a baseline record, confirming unusual alerts, removing sources of infection where appropriate, conserving beneficial organisms and rotating pesticide modes of action according to approved guidance. Students should also consider pesticide-residue requirements and pollinator activity when planning interventions in flowering crops.

5. Harvest prediction, quality and postharvest management

Harvest timing affects flavour, firmness, colour, shelf life and transport performance. Computer vision and spectral methods are being investigated to estimate fruit size, colour, maturity and selected internal quality attributes. After harvest, temperature and humidity monitoring, cold-chain sensors and digital lot records can help identify handling problems and improve traceability. Predictions should be calibrated against suitable reference measurements such as firmness, soluble solids, acidity or dry matter. No single visual feature reliably measures every aspect of eating quality.

Harvest indices are crop-specific. Depending on the commodity, they may include days after flowering, fruit size, background colour, firmness, soluble solids, acidity, dry matter or a combination of traits. A model developed for one cultivar or production region may not transfer to another because temperature, light, crop load and growing practices affect development. After harvest, rapid removal of field heat, suitable temperature and humidity, careful packaging and hygienic handling can be as important as prediction technology. Cold-chain sensors are most useful when records are linked to a particular lot and to defined thresholds that prompt corrective action.

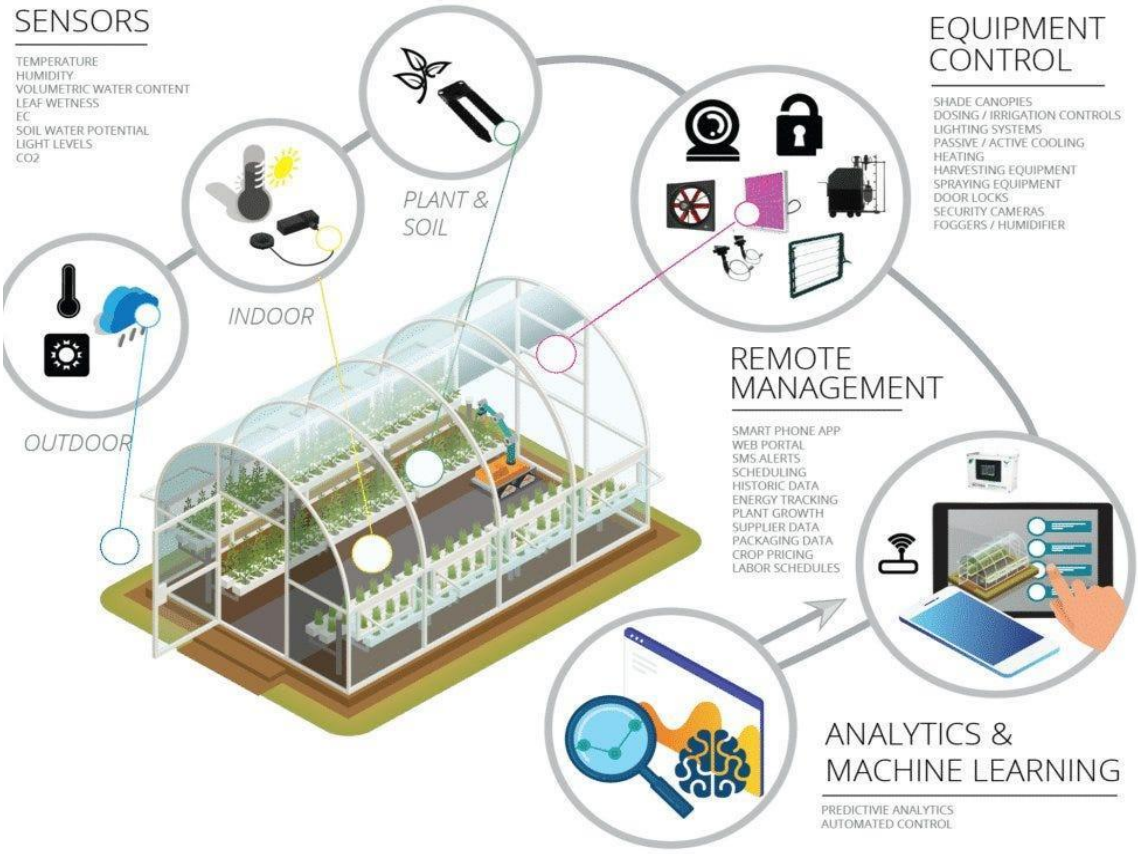


Figure 2. Technologies Across Horticulture

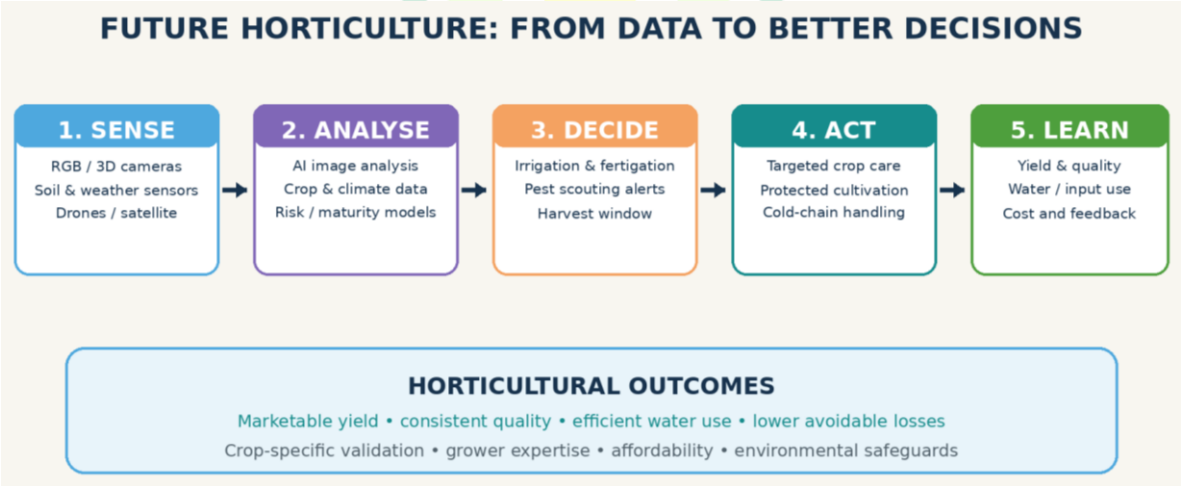


Figure 3. Smart-horticulture decision cycle linking sensing, AI analysis, management action and outcome evaluation

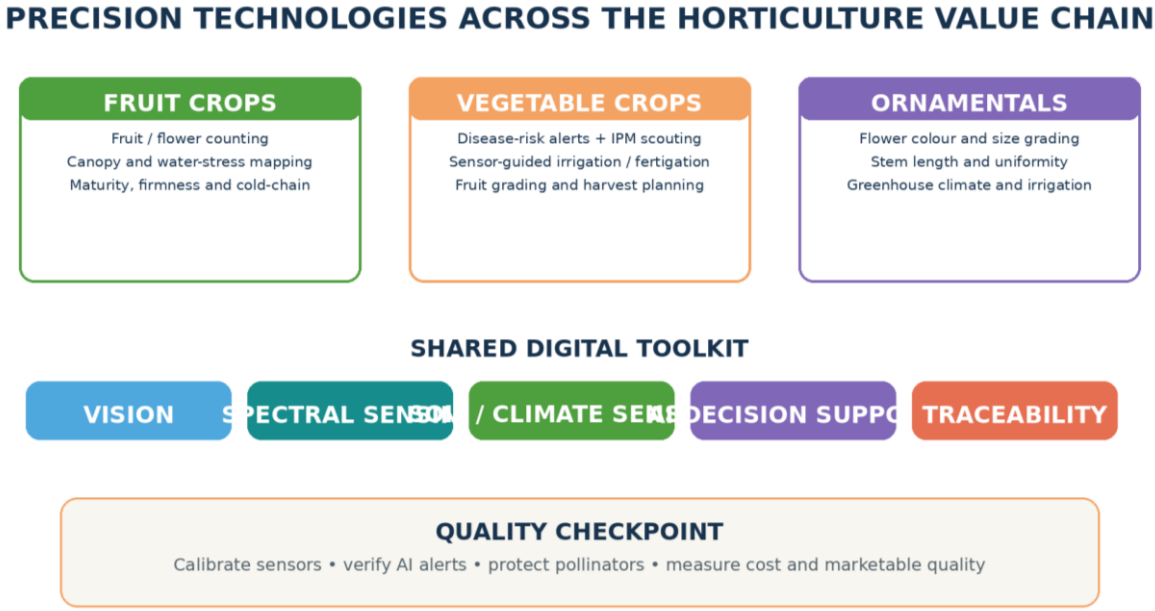


Figure 4. Crop-specific applications of precision technologies in fruit, vegetable and ornamental production.

Table 1. Digital technologies and practical horticultural applications

Technology	Potential application	Important caution
RGB / 3D imaging	Fruit counting, flower detection, canopy structure, size grading	Lighting, occlusion and cultivar differences affect results
Soil and climate sensors	Irrigation scheduling, greenhouse control, frost/heat alerts	Requires placement, calibration and maintenance
Spectral / thermal sensing	Maturity or stress screening; selected quality traits	Must be calibrated against crop-specific reference tests
AI decision-support tools	Risk alerts, harvest planning, scouting prioritization	Prediction is not diagnosis; independent validation is needed
Digital traceability	Lot identity, cold-chain records and quality documentation	Records help only when accurate and linked to real tests

6. What should horticulture students learn?

Future horticulturists benefit from combining plant science with data literacy. Core skills include crop physiology, phenology, soil and water management, plant protection, postharvest biology and experimental design. Digital skills can be built progressively: collecting reliable observations, using spreadsheets and basic statistics, interpreting sensor data, understanding model errors and presenting results clearly. Students should ask whether a tool measures the target trait, how it was validated, what it costs per hectare or per kilogram of marketable produce, and who maintains it. Small, well-designed trials are often more informative than adopting expensive technology without a clear management question.

A practical student project could compare sensor-guided irrigation with a locally recommended schedule, assess image-based fruit counts against manual counts, or test whether a maturity model predicts a recognized harvest index. Each project should define a hypothesis, replication, reference method and success criterion before data collection. Students should maintain a clean dataset with units, dates, cultivar names and missing-value codes; plot the data before modelling; and report uncertainty and limitations. Knowledge of experimental design and statistics remains essential because sophisticated software cannot compensate for biased sampling or weak comparisons.

7. Barriers and a practical roadmap

Barriers include upfront cost, unreliable connectivity, limited technical support, fragmented data, privacy concerns and models that do not transfer between crops or regions. Begin with a defined problem-such as irrigation timing, fruit counting or cold-chain monitoring-then compare digital recommendations with standard

practice across representative conditions. Measure marketable quality, water and fertilizer use, labour, energy, rejected produce and net return, not yield alone. Universities, extension services, farmer groups and equipment providers can support training, shared demonstrations and local validation.

Adoption should be assessed using a whole-farm perspective. A tool may improve one indicator but increase maintenance, electricity use or labour elsewhere. Useful indicators include marketable yield, grade distribution, water-use efficiency, fertilizer-use efficiency, pesticide applications, postharvest rejection, energy demand and net return. Smallholder suitability also depends on repair services, language, training, connectivity and whether the tool can operate with intermittent internet access. Cooperatives, custom-hiring services and extension demonstrations may help share the cost of equipment and build confidence before individual investment.

Responsible data practices also matter. Farm records may reveal production volumes, input use and marketing patterns, so growers should know who can access their data, how long it is retained and whether it can be exported to another service. Recommendations should be presented in understandable language, with uncertainty and limitations made clear. Local-language interfaces, offline functions and accessible repair services can be as important as model performance for adoption.

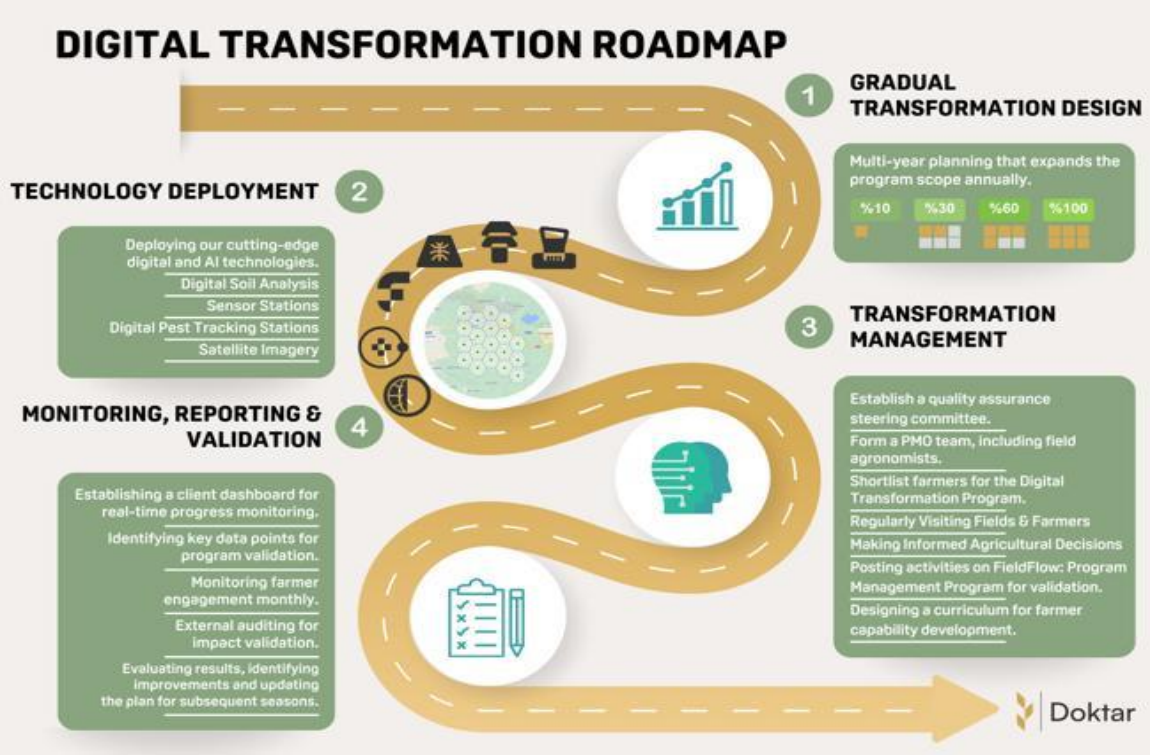


Figure 5. Implementation Roadmap

Conclusion

Precision horticulture is not simply the addition of gadgets to crop production. It links accurate observation, crop science, targeted action and evaluation of outcomes. AI, sensors, protected cultivation and digital traceability can help growers manage variability, conserve resources and improve quality when tools are affordable, validated and suited to local conditions. For horticulture students, the strongest future skill is the ability to connect technology with crop biology and farm economics. Sustainable innovation begins with a sound horticultural question, reliable measurements and evidence that the solution benefits growers, consumers and the environment. The future of horticulture will not be fully automated in every setting. The most successful systems are likely to combine human expertise with targeted sensing, transparent recommendations and feedback from actual crop outcomes. A grower or horticulturist should be able to understand what a tool measures, where it may fail and when a manual inspection is still needed. The guiding principle is simple: use technology where it improves a defined horticultural decision, demonstrate the benefit under local conditions and retain sound crop management as the foundation.

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Supercharging Live Feeds: Enhancing Fish Larval Survival with Enriched Rotifers and Artemia

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Abstract:

Aquaculture now supplies more than half the seafood consumed worldwide, yet its growth hinges on a fragile two-to-three-week window that few outside the industry ever consider: the first feeding stage of a fish larva. Hatched with a mouth barely able to open and a digestive system still under construction, marine larvae depend entirely on live prey - rotifers and brine shrimp (Artemia) -small enough to swallow and active enough to trigger a feeding response. But these organisms are only as nutritious as what they themselves were fed, and in their unmodified state they fall well short of what fast-developing larval tissue requires. This article reviews how hatcheries close that gap through enrichment: suspending rotifers and Artemia in nutrient-rich emulsions, microalgae, vitamins, and even probiotic bacteria so that the prey absorb and carry these compounds directly into the larvae that eat them. Drawing on published trials spanning species from gilthead sea bream and barramundi to Pacific cod and golden pompano, it examines the outsized role of highly unsaturated fatty acids (DHA, EPA, ARA) in larval survival and skeletal development, the contributions of vitamin C, taurine, and vitamin A, and the emerging use of bioencapsulated probiotics for disease resistance. A recurring finding cuts against the assumption that more nutrition is always better: several studies show that over-enriching live feed can sharply reduce survival, underscoring that precision - not maximalism - is what separates a successful hatchery protocol from a failed one.

Key words: Live feed enrichment, Rotifers, Artemia, Marine fish larvae, Bioencapsulation, HUFAs, Larval survival.

Introduction: The Smallest Yet Most important Meal in Aquaculture

Aquaculture is the world's fastest-expanding food production sector, but one of its greatest challenges is not related to ponds, cages - it lies within the first few weeks of a fish's life. Marine finfish larvae hatch in a highly undeveloped condition, with their eyes still maturing, jaws only partially formed, and digestive systems not yet capable of processing dry formulated feeds. During this crucial "first-feeding" phase, which generally lasts two to three weeks, mortality rates can be extremely high, even in well-managed hatcheries. Consequently, the limited availability of healthy, high-quality larvae continues to be a major obstacle to expanding the production of many cultured marine fish species.

The need for a live-feed industry arises primarily from the feeding biology of newly hatched larvae. At this stage, larvae can consume only prey that falls within a very specific size range. In addition, they are visual predators whose feeding responses are stimulated by movement. As a result, inert feed particles are often ignored, whereas small moving organisms are readily captured and eaten. Rotifers belonging to the genus *Brachionus*, typically measuring about 100–300 µm in length, serve as the ideal first feed for many marine fish species during their initial one to two weeks of life. As the larvae grow and their mouth size increases,



Fig 1: Artemia

hatcheries gradually replace rotifers with newly hatched *Artemia* nauplii, followed by larger *Artemia*, before eventually transitioning the fish to formulated microdiets.

Rotifers and *Artemia* are widely used because they offer several practical advantages. They can be produced economically on a large scale, their swimming movements effectively stimulate the feeding behavior of fish larvae, and they remain alive and suspended in the water column. This characteristic helps maintain better water quality by reducing the accumulation of uneaten feed that would otherwise settle and decompose. However, despite these benefits, a significant nutritional challenge remains. The nutritional quality of rotifers and brine shrimp depends entirely on the diet they receive during culture. Common feeds used in mass production, such as baker's yeast or standard algal pastes, often fail to provide all the nutrients required by developing larvae. Unless this nutritional deficiency is corrected, it can lead to poor larval performance and, in severe cases, substantial production losses.

Why Not Use a Formulated Micro diet from the Very Beginning?

At the first-feeding stage, marine fish larvae do not yet possess a fully developed stomach or a complete set of digestive enzymes needed to efficiently process formulated feeds. In addition, they have difficulty recognizing and capturing non-moving feed particles. Live prey overcomes both of these limitations by providing a digestible food source that actively swims in the water, stimulating the larvae's natural feeding response. For this reason, despite many years of research aimed at developing inert microdiets, live feed continues to be the primary starter diet used in marine fish hatcheries around the world.

The Nutritional Deficiency of Unenriched Live Feed

Marine fish differ from most terrestrial vertebrates in their limited ability to synthesize long-chain omega-3 fatty acids from shorter precursor molecules. This limitation arises because the enzymes responsible for fatty acid desaturation and elongation are either weakly expressed or absent in many marine fish species. As a result, three essential fatty acids-docosahexaenoic acid (DHA), eicosapentaenoic acid (EPA), and arachidonic acid (ARA)-collectively known as highly unsaturated fatty acids (HUFAs), must be obtained directly from the diet (Sargent et al., 1999). However, rotifers and *Artemia* reared on conventional culture feeds generally contain low levels of these critical nutrients. A widely referenced review on marine larval nutrition reported that larvae fed rotifers deficient in n-3 HUFAs exhibited reduced growth and increased mortality, whereas increasing the n-3 HUFA content of rotifers to approximately 5.5% of their dry weight significantly enhanced larval growth, survival, and activity.

Deficiencies are not limited to fatty acids alone. The vitamin content of live feed organisms, particularly vitamin C, can vary considerably depending on the culture conditions and feed provided. In many cases, the naturally occurring levels are insufficient to meet the demands of rapidly developing fish larvae. Similar inadequacies have been observed for taurine, vitamin A, riboflavin, and several B-complex vitamins. Although these nutrients are present in live feeds, their concentrations are often too low to support the rapid development of skeletal structures, nervous tissues, and visual systems that occurs during the larval stage.

When these nutritional shortcomings are not corrected, they can lead to several practical problems in hatcheries. Common consequences include slower growth, impaired swimming performance, reduced resistance to handling stress, and various developmental abnormalities. These may include spinal deformities, jaw malformations, and irregular pigmentation patterns, particularly in flatfish species. Such defects can greatly reduce the market value of juvenile fish, even when they appear otherwise healthy. To overcome these challenges, the practice of live-feed enrichment was developed.

Bioencapsulation: Converting Live Feed into Nutrient Carriers

The effectiveness of live-feed enrichment is based on a biological process rather than a technological one. Rotifers and *Artemia* nauplii are non-selective filter feeders that readily consume particles of an appropriate size suspended in the surrounding water. Within a short period, the ingested nutrients become incorporated into their tissues. Hatchery operators take advantage of this characteristic by transferring live feed organisms into a separate enrichment tank shortly before harvest. This tank contains a concentrated nutrient source, such as a commercial oil emulsion, HUFA-rich microalgal paste, or live microalgal culture. The organisms are allowed to feed for a specific enrichment period, typically ranging from three to twenty-four hours, after which they are harvested,

rinsed, and supplied to fish larvae. Through this process, the live feed effectively functions as a living and mobile nutrient delivery system.

This method, commonly referred to as **bioencapsulation**, has proven highly effective for delivering nutrients to fish larvae. Studies conducted by researchers associated with the Sorgeloos research group in Belgium demonstrated that enriching live feed with ascorbyl palmitate, a stable lipid-soluble form of vitamin C, increased the vitamin C content of rotifers by approximately ten times over a three-day culture period. Similarly, *Artemia* enriched for 24 hours achieved ascorbic acid concentrations of nearly 2,000 µg g^{-1} dry weight. The same principle has subsequently been applied to deliver a wide range of beneficial substances, including probiotics, immunostimulants, and therapeutic agents, directly into the digestive systems of fish larvae.



Fig 2: Rotifer under microscope

At present, two major enrichment approaches are widely used in commercial hatcheries. The first involves standardized commercial enrichment emulsions specifically formulated to provide precise and consistent levels of DHA, EPA, and ARA in predetermined ratios. The second approach utilizes microalgae, either supplied directly to rotifers and *Artemia* or incorporated into mixed-species feeding regimes. Commonly used microalgal species include *Nannochloropsis*, *Isochrysis galbana*, *Tetraselmis*, and *Chlorella*, all of which are valued for their favorable fatty acid compositions. Both enrichment methods have demonstrated effectiveness, although their relative performance often varies according to fish species and even genetic strain, which explains the large number of comparative studies reported in the scientific literature.

The HUFA Story: DHA, EPA, and ARA as the Foundation of Larval Survival

One of the most consistent findings from decades of live-feed research is the critical role played by three highly unsaturated fatty acids (HUFAs): DHA, EPA, and ARA. DHA (docosahexaenoic acid) is an essential structural component of cell membranes, particularly in the brain and retina, and is strongly associated with visual development and swimming ability. EPA (eicosapentaenoic acid) contributes to membrane structure and participates in physiological signalling processes. Along with EPA, ARA (arachidonic acid) serves as a precursor for eicosanoids, hormone-like compounds that regulate immune responses and stress adaptation. Since marine fish larvae have a limited ability to synthesize these fatty acids from simpler precursors, the HUFA content of their initial live feed has a profound influence on growth and survival.

Research supporting the importance of HUFAs has been reported across a wide range of species and culture environments:

Greater amberjack (Seriola dumerili)

Increasing the n-3 HUFA concentration in enriched Artemia resulted in improved larval growth and survival, while also reducing the incidence of skeletal deformities (Roo et al., 2019).

Barramundi (Lates calcarifer)

Rotifers enriched with a 50:50 combination of Nannochloropsis oculata and Chlorella vulgaris performed better than rotifers enriched with a single algal species. Larvae fed this mixed-algae treatment showed greater body length, larger eye size, improved body depth, and achieved an 85% survival rate during a standardized stress test, representing the highest performance among all treatments evaluated (Thépot et al., 2016).

Pacific cod (Gadus macrocephalus)

Supplementing Artemia with increasing levels of DHA led to significant changes in larval growth, survival, and whole-body fatty acid composition (Choi et al., 2022).

Asian sea bass (Lates calcarifer) under heat stress

A study conducted in 2023 demonstrated that larvae fed n-3 HUFA-enriched Artemia achieved higher final body weight and growth rates when reared at an elevated temperature of 34°C. In addition, the enriched diet reduced the occurrence of skeletal abnormalities, highlighting its potential value for hatcheries facing rising water temperatures in tropical regions.

Haddock (Melanogrammus aeglefinus)

Not all studies have reported substantial improvements in survival. One investigation comparing different HUFA enrichment emulsions observed clear differences in rotifer fatty acid profiles and nutrient transfer to larvae, yet survival rates remained similar up to 40 days after hatching. The findings suggested that the mixed-algae diet used as the baseline treatment may have already supplied sufficient essential fatty acids to satisfy the species' nutritional requirements.

Atlantic cod (Gadus morhua)

Research published in the ICES Journal of Marine Science showed that rotifers containing approximately 1.6% DHA on a dry-weight basis supported better larval growth and survival than rotifers containing 1.1–1.2% DHA. However, the study also noted that previous work on a closely related cod species linked DHA levels above about 1% to an increased frequency of developmental abnormalities. These contrasting findings emphasize that optimal HUFA requirements can vary considerably among species, strains, and rearing conditions.

Collectively, these studies explain why HUFA enrichment of rotifers and Artemia has become a standard practice in marine fish hatcheries worldwide. Across diverse species, environmental conditions, and production systems, increasing DHA, EPA, and ARA levels in live feed consistently enhances larval survival, growth performance, and skeletal development, provided that the enrichment level is appropriate for the species being cultured.

The Goldilocks Problem: When Excess HUFA Becomes Detrimental

One of the most surprising discoveries in live-feed nutrition research is that there is an upper limit to the benefits of HUFA enrichment, and exceeding that limit may be more harmful than providing no enrichment at all.

A study conducted on golden pompano (*Trachinotus ovatus*) in 2021 compared rotifers enriched with three different commercial products. The researchers found that the treatment producing the highest DHA concentration in the rotifers, using a product known as Algamac 3080, resulted in larval survival rates that were only about half of those observed in the unenriched control group (Fu et al., 2021). Earlier work by the same research team had already demonstrated that golden pompano larvae are highly sensitive to the nutritional composition of their initial live feeds, particularly with respect to jaw and skeletal development (Ma et al., 2014).

This phenomenon is not unique to a single species. Although HUFAs are essential nutrients, they are also highly susceptible to oxidation because of their multiple double bonds. When present in excessive amounts, these fatty acids can generate reactive oxidation products that may damage or stress larval tissues rather than support healthy development. For this reason, HUFA enrichment strategies are often combined with antioxidant supplements such as vitamins E and C to reduce oxidative stress.

In addition, research has shown that the balance among DHA, EPA, and ARA is just as important as their total concentration. An imbalanced ratio of these fatty acids can reduce or even negate the benefits of high HUFA levels, despite apparently adequate overall lipid content.

For hatchery operators, the key lesson is that enrichment protocols should not simply aim for the highest possible HUFA concentration. Optimal HUFA requirements vary among species and developmental stages and may also be influenced by environmental factors such as rearing temperature. As a result, published studies serve as an important reference for defining safe and effective enrichment ranges, gradually building a knowledge base tailored to individual species and culture conditions.

Case in point
In golden pompano, the rotifer enrichment product that delivered the most DHA produced the worst Survival outcome of the three products tested - a clear demonstration that, in live-feed nutrition, More is not automatically better (Fu et al., 2021).

Beyond Fatty Acids: The Role of Vitamins, Taurine, and Other Micronutrients

Although highly unsaturated fatty acids (HUFAs) receive most attention in live-feed enrichment studies, they represent only one aspect of larval nutrition. Increasingly, researchers have focused on vitamins and other biologically important compounds, many of which have demonstrated significant benefits for larval development and survival.

Vitamin C

Vitamin C (ascorbic acid) is particularly important because it is unstable and its concentration in live feed organisms can vary greatly. To overcome this limitation, hatcheries often enrich live feeds using stable vitamin C derivatives such as ascorbyl palmitate, achieving concentrations of up to approximately 2,500 μg g^{-1} dry weight. In milkfish (*Chanos chanos*), larvae fed rotifers and *Artemia* enriched with both HUFAs and vitamin C exhibited about a 50% reduction in opercular (gill-cover) deformities compared with larvae receiving unenriched feed. These enriched diets also improved growth performance in both indoor hatchery tanks and outdoor nursery ponds (Gapasin et al., 1998). Earlier research by the same author demonstrated that DHA-enriched live feed alone was effective in reducing opercular deformities in milkfish (Gapasin & Duray, 2001).

Studies involving European sea bass and African catfish further showed that high-dose vitamin C supplementation through enriched live prey significantly enhanced larval tolerance to handling stress (Merchie et al., 1997). The importance of adequate vitamin C nutrition becomes even more evident when compared with deficiency conditions. In one study involving carp larvae, fish fed a formulated diet lacking sufficient vitamin C experienced mortality rates as high as 56%, whereas larvae fed live food showed only 0.6% mortality. The vitamin C-deficient groups also displayed typical deficiency symptoms, including fin erosion and deformities of the gill arches.

Taurine

Taurine has also received considerable attention as a valuable enrichment component. Rotifers enriched with taurine improved both growth and survival in red sea bream (*Pagrus major*) larvae (Chen et al., 2004). Similar growth-promoting effects were later reported in Japanese flounder (*Paralichthys olivaceus*) larvae (Chen et al., 2005). This finding is particularly significant because taurine is largely absent from plant-derived feed ingredients, making live-feed enrichment one of the most practical methods for supplying taurine during early larval development.

Vitamin A

The delivery of vitamin A through enriched rotifers has also been investigated extensively. Studies on gilthead sea bream (*Sparus aurata*) showed that different vitamin A supplementation levels influenced both larval performance and the occurrence of skeletal deformities (Fernandez et al., 2008). These findings indicate that vitamin A requirements follow an optimal range rather than a simple linear response. Similar to DHA, both deficiency and excess can be problematic, as excessive vitamin A and its derivatives are known to cause developmental abnormalities in fish larvae.

Riboflavin

Riboflavin enrichment has demonstrated another pathway for nutrient transfer within the live-feed system. By enriching the microalgae used to culture rotifers, riboflavin was successfully transferred through the food chain to white sea bream and gilthead sea bream larvae. This enrichment resulted in measurable improvements in larval length and survival, illustrating that nutritional enhancement can begin at the microalgal level rather than only during the rotifer or *Artemia* enrichment stage.

Probiotics: Expanding Enrichment Beyond Nutrition

The filter-feeding behavior that allows rotifers and *Artemia* to accumulate nutrients also enables them to serve as highly effective carriers of beneficial microorganisms. When probiotic bacteria are introduced into enrichment tanks, the live feed organisms ingest and concentrate these microbes within their digestive tracts and tissues. Once consumed by fish larvae, the probiotics are delivered directly into the larval gut.

This approach has attracted significant interest in hatchery systems, particularly because disease outbreaks are common in environments characterized by warm temperatures, high stocking densities, and the constant

presence of pathogenic bacteria such as *Vibrio* species. As a result, probiotic bioencapsulation is increasingly viewed as a promising alternative to antibiotic use.

Numerous studies have reported positive outcomes. In Persian sturgeon (*Acipenser persicus*), *Artemia* bioencapsulated with *Bacillus* probiotics delivered approximately 60 million colony-forming units of bacteria per larva to the digestive tract after one month of feeding. Larvae receiving the enriched *Artemia* showed improved body weight and length compared with controls.

Similarly, hybrid catfish larvae fed *Artemia* enriched with a synbiotic mixture consisting of probiotic bacteria and prebiotic fiber exhibited enhanced growth, improved nutrient utilization, higher survival rates, and beneficial changes in gut microbial composition. In another study, *Artemia* nauplii enriched with the probiotic *Lactiplantibacillus plantarum* improved larval health and increased resistance during a disease challenge involving the pathogen *Vibrio parahaemolyticus*.

One of the most remarkable findings in probiotic enrichment research comes from a challenge trial in which larvae fed rotifers carrying a *Carnobacterium* probiotic achieved a survival rate of 53%, whereas larvae fed non-enriched rotifers showed only 8% survival. This nearly six-fold improvement was attributed solely to the delivery of a single probiotic bacterial strain through live feed.

More broadly, reviews of bioencapsulation studies have reported that probiotic supplementation via live feed can improve growth and survival by approximately 25–30% across various fish species. In addition, probiotic-treated larvae often exhibit enhanced immune responses, including increased lysozyme activity and greater antioxidant enzyme activity.

Today, probiotic bioencapsulation is being investigated in a wide variety of cultured aquatic organisms, including sturgeon, tilapia, catfish, and several shrimp species. Increasingly, it is being integrated with conventional nutritional enrichment strategies rather than treated as a separate approach, since both methods depend on the same filter-feeding characteristics of rotifers and *Artemia* for successful delivery.

Evidence Across Different Fish Species

The studies summarized below provide a representative overview of published research demonstrating the effectiveness of live-feed enrichment across a diverse range of fish species and culture conditions. The findings highlight the broad applicability of enrichment strategies in improving larval performance, survival, growth, and developmental quality.

Species	Enrichment Focus	Main Reported Outcome	Reference
Greater amberjack	n-3 HUFA-enriched *Artemia*	Enhanced larval growth and survival, along with a reduction in skeletal deformities	Roo et al., 2019
Barramundi	Rotifers enriched with a mixed-algae HUFA diet	Achieved 85% survival during a stress challenge and produced the best overall growth and developmental performance	Thépot et al., 2016
Golden pompano	DHA-enriched rotifers	The treatment containing the highest DHA level resulted in approximately half the survival rate observed in the control group	Fu et al., 2021
Milkfish	HUFA and vitamin C enrichment	Reduced opercular deformities by 50% and improved larval growth performance	Gapasin et al., 1998
Red sea bream	Taurine-enriched rotifers	Increased growth, survival, and larval activity	Chen et al., 2004
Gilthead sea bream	Vitamin A-enriched rotifers	Produced dose-dependent effects on the occurrence of skeletal deformities	Fernandez et al., 2008
Asian sea bass	n-3 HUFA-enriched *Artemia* at 34°C	Improved growth performance and reduced deformities under elevated temperature conditions	Pham et al., 2023

Collectively, these studies demonstrate that live-feed enrichment can significantly influence larval quality and performance across multiple fish species. The outcomes vary depending on the nutrient or bioactive compound delivered, but improvements in growth, survival, stress resistance, and skeletal development are commonly reported.

From Research Findings to Hatchery Application

Applying live-feed enrichment strategies in commercial hatcheries involves several practical considerations that are often less visible than the results reported in scientific studies.

Enrichment Duration

The length of the enrichment period is one of the most important management decisions. Short enrichment periods, typically between three and six hours, are easier to integrate into hatchery feeding schedules and place less stress on rotifers and *Artemia*. However, these shorter periods may not allow maximum nutrient accumulation. In contrast, longer enrichment periods, extending up to 24 hours, generally result in greater nutrient loading but may negatively affect the health and survival of the live feed organisms. Extended enrichment also requires stricter monitoring and management of water quality within the enrichment tanks.



Fig 2: Enrichment tanks of Rotifer and Artemia.

Nutrient Retention Following Harvest

The benefits of enrichment can diminish rapidly after harvest. Once enriched rotifers or *Artemia* are introduced into larval rearing tanks, their stored nutrients gradually decline as a result of their own metabolic activity. Fatty acids, vitamins, and other enriched compounds may be depleted within a few hours. Consequently, the interval between harvesting the live feed and feeding it to larvae is a critical factor that directly influences how much of the nutritional enhancement is ultimately delivered to the fish.

Importance of the Baseline Diet

Enrichment should be viewed as a supplement to, rather than a replacement for, a high-quality culture diet. Studies have shown that rotifers raised on different microalgal species possess distinct fatty acid profiles before enrichment even begins. Therefore, hatcheries using the same commercial enrichment product may still achieve different outcomes depending on the nutritional quality of the live-feed culture system employed prior to enrichment.

Balancing Cost and Consistency

Commercial HUFA enrichment emulsions provide reliable and standardized nutrient delivery, making them convenient and predictable. However, they involve ongoing operational expenses. Alternatively, live microalgae and algal pastes, which may also be used directly in larval tanks as part of a “green-water” system, can reduce costs in large-scale operations. Nevertheless, these approaches require greater technical expertise in algae

production and more rigorous quality-control measures to minimize batch-to-batch variability, a challenge frequently highlighted in scientific studies.

No Single Protocol for All Species

Perhaps the most important lesson from enrichment research is that there is no universally applicable protocol. The optimal enrichment strategy depends on species, developmental stage, and environmental conditions such as temperature. A procedure that produces excellent results in gilthead seabream, for example, may not be equally effective for golden pompano or Atlantic cod. Therefore, enrichment protocols must be tailored to the specific biological requirements of each cultured species.

Advances and Future Perspectives in Live-Feed Enrichment

Even when optimally enriched, rotifers and *Artemia* remain substitutes for the natural prey consumed by marine fish larvae in the wild. Copepods, which constitute a major component of the natural diet of many marine fish larvae, generally possess a more balanced profile of HUFAs and amino acids than enriched rotifers or *Artemia*. As a result, increasing attention is being directed toward the commercial-scale cultivation of copepods, particularly for marine ornamental species and other fish that are difficult to rear using conventional live feeds.

Sustainability considerations are also influencing the development of new enrichment products. Traditionally, many HUFA enrichment emulsions have relied on fish oil as their primary source of DHA and EPA. However, fish oil is a finite resource, and concerns regarding its long-term availability have encouraged the search for alternatives. A review published in 2025 on *Artemia* enrichment approaches reported a growing shift toward oils derived from microalgae as sustainable sources of HUFAs. This strategy reduces dependence on fishmeal and fish oil while still supplying larvae with essential fatty acids, amino acids, vitamins, and pigments (Ramena et al., 2025).

Additional research areas include the enrichment of live feed with organic minerals such as selenium, often combined with HUFAs to enhance growth performance and resistance to stress. Scientists are also investigating synbiotic approaches that combine probiotics with prebiotic compounds, as well as molecular studies examining how nutrients such as DHA regulate genes involved in skeletal and jaw development. These advances may eventually enable hatcheries to predict the nutritional requirements of new species more accurately rather than relying solely on trial-and-error experimentation.

Conclusion

The development of live-feed enrichment technology reflects the broader evolution of modern aquaculture science. A fundamental hatchery challenge-providing adequate nutrition to larvae that are too small and physiologically immature to consume formulated feeds-has been addressed not through a single discovery but through decades of systematic research examining species-specific nutritional requirements.

The collective evidence demonstrates that optimizing the nutritional composition of rotifers and *Artemia*, including their HUFA content and balance, levels of vitamin C, taurine, vitamin A, and even the beneficial microorganisms they carry, can significantly improve larval survival, growth, stress resistance, and skeletal development.

At the same time, research has shown that more enrichment is not always better. Findings from studies on species such as golden pompano, where excessive DHA supplementation resulted in reduced survival, illustrate that larval nutrition follows an optimal range rather than a simple linear relationship. Effective enrichment therefore requires precision and balance rather than maximizing nutrient levels indiscriminately.

As the global demand for seafood continues to grow and aquaculture expands into new species and increasingly intensive production systems, the ongoing refinement of live-feed enrichment practices will remain a crucial factor in improving hatchery success and supporting the sustainable development of the aquaculture industry.

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Neem-Based Bio-Inputs for Ecological Farming

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Abstract

Neem-based bio-inputs are gaining considerable attention as sustainable alternatives to synthetic agrochemicals in ecological farming. They contain bioactive compounds, particularly azadirachtin, nimbin, and salannin, which contribute to pest suppression through antifeedant, repellent, and insect growth-regulating activities. In addition to pest management, neem-based products can support soil fertility, nutrient cycling, beneficial microbial activity, and the recycling of agricultural resources. Their integration with integrated pest management, organic farming, and natural farming practices offers opportunities to reduce chemical dependency and promote environmental sustainability. However, product standardisation, formulation stability, field efficacy, and farmer awareness remain important challenges. Further research and long-term field evaluation are essential to establish their effectiveness and economic viability. Neem-based bio-inputs represent a promising component of resilient and environmentally responsible agricultural systems.

Keywords: Neem Cake, Oil Extraction, Organic Pesticide, Sustainability

Introduction

Agriculture is undergoing a massive transformation toward environmentally sustainable production practices to maintain food output while safeguarding land, water, biodiversity and other natural resources. Increasing use of chemical pesticides and synthetic fertilizers has led to concerns about cost of production, pesticide resistance, environmental contamination, decreased soil biological activity and probable damage to non-target organisms. Chemical inputs have contributed much to increasing agricultural productivity, but their overuse or misuse can lead to ecological imbalances and threaten the long-term stability of farming systems (**Kumar *et al*., 2026)**. However, ecological farming is getting more and more important as an agricultural production strategy, which combines biological resources, natural processes, recycling of nutrients and ecologically friendly pest control strategies. Ecological farming is concerned with the efficient use of locally accessible resources, the conservation of beneficial species, the enhancement of soil health and the decrease of unnecessary dependence on external agricultural inputs. It embraces methods such as crop rotation, intercropping, mulching, composting, biological pest control and utilization of plant-derived bio-inputs (Saxena 2004). In these circumstances, botanical resources provide substantial prospects as plants naturally synthesize a diverse variety of chemicals, which are involved in their defence against insects, diseases and other environmental challenges. Neem is a tree that is found all over India and in other tropical and sub-tropical areas. It is of great importance because of its extensive agricultural, medicinal and environmental uses. Neem seeds, leaves, bark, and other plant parts contain biologically active substances that have attracted considerable scientific attention. Among these substances, azadirachtin is one of the best-known compounds associated with insect antifeedant activity (Patel *et al*., 2026). Other neem constituents, including salannin, nimbin, and related limonoids, may also contribute to biological effects, depending on the plant part and extraction method. The composition and concentration of these compounds vary according to genetic characteristics, climatic conditions, seed maturity, processing techniques, and storage conditions. This variation is important when neem materials are developed into agricultural products

because the effectiveness of an individual formulation depends partly on its chemical composition and quality (Saha *et al*., 2011).

Neem based bio-inputs have importance in agriculture beyond pest suppression. When properly selected and included in crop management, they may have a role in diversified pest-control strategies, recycling of resources, and reduced reliance on some synthetic pesticides. Neem cake may be used to complement nutrient-management programs and neem-derived botanical preparations may be used to manage selected insect pests as part of integrated pest management (IPM). However, their effectiveness depends on the target pest, crop species, formulation, application timing, weather conditions and compatibility with beneficial organisms. Therefore, neem products should not be seen as a panacea, completely harmless or a direct replacement of all conventional agricultural inputs (Patel *et al*., 2025).

Types of Neem-based inputs

1. Neem Oil

Neem oil is extracted from neem seed and kernels mainly by mechanical pressing or other extraction methods. The oil is a mixture of fatty acids with varying concentrations of biologically active compounds depending on the source material and the method of extraction. Neem oil is a complex natural product and properties can vary from batch to batch and formulation. Commercial products may be processed or formulated to enhance handling, stability and application performance.

Neem oil is mainly used as a botanical input in organic farming to control specific insect pests. Depending on the formulation and target organism, it can act as a repellent, feeding deterrent and interfere with insect development (Correa *et al*., 2026). Oil-based formulations may also affect susceptible insects through contact, but the effectiveness of such action varies. Neem oil is not equally effective against all pests; its efficacy depends on the insect species, developmental stage, spray coverage, concentration and environmental conditions.

2. Neem Seed Kernel Extraction (NSKE)

Neem seed kernel extract is a botanical preparation that is made from the compounds in the kernels of neem seeds, usually extracted using water-based methods. The kernels contain neem derived limonoids including azadirachtin. However the amount retained in the final extract depends on the quality of the seed, preparation procedure, extraction time and storage conditions. NSKE is widely discussed in botanical pest management, as it provides a way to use neem seeds in agricultural production.

3. Neem Cake

The solid left after extraction of oil from the neem seeds. It contains organic matter, plant nutrients and compounds which are left over from the neem. The composition however depends on the raw material and the method of processing. The major use of neem cake is as a soil amendment and as a supplement to provide nutrients as an agricultural input. Adding it to land can help recycle nutrients by returning plant-derived materials to agricultural land. Neem cake has also been investigated for its potential influence on nitrogen transformations in soil. Certain neem-derived compounds may affect nitrification, a microbial process through which ammonium is converted into nitrate (Garg *et al*., 2024). Under suitable conditions, influencing this process may help manage nitrogen availability and losses. However, the magnitude and consistency of this effect depend on the neem material, soil properties, fertilizer source, application rate, and environmental conditions. Neem cake should not be treated as a guaranteed nitrification inhibitor unless the particular material and use have been appropriately evaluated. Neem cake also has been impact on soil nitrogen changes like nitrification, a microbiological process that transforms ammonium into nitrate, may be impacted by certain chemicals generated from neem. Under the right circumstances, controlling this mechanism could aid in controlling nitrogen losses and availability. However, the neem material, soil characteristics, fertilizer source, application rate, and environmental factors as well strength and consistency.

4. Neem Leave Extract

Neem leaf extract is prepared from fresh or dried neem leaves using water or other suitable extraction procedure. Neem leaves contains several secondary metabolites, including compounds with potential biological activity against certain insects. However, the concentration and composition of these substances vary with leaf age, season, growing conditions, extraction method, and storage (Gaikwad 2025). As a results, leaf extracts generally

have less standardized compositions than commercial products with declared active ingredients. From a resources-use perspective, neem leaf extract offers an opportunity to utilize locally available plant material, and compound effects on target pests, crop tolerance, and potential effects on beneficial organisms.

Mechanisms of Action of Neem-Based Bio-inputs

Neem-based bio-inputs contain biologically active compounds that can influence insect behaviour, development, and reproduction. Their mechanism differs according to the chemical composition of the product, the target organism, and the route of exposure. Understanding these mechanisms is important for selecting appropriate neem formulations and integrating them effectively into ecological pest management (Fig. 1)

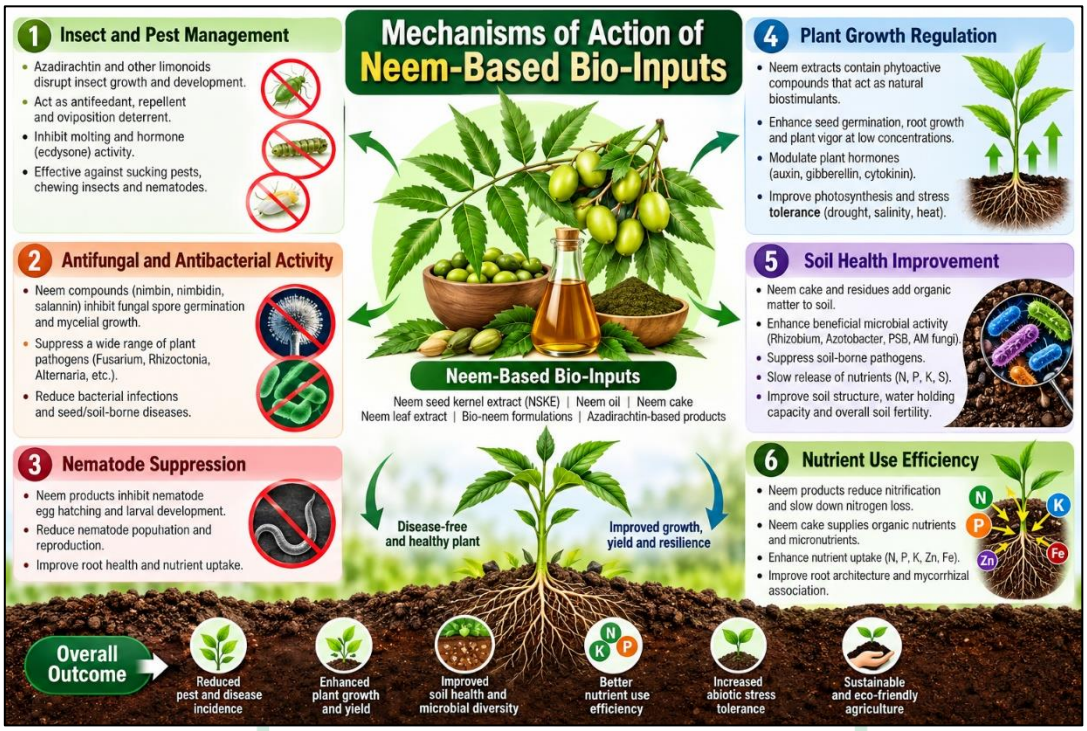


Fig. 1: Mechanism of Neem-based Bio-inputs

Benefits and Environmental Significance

1. Reduced dependence on Synthetic Pesticides

One potential benefit of neem-based bio-inputs is the opportunity to reduce the use of selected synthetic insecticides when neem provide effective control of the target pest. Diversifying pest-management strategies may help reduce repeated reliance on the same pesticide and support more integrated crop protection. However, the extent of pesticide reduction depends on pest pressure, the availability of effective neem formulations and the performance of alternative control methods. Neem products should be incorporated into evidence-based pest-management preprogrammes rather than assumed to replace all conventional pesticides.

2. Biodegradable and Environmental Compatibility

Neem based input derived many compounds undergo degradation through sunlingh, oxidation, and biological processes, their persistence varies with chemical compound, formulation, environmental conditions, and application method. Under some circumstances, relatively rapid degradation can reduce the duration of environmental exposure.

3. Conservation of Beneficial Organisms

Beneficial organism, including pollinators, predators, parasitiods, earthworms, and soil microorganism, contribute to important ecological functions in agricultural systems. Their conservation is a major objective of ecological farming because they support pollination, natural pest suppression, decomposition, and nutrient cycling.

Neem-based products may help reduce dependence on same broad-spectrum insecticide when used effectively.

4. Contribution to Sustainable Agriculture Production

Neem-based bio-inputs can support sustainable agriculture production through the integration of botanical pest management, organic-residue recycling, and supplementary nutrient management. Their use may diversify farm inputs and create opportunities for locally available biological resources to be used productivity. The contribution of neem to substantiality should be assessed across environmental, agronomic and agronomic, and economic dimensions.

5. Support for Rural livelihood and local enterprises

Neem seeds and other plant materials can serve as raw materials for the preparation or manufacturing of selected agricultural products. Where collection, processing, and quality control facilities are available, neem-based products may create opportunities for rural enterprises, cooperative, and bio-input producers.

Future Perspective

Neem-based bio-inputs have considerable potential to promote ecological cultivation by reducing dependence on synthetic agrochemicals and supporting environmentally sustainable crop production. their integration into natural farming, organic agriculture, and integrated pest management systems may improve pest suppression, soil biological activity, nutrient cycling, and overall agroecological resilience. Furthermore, long-term field experiments are needed to assess their effects on crop productivity, soil health, biodiversity, and economic sustainability under diverse agroclimatic conditions. Strengthening farmer awareness, quality-control mechanisms, supportive policies and commercialisation pathways will be essential for the wider adoption of neem-based bio-inputs in ecological cultivation (Fig. 2).



Fig. 2: Future Perspective of neem-based bio-inputs

Conclusion

Neem-based bio-inputs offer promising opportunities for ecological farming through botanical pest management, organic residue recycling, and supplementary nutrient management. Neem oil and seed kernel extracts are primarily relevant to the management of selected insect pests, while neem cake can contribute organic matter and nutrients to agricultural soils. Neem leaf extract may provide additional options when its composition, intended use, and effectiveness are appropriately established. The potential benefits of neem-based products include diversification of pest-management strategies, improved utilisztion of locally available biological resources, and

reduced reliance on selected synthetic pesticides. However, their effectiveness depends on product quality, target organisms, crop conditions, application methods and environmental factors. Natural origin alone does not guarantee safety, consistent performance, or improved crop productivity.

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Beyond Boundaries: Kisan Mela Unlocking Opportunities and Inspiring a New Generation of Entrepreneurs

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Introduction

G.B. Pant University of Agriculture and Technology, Pantnagar, Uttarakhand, is renowned for organizing its annual Rabi and Kharif farmers' fairs, popularly known as *Krishi Kumbh*. These events serve as important platforms for bringing together farmers, agricultural scientists, entrepreneurs, agribusiness organizations and technology providers from different parts of the country. The university campus comes alive with the participation of farming communities, providing opportunities for knowledge exchange, exposure to agricultural innovations and the promotion of rural enterprises.



Hon'ble Governor addressing the gathering at Gandhi Auditorium

The **120th All-India Farmers' Fair & Agro-Industrial Exhibition** was organized during October 3-6, 2026 under the theme *"Smart Kheti- Swasth Dharti- Samriddh Kisan."* The inaugural ceremony was graced by the Hon'ble Governor of Uttarakhand, Lieutenant General Gurmit Singh, as the Chief Guest, while Shri Ganesh Joshi, Agriculture Minister, Uttarakhand, attended as the Guest of Honour. After arriving at the mela premises, the Hon'ble Governor visited the various stalls set up across the fairground, interacted with the participating farmers, and appreciated their efforts, innovations, and contributions to the agricultural sector. Approximately 40,000 farmers participated in the four-day event.

Around 675 stalls of different sizes were established across the fairground, showcasing agricultural machinery, seeds, fertilizers, horticultural plants, value-added products and locally manufactured goods. Beyond conventional agricultural displays, the fair highlighted horticultural diversity, women-led enterprises, millet-based food products, livestock resources and opportunities for practical learning through university research facilities.

Horticultural Diversity and Innovation: A Major Attraction

One of the notable features of the 120th fair was the organized display of ornamental plants and nursery products. Nursery operators were accommodated in a common pavilion, enabling visitors to explore a diverse range of flowering plants and horticultural novelties at one location.

Exotic ornamental plants such as anthuriums, peace lilies and different varieties of begonias attracted visitors' attention. Terrariums and adenium bonsai were among the distinctive attractions, demonstrating the potential of ornamental horticulture as an entrepreneurial activity for nursery owners and small-scale growers.

In each mela, university horticulture department always organize competition regarding unique production in vegetable production, fruit production and in floriculture section the farmers excelling in the production of flowers, vegetables and fruits get felicitated during the valedictory function of kisan mela. Such recognition encourages farmers to pursue quality production, adopt improved cultivation practices and explore commercial opportunities in horticulture.

In addition, nine progressive farmers associated with Krishi Vigyan Kendras (KVKs) located in nine districts and connected with the university's extension network were felicitated by the Hon'ble Governor during the inaugural

ceremony. Their recognition highlighted the contribution of agricultural extension institutions in promoting innovation and strengthening farmers' livelihoods.

Empowering Rural Women and Encouraging Young Entrepreneurs

Beyond conventional agricultural exhibitions, the fair provided a platform for emerging entrepreneurs, rural artisans, women's self-help groups (SHGs), farmer producer organizations (FPOs) and university students.

Women entrepreneurs displayed a variety of handcrafted products, including traditional Aipan art, resin earrings, coasters, baskets made from moonj grass and pine needles (pirul), and decorative articles. These products reflected the potential of local resources, traditional skills and indigenous knowledge to generate additional income.

Several SHGs showcased products made from cow dung and clay, including decorative idols, key rings, diyas and incense sticks. These enterprises demonstrated how locally available materials and traditional craftsmanship can be transformed into marketable products, supporting livelihood diversification and women's economic participation.



Hon'ble governor interacting with SHG members at Kisan Mela

The promotion of nutritious millets was another noteworthy feature. Women entrepreneurs offered a variety of millet-based products, including ragi momos, savoury snacks, sorghum biscuits and laddoos. These initiatives reflected the growing scope for value addition in millets and the development of innovative food products that connect traditional crops with contemporary consumer preferences.

FPOs also displayed and sold processed products, including pickles prepared from bamboo shoots, chillies, jackfruit, karonda and garlic. Such products illustrated how collective enterprises and local processing can create market opportunities for agricultural produce and support income diversification.

University students also participated in the fair by operating confectionery and ice-cream stalls, gaining practical exposure to entrepreneurship and customer engagement. The sale of books, ranging from storybooks to the Bhagavad Gita, added another dimension to the diverse marketplace.

The food stalls offered visitors a culinary journey across regions. Rajasthani dal-baati-churma, South Indian idli, dosa and uttapam, traditional Pahadi sel roti, Nepali momos and Himachali siddu were among the delicacies available to visitors.

Together, these activities demonstrated that agricultural fairs can extend beyond crop production and farm machinery to become vibrant platforms for rural enterprise development, cultural exchange and the promotion of locally produced goods.

Agricultural Machinery and Technology on Display

Agricultural machinery remained an important component of the exhibition. Stalls featuring equipment such as power weeders, threshers and other farm implements attracted farmers seeking solutions to labour-intensive agricultural operations. Manufacturers and agricultural input providers from different regions provided opportunities for farmers to explore available technologies and interact directly with representatives.



Agricultural machineries at Kisan Mela

Such exhibitions can support informed decision-making regarding farm mechanization and the selection of technologies suited to local production systems. The combination of machinery displays, horticultural

innovations and locally developed products reflected the diverse needs of contemporary agriculture, ranging from improved productivity to value addition and enterprise development.

Mahila Club: Serving with Care and Contributing to Charity

Throughout the four days of the Kisan Mela, the Mahila Club played a significant role by providing delicious, home-cooked meals to visitors, security personnel, and members of the organizing team. The food was made available for purchase, offering a convenient and wholesome dining option while supporting the club's activities.



Mahila Club members showcasing their contribution to the Kisan Mela."

The Mahila Club is headed by the First Lady of the University, the wife of the Hon'ble Vice-Chancellor, adding special significance to its participation in the event. In recognition of its valuable contribution and dedicated service, the Mahila Club was felicitated with a **"Very Special Award"** by the Hon'ble Vice-Chancellor during the valedictory function.

In a commendable gesture of social responsibility, the Mahila Club members also pledged to donate the entire amount generated through the sale of food during the Kisan Mela to charitable causes, reflecting their commitment to community welfare and service to society.

Cultural Programmes: A Celebration of Art, Talent and Tradition

Cultural programmes added colour, vibrancy and entertainment to the four-day Farmers' Fair. The evening of the first day featured captivating performances by students of Shishu Mandir, who delighted the audience with their enthusiasm and talent. On the second evening, students from the university and Campus School showcased their artistic abilities through a variety of cultural performances. The third evening witnessed a mesmerising *Kavi Sammelan*, where poets enthralled the audience with their thought-provoking verses, humour and literary expressions. These evening programmes provided a lively platform for young talent and celebrated the rich cultural and literary traditions of the region, making the Farmers' Fair a memorable experience for visitors and participants alike.



Glimpses of cultural performances

Educational Visits: Connecting Farmers with University Research

A distinctive feature of the four-day fair was the arrangement of educational visits for farmers to various research, demonstration and production units of the university. These included the Horticultural Research Centre, Vegetable Research Centre, dairy farm, Livestock Production Management Farm, Institutional Poultry Farm and Honey Bee Training and Research Centre.

Buses were arranged near the Nagla Gate to facilitate farmers' visits to these units. The programme enabled participants to observe research and production facilities, interact with university personnel and gain practical exposure to agricultural and allied-sector technologies.

An important aspect of these visits was the opportunity to learn about livestock resources developed through the scientific efforts of university researchers. At the Institutional Poultry Farm, farmers were introduced to the **Uttara fowl**, while at the Livestock Production Management Farm, they learned about the **Pantja goat breed**. Both breeds were developed through the research efforts of scientists and researchers at G.B. Pant University of

Agriculture and Technology. These demonstrations familiarized farmers with the breeds and provided opportunities to gain practical knowledge about their characteristics and management.

Farmers were also informed about the availability of university-produced seeds of crops such as rice, wheat and vegetables, along with honey and other agricultural products. Chicks produced by the university's poultry farm were made available at government-approved rates. Information about the Uttara fowl and Pantja goat further highlighted the contribution of university research to livestock-based livelihood opportunities.

These educational visits were valuable because they complemented theoretical information with direct observation and practical learning. Farmers could interact with experts, clarify their doubts and explore the suitability of improved technologies and livestock enterprises for their own farming conditions. Information about ongoing government schemes related to agriculture and allied sectors was also shared, helping participants become more aware of available opportunities and institutional support.

Research Innovations and Knowledge Dissemination: Bridging the Gap Between Science and Farmers

Working models based on the theme of the Kisan Mela were prepared by students from various colleges of the university to enhance farmers' understanding of modern agricultural technologies and practices. These models were exhibited throughout the fair, with students explaining their concepts and functioning to visitors, thereby promoting interactive learning and knowledge exchange.



Students showcasing innovative working models

Stalls showcasing the research and technological advancements of the university's **Horticulture Research Centre, Vegetable Research Centre, and Model Floriculture Centre** were also set up, providing visitors with valuable insights into ongoing research and improved agricultural practices. The Honeybee Research and Training Centre attracted visitors with its locally produced honey, which was sold by the centre's staff, highlighting the commercial potential of beekeeping.

The **Agricultural Technology Information Centre (ATIC)** emerged as a major attraction for farmers. Visitors purchased a wide range of agricultural inputs, including wheat and paddy seeds, pulses, and saplings of various plants. These sales generated revenue amounting to approximately **₹2 crore**, demonstrating the centre's significant contribution to farmers' access to quality planting material and the university's technology dissemination efforts.

Kisan Goshthis: Strengthening Farmer–Scientist Interaction

Farmer–scientist interaction remained central to the fair through the organization of daily *Kisan Goshtis* in the Gandhi Auditorium during the afternoon sessions.

Farmers from different regions actively participated in these discussions, presenting problems encountered in their fields and seeking technical guidance from university scientists. The sessions provided opportunities to discuss crop production, plant protection and other agricultural and allied-sector concerns.

An important aspect of these interactions was the sharing of innovations already being practised by farmers on their own farms. Such exchanges enabled farmers to learn from one another's experiences while helping scientists understand field-level challenges and information needs.

The goshtis also facilitated the dissemination of information about improved agricultural practices and emerging technologies. By creating a common platform for farmers and experts, these sessions reinforced the role of agricultural fairs as channels of two-way communication rather than merely venues for the display of products.

Effective Management and Security Arrangements

The successful conduct of a large public event requires effective coordination and careful management. During the four-day fair, university security personnel and Uttarakhand Police remained involved in security arrangements to facilitate the movement and participation of visitors.

The coordination of exhibitions, educational visits, farmer–scientist discussions and commercial stalls contributed to the overall functioning of the event. The diverse activities ensured that visitors could explore agricultural

technologies, learn about research developments and discover opportunities for enterprise and livelihood diversification.

Conclusion

The 120th All-India Farmers' Fair & Agri-Industrial Exhibition at Pantnagar illustrated the expanding role of agricultural fairs in a changing agricultural landscape. While farm machinery, seeds and production technologies remained important attractions, the fair also highlighted horticultural entrepreneurship, millet-based value addition, women's self-help groups, FPO-led marketing, student enterprises and livestock-based livelihoods.

The educational visits to university research and production units provided farmers with opportunities to learn about the Uttara fowl and Pantja goat, both developed through the university's research efforts. The daily Kisan Goshtis further strengthened the connection between agricultural research and field-level farming practices by enabling farmers to discuss their problems and exchange practical experiences with scientists.

The theme, *"Smart Kheti- Swasth Dharti- Samriddh Kisan"* reflected the importance of integrating scientific knowledge, sustainable resource use, entrepreneurship and farmer empowerment. By bringing together research institutions, farming communities, entrepreneurs and technology providers, the fair demonstrated how agricultural exhibitions can support knowledge exchange and encourage diversified livelihood opportunities.

Ultimately, the significance of a Kisan Mela lies not only in the number of stalls or visitors but also in its ability to inspire farmers, promote innovation and translate scientific advancements into practical opportunities for improving agricultural livelihoods. The 120th farmers' fair at Pantnagar offered a comprehensive glimpse of this potential, connecting agricultural research, traditional knowledge and entrepreneurship in the pursuit of a more sustainable and prosperous farming future.

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Comparative Review of Pure Jersey and Jersey Crossbred Cattle for Tropical Dairy Production

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Abstract

Jersey cattle are recognized for their relatively small body size, efficient milk production, high milk-fat concentration and moderate maintenance requirements. However, under tropical conditions, actual dairy performance is influenced by heat stress, feed availability, disease pressure, reproductive efficiency and farm management. Jersey crossbreeding combines the productive characteristics of Jersey cattle with the adaptive characteristics of indigenous or non-descript cattle and has therefore become important in Indian dairy production. This review compares pure Jersey and Jersey crossbred cattle with respect to milk yield, milk composition, maintenance requirement, feed utilization, heat tolerance, health, reproductive performance, durability, management and economic suitability. Pure Jersey cattle generally have lower absolute maintenance requirements and favourable milk-fat characteristics because of their smaller body size and breed characteristics. Jersey crossbreds generally have a moderate body size and can achieve higher practical production under tropical field conditions while retaining useful milk composition and environmental adaptability. Large-scale field evaluations of Jersey crossbred cattle in Tamil Nadu have reported approximately 2.4–2.5 tonnes of milk during a standard lactation, although performance varies with genetic group, parity, season, agro-climatic region and management. Jersey crossbreds are not completely resistant to heat stress or disease, and high-producing animals still require appropriate nutrition, housing and health management. Overall, pure Jersey is advantageous where low maintenance and high-fat milk are priorities, whereas Jersey crossbred cattle provide a balanced combination of productivity, adaptability and economic suitability for many medium-input tropical dairy systems.

1. Introduction

Dairy cattle selection is an important factor determining the productivity and profitability of dairy farms. In tropical countries, breed performance is influenced not only by genetic potential but also by high temperature, humidity, seasonal feed availability, disease pressure, reproductive stress and management conditions. Therefore, a dairy animal that produces high milk under favourable conditions may not necessarily be the most profitable animal under tropical field conditions.

Jersey cattle are widely valued for their small-to-medium body size, relatively low maintenance requirement, good milk production relative to body size and high milk-fat concentration. These characteristics make Jersey useful for dairy farming and crossbreeding. Jersey crossbred cattle are developed to combine these productive characteristics with the environmental adaptability of indigenous cattle.

The comparison between pure Jersey and Jersey crossbred cattle should therefore consider not only milk yield but also maintenance cost, feed requirement, heat tolerance, health, reproduction, productive life and economic return. The present review synthesizes available evidence to determine the relative strengths and limitations of both genetic types under tropical dairy production systems, with particular relevance to Indian conditions.

2. Pure Jersey and Jersey Crossbred Characteristics

Pure Jersey is a specialized dairy breed with a relatively small mature body size. Its smaller frame reduces absolute maintenance requirements compared with larger dairy cattle. Jersey milk is also characterized by comparatively high fat concentration, which can provide an economic advantage where milk payment is influenced by fat and solids.

Jersey crossbred cattle are produced by combining Jersey inheritance with indigenous or non-descript cattle. Their body size, milk production and reproductive performance vary according to the proportion of Jersey

inheritance and the genetic background of the indigenous parent. The major objective of crossbreeding is to achieve a practical balance between milk production and adaptation rather than maximizing a single trait.

Table 1. General comparison

Character	Pure Jersey	Jersey Crossbred
Body size	Small–medium	Medium
Maintenance requirement	Low–moderate	Moderate
Milk production potential	Good–high	Moderate–high
Milk fat	Generally high	Generally good–high
Feed requirement	Relatively lower	Moderate
Tropical adaptability	Good	Generally very good
Heat tolerance	Relatively good	Good, influenced by indigenous inheritance
Disease resilience	Good with management	Generally better adapted to local conditions
Production variation	Comparatively lower	Higher
Suitability	Low/medium-input farms	Tropical small/medium dairy farms
Main strength	Low maintenance and milk composition	Production–adaptability balance

3. Milk Production Performance

Milk yield is the most visible production trait, but actual yield depends on genetics, nutrition, climate, parity, lactation stage and management. Pure Jersey has substantial genetic potential for milk production relative to body size, but performance under tropical conditions can be lower than breed-level potential.

Long-term evaluation of pure Jersey cattle under tropical conditions demonstrated approximately 1,492 kg 305-day milk yield and approximately 1,561 kg total lactation yield in one organized herd. This illustrates that environmental conditions can considerably affect the expression of genetic potential.

In contrast, large-scale field evaluations of Jersey crossbred cattle in Tamil Nadu have demonstrated substantially higher practical production. A dataset covering 81,653 Jersey crossbred cows reported approximately 2,459 kg 305-day milk yield, 2,471 kg total lactation yield, 10.69 kg peak yield and approximately 298 days lactation length. Another evaluation of more than 75,000 Jersey crossbred cows reported approximately 2,394 kg 305-day milk yield and 2,480 kg total milk yield. These results suggest that well-managed Jersey crossbreds can provide considerable milk production under tropical field conditions.

Table 2. Reported milk-production performance

Parameter	Pure Jersey*	Jersey crossbred**
305-day milk yield	~1,492 kg	~2,394–2,459 kg
Total lactation yield	~1,561 kg	~2,471–2,480 kg
Peak yield	—	~10.7 kg/day
Lactation length	~303 days	~298 days
Interpretation	Strong breed potential but environmental effect is important	High practical field performance with considerable variation

4. Milk Fat and Milk Composition

Milk composition is an important advantage of Jersey genetics. Pure Jersey is traditionally associated with relatively high milk-fat concentration, commonly around 4.5% under breed descriptions, although actual values vary with nutrition, lactation stage and individual genetics.

Jersey crossbred cattle can retain a substantial proportion of this favourable milk-composition characteristic. Reported studies have recorded milk-fat concentrations around or above 4% in several Jersey crossbred populations. In Jersey × Sahiwal cattle, one study reported approximately **4.48% fat**, demonstrating that useful milk composition can be maintained after crossbreeding.

Therefore, pure Jersey generally has an advantage in terms of the characteristic high-fat milk, while Jersey crossbreds can combine good milk composition with greater tropical adaptability and higher practical milk production.

5. Maintenance Requirement and Feed Utilization

Maintenance requirement is strongly related to body weight and metabolic size. The smaller body frame of pure Jersey results in a relatively lower absolute maintenance requirement. This can be advantageous when feed resources are limited or expensive.

Jersey crossbreds are generally somewhat larger and therefore require more nutrients for maintenance. However, higher maintenance expenditure does not necessarily mean lower economic efficiency. A crossbred cow consuming more feed but producing substantially more milk may generate greater net income. Feed efficiency should therefore be assessed using milk produced per unit of dry matter intake or feed cost per litre rather than feed consumption alone.

Important economic principle

Low feed requirement per cow ≠ automatically lower cost per litre.

The correct comparison is:

Feed cost per litre = Total feed cost ÷ Total milk produced

and:

Net return = Total income − Total production cost

Jersey crossbreds can be particularly suitable for medium-input systems where green fodder, dry fodder and concentrate are available and milk production is sufficiently high to justify the additional input.

6. Feed Requirement

Both pure Jersey and Jersey crossbred cattle require a balanced supply of energy, protein, fibre, minerals and water. Feed requirement changes according to body size, milk yield, pregnancy, growth and environmental stress. Pure Jersey generally requires less feed for maintenance because of its smaller body size. Jersey crossbred cows with higher milk production require additional nutrients to support production.

The major components of a practical ration include:

- green fodder
- dry fodder
- concentrate
- mineral mixture
- adequate clean water.

The quantity of concentrate should be adjusted according to individual milk production rather than providing the same quantity to every animal.

7. Heat Tolerance and Tropical Adaptability

Heat stress is one of the major limitations to dairy production in tropical regions. It reduces feed intake, alters physiological responses and can reduce milk production and reproductive efficiency. Jersey cattle generally show better heat adaptability than several larger temperate dairy breeds. Jersey crossbreds can obtain additional adaptive characteristics from indigenous genetic backgrounds. However, neither pure Jersey nor Jersey crossbred cattle should be considered completely heat resistant. Research on Jersey crossbred cows has shown increased respiration rate and body temperature under high temperature-humidity index conditions. At THI above approximately 80, high-producing cows can experience substantial milk-yield reductions.

Therefore, genetic adaptability should be supported by:

- adequate shade
- ventilation
- sufficient drinking water
- cooling systems where required
- appropriate feeding times
- heat-stress monitoring.

Table 3. Adaptability comparison

Trait	Pure Jersey	Jersey Crossbred
Heat adaptability	Good	**Generally better under tropical field conditions**
High-THI response	Stress occurs at severe heat	Stress still occurs
Water requirement	Moderate	Moderate–high according to yield
Environmental flexibility	Good	**Generally high**
Need for cooling	Moderate in severe summer	Important for high-producing animals

8. Health, Disease and Durability

Health is directly related to dairy profitability because disease increases veterinary expenditure, reduces milk production and can prolong reproductive intervals. Important dairy health problems include mastitis, reproductive disorders, metabolic disorders, parasitic infections and infectious diseases. Pure Jersey cattle can perform successfully when proper preventive health management is provided. Jersey crossbreds may have an adaptive advantage in tropical field conditions because of their indigenous genetic component. However, they should not be described as universally disease resistant. Disease occurrence is influenced by hygiene, vaccination, nutrition, housing, parasite control, climate and management. Durability should be assessed through the ability of a cow to remain healthy, reproductive and productive across several lactations. Jersey crossbreds can be advantageous in tropical environments when their genetic composition and management are appropriate.

9. Reproductive Performance

Reproductive efficiency is essential for maintaining continuous milk production and reducing non-productive periods. Important indicators include age at first calving, service period, conception rate, days open and calving interval. Pure Jersey is generally recognized as an early-maturing dairy type and can show satisfactory reproductive performance under suitable management. Jersey crossbred performance is more variable because different animals may have different proportions of Jersey and indigenous inheritance. For example, Jersey × Sahiwal cattle have shown favourable reproductive characteristics in some studies, including shorter service period and calving interval compared with Sahiwal. However, Jersey × Red Sindhi populations have also shown relatively long reproductive intervals in some datasets. Therefore, reproductive performance should not be attributed to breed alone. Nutrition, heat stress, body condition, disease and breeding management have major effects.



10. Lactation Length and Dry Period

Lactation length is important because it determines the duration over which milk income is generated. Pure Jersey under tropical conditions has demonstrated lactation lengths close to 300 days. Large field evaluations of Jersey crossbred cattle have similarly reported approximately 298 days. The dry period is required for mammary recovery and preparation for the next lactation. Excessively long dry periods increase non-productive days,

whereas insufficient dry periods may affect subsequent production. Consequently, proper reproductive and dry-period management is important for both pure Jersey and Jersey crossbred cattle.

11. Housing, Water and Labour Requirement

Both genetic types require comfortable and hygienic housing. Important housing characteristics include adequate space, ventilation, shade, drainage, clean flooring and easy access to water. Because Jersey crossbreds may be larger and more productive, housing dimensions and feeding facilities should be adjusted according to actual animal size. Water requirement increases with milk production and ambient temperature. High-producing Jersey crossbreds therefore require particular attention to water availability during hot weather. Labour requirements are generally determined more by herd size and management intensity than by breed. Routine activities include feeding, milking, cleaning, health observation, breeding management and manure handling.

12. Economic Performance

Economic performance should be assessed by considering both income and total cost.

Total income

Milk income + calf value + manure value + other income

Total cost

Feed + labour + veterinary + breeding + housing + electricity + water + miscellaneous costs

Net return

Net return = Total income − Total cost

Pure Jersey has an advantage in lower absolute maintenance expenditure. Jersey crossbreds may have higher feed requirements but can compensate through higher milk production. Consequently, economic superiority depends on the ratio between additional production and additional input.

Table 4. Economic comparison

Economic factor	Pure Jersey	Jersey Crossbred
Maintenance feed cost	**Lower**	Moderate
Potential milk income	Moderate–high	High under suitable management
Milk-fat value	Favourable	Favourable
Feed cost/litre	Potentially low	Potentially low if production is high
Veterinary cost	Management dependent	Management dependent
Labour cost	Similar	Similar
Climate-related cost	Moderate	Moderate
Commercial potential	Good	Very good under tropical conditions

13. Suitability for Different Farming Systems

The choice between pure Jersey and Jersey crossbred should be based on the production system.

Low-input system

Pure Jersey can be advantageous because of its smaller body size and lower maintenance requirement. However, appropriately selected Jersey crossbreds can also perform well when local adaptation is important.

Medium-input system

Jersey crossbreds are particularly attractive because they can combine useful milk production with tropical adaptability and moderate input requirements.

High-input system

Both pure Jersey and high-performing Jersey crossbreds can perform well when balanced nutrition, cooling, reproductive management and health care are available.

14. Advantages and Limitations

Pure Jersey – Advantages

- Smaller body size.
- Lower absolute maintenance requirement.
- Good milk production relative to body size.
- High milk-fat concentration.

- Good adaptability compared with many larger exotic dairy breeds.
- Suitable for farms with moderate feed resources.

Pure Jersey – Limitations

- Actual production can decline under severe tropical stress.
- Genetic potential depends strongly on nutrition and management.
- May have less environmental adaptability than appropriately selected indigenous-influenced crossbreds.

Jersey Crossbred – Advantages

- Combines Jersey production traits with indigenous adaptability.
- Good practical milk production under tropical conditions.
- Moderate body size.
- Good milk-fat characteristics.
- Suitable for semi-intensive systems.
- Strong potential for small and medium dairy farms.
- Better balance between production and environmental adaptation.

Jersey Crossbred – Limitations

- Greater variation among animals.
- Performance depends on genetic composition.
- Higher nutrient requirement when production is high.
- Not completely heat or disease resistant.
- Reproductive performance can decline under poor nutrition and heat stress.

15. Research Gaps

Future studies should focus on direct, long-term comparisons between pure Jersey and Jersey crossbred cattle under identical environmental and management conditions.

Important areas include:

1. Lifetime milk production.
2. Lifetime feed efficiency.
3. Productive herd life.
4. Replacement rate.
5. Heat tolerance genetics.
6. Reproductive efficiency under heat stress.
7. Disease resilience.
8. Methane emission and environmental efficiency.
9. Precision dairy and IoT-based monitoring.
10. Lifetime economic profitability.
11. Optimum Jersey inheritance level for different agro-climatic regions.

Greater use of automated milk recording, activity monitoring, rumination sensors, body-temperature monitoring and digital health records may help identify animals with superior production efficiency and environmental resilience.

16. Conclusion

The comparative review demonstrates that pure Jersey and Jersey crossbred cattle each possess distinct advantages. Pure Jersey cattle are characterized by relatively small body size, lower absolute maintenance requirements and favourable milk-fat concentration. These characteristics make them particularly attractive where feed resources are limited and milk composition is economically important. Jersey crossbred cattle provide a broader combination of productive and adaptive characteristics. Their indigenous genetic component can improve suitability to tropical conditions while retaining useful Jersey characteristics for milk production and composition. Large-scale field evaluations in Tamil Nadu have demonstrated approximately 2.4–2.5 tonnes of milk during a standard lactation in Jersey crossbred populations, although substantial variation exists according to genetic group, parity, season, agro-climatic zone and management.

The comparison also demonstrates that neither genetic type should be considered completely resistant to heat stress or disease. High-producing animals require appropriate nutrition, water, housing, health care and heat-stress management to maintain production and reproduction. From an economic perspective, the most important criterion is not simply the lowest maintenance requirement or highest milk yield. Feed cost per litre, reproductive efficiency, health expenditure, productive lifetime and net return per cow provide a more meaningful basis for evaluating dairy cattle. Overall, pure Jersey is particularly suitable when low maintenance, small body size and high-fat milk are the main priorities, while Jersey crossbred cattle provide a stronger balance between milk yield, maintenance requirement, tropical adaptability, durability and economic performance. For small and medium dairy farms operating under tropical Indian conditions, particularly medium-input and semi-intensive systems, well-selected Jersey crossbred cattle can therefore be considered a highly practical dairy genetic resource.

The final conclusion is that Jersey crossbred cattle should not be considered universally superior to pure Jersey cattle. Instead, the most suitable genetic type depends on the interaction of genetic potential, feed availability, climate, management intensity, health status and milk-market conditions. Future breeding programmes should therefore place equal emphasis on milk production, feed efficiency, heat tolerance, reproductive performance, health, longevity and lifetime profitability, rather than selecting animals solely on maximum milk yield.

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WINTER VEGETABLE PRODUCTION THROUGH RAINWATER HARVESTING (*JALKUND*): A SUCCESS STORY OF A GARO TRIBAL FARMER UNDER TDC-NICRA IN WEST GARO HILLS, MEGHALAYA

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Abstract

The hilly terrain of West Garo Hills, Meghalaya, faces significant challenges due to unpredictable and seasonal rainfall, severe moisture stress, and the lack of reliable irrigation during the rabi (winter) season. Through the National Innovations in Climate Resilient Agriculture (NICRA) program, Mr. Tengseng Sangma from Village Bagugre adopted climate-resilient technology called Jalkund (a farm-level rainwater harvesting structure for production of winter vegetable. The integration of the Jalkund technology helped ensure reliable irrigation for his 1.20 ha area during the rabi season. As a result, Mr. Sangma was able to achieve a net return between Rs. 1,30,160 and Rs. 1,66,000 per ha with BCR of 2.13 to 2.30 from his vegetable production using Jalkund, which greatly exceeded the net return from rainfed traditional practice. His farm has since become a community learning platform, encouraging technology adoption among 12neighbouring farmers.

Keywords: Jalkund, rainwater harvesting, rabi vegetables, NICRA, West Garo Hills, climate resilience

Agriculture in Meghalaya faces high climate risk as it is completely dependent on the rainfed agriculture system, making farming more challenging during the dry season. Although Meghalaya is known to receive one of the highest annual rainfall amounts in the country (1544.90 mm), but the rain distribution in the region is seasonal, with June - September being the monsoon months. The kharif season witnesses abundant moisture, while rabi season isknown to have prolonged dry spells, leaving smallholder farmers bereft of adequate water for the production of winter vegetables during the rabi season. This seasonal deficit of water, compounded by hilly terrain, accelerates surface runoff, causing a strongincreasein soil erosion andmaking year-round vegetable production challenging for marginalised tribal farmers of the district and Meghalaya as a whole. Therefore, under the National Innovations in Climate Resilient Agriculture (NICRA) programme, ICAR-KVK, West Garo Hills, Sangsanggre, Meghalaya has been promoting climate-resilient technologies (CRTs)based on the agro-ecological conditions and addressing the vulnerability of the region. Among various CRTs, Jalkund- a farm-level rainwater harvesting structure, has emerged as a highly impactful intervention for the production of winter vegetablesduring the rabi season, thereby creating a sufficient water storage facility and increasing the potential and usage of the stored water during the dry season, significantly increasing the productivity and food security. This CRT (Jalkund) improves water management strategies and promotes scientific watershed approaches, making it essential to mitigate the water loss and enhance the utilization of the stored water, thus harnessing the rich water resource through scientific intervention and ensuring water security, allowing the year-round vegetable production in the region. Therefore, this success story documents the transformative impact of Jalkund on the livelihood and farm productivity of Mr. Tengseng Sangma, a smallholder farmer of Village Bagugre, Block Dalu, West Garo Hills district, Meghalaya.

Farmer's profile

Mr. Sangma is an example of the resilient small-scale farmer of Meghalaya who, although uneducated formally and facing restrictions in resource endowment, has made it possible to improve his land and make it economically profitable and environmentally sustainable by taking scientific advice. Mr. Sangma's association with ICAR-KVK since 2017 has played a key role in this respect.

Name	Mr. Tengseng Sangma
Village and Block	Bagugre, Dalu
District and State	West Garo Hills, Meghalaya
Total Land Holding	2.5 hectares
Irrigated Area (post-Jalkund)	1.20 hectares
Water Resource	*Jalkund* (Rainwater Harvesting Structure)
Educational Qualification	Class VI Pass
Support Programme	TDC-NICRA Project, ICAR-KVK West Garo Hills
Principal Enterprise	Rabi Vegetable Cultivation - Cabbage, Cauliflower, Tomato and Chilli

Jalkund - A farm level rainwater harvesting structure for assured irrigation

Concept and design

A Jalkund is a farm-level, effective in situ rainwater harvesting structure designed to capture and store rainwater during the kharif monsoon season for subsequent utilisation during rabi season for winter vegetable production. Structurally, it comprises an excavated pond-like structure lined with a high-density polyethylene (HDPE) sheet of 300 GSM to prevent water loss through seepage, thereby maximising storage efficiency. The design is decentralised and can be managed at the farm level, making it inherently suited to the undulating terrain. Under the NICRA intervention, ICAR-KVK, West Garo Hills provided technical guidance and material support for the construction of a Jalkund of size 5x4x1.5m (length x breadth x depth) having a capacity of holding 30000 litres of water. The construction process of Jalkund comprised several steps to ensure the effectiveness and longevity of the rain water harvesting structure. The first step is the selection of a suitable site, after which the excavation of the kund should be started and completed before the onset of the monsoon. Secondly, the kund was levelled by removing stones or any other materials that damage the lining material. Thirdly, the inner walls as well as the bottom of the excavated kund were carefully plastered and smoothed with clay and cow dung mixed in a proportion of 5:1 ratio. After plastering, 3 to 5 cm thickness of locally available cushioning material, such as dry leaves were placed on the walls and bottom of the kund in order to avoid damage to the lining material.Lastly, HDPE sheet of 300 GSM was laid down carefully so that it touches the bottom and walls loosely and uniformly, with the outer edge of around 50 cm buried in the soil to tightly bind from all sides. In this way, the water loss through seepage was completely checked.

Transformation of on-farm water availability

Prior to the construction of Jalkund, winter vegetable production during the rabi season was severely limited due to the absence of an assured irrigation facility, as the production is completely dependent on residual moisture from the monsoon season. Therefore, the potential of winter vegetable production was low and associated with high risks of failure due to moisture stress during vegetative stages, flowering, fruit formation, and development stages of different crops, which resulted in failure of establishment of crops, poor yield and even crop failures. Consequently, the farm remained largely underutilized in terms of growing crops during the rabi season. Hence, the construction of Jalkund provided a significant difference in the availability of water resources on the farm through harvesting of monsoon water runoff which was being lost through surface drainage. The structure was thus creating a reserve of water resources which would then provide assured irrigation in case of drought during the rabi season. This assured irrigation made it possible for Mr. Sangma to grow vegetables on an area of 1.20 ha. This in turn, facilitated the cultivation of valuable vegetable crops like cabbage (cv. Golden acre), cauliflower (cv. Pusa Snowball), tomato (cv. Arka Abhed) and chilli (cv. Arka Khyati) with assured and timely irrigation at all critical phenological stages. Beyond increasing production, the intervention contributed to improved cropping intensity, farm productivity, and livelihood security by enabling opportunities for sustainable vegetable production during the rabi season.

Impact of Jalkund on winter vegetable production

Among the four vegetable crops cultivated under Jalkund based irrigation by Mrs. Sangma, Cauliflower recorded the highest yield (128.74 q/ha), followed by Cabbage (122.58 q/ha), Tomato (111.60 q/ha), and Chilli (96.42 q/ha) (Fig. 1). The yield performances of the four crops exhibited the agronomic advantage conferred by scheduled, demand-based irrigation obtained from the Jalkund as it allowed sufficient availability and supply of water at different developmental stages of the plants including transplanting, vegetative stage, flowering, and fruiting stages without disruptions associated with irrigation using stream water. Such a factor is very important in case of vegetable such as tomato and chilli where any moisture deficit during flowering stage leads to flower shedding. Comparison of yields of tomato crop in NICRA (111.60 q/ha) and farmers' practice (76.80 q/ha) proves this point as the yield gain using irrigation obtained from Jalkund is about 45.30%.

The economic analysis corroborates and further strengthens the superior agronomy demonstrated above. Tomato grown under the Jalkund-based irrigation had a maximum gross return (GR) of Rs. 2,76,500/ha and net return (NR) of Rs. 1,66,000/ha, followed by Cauliflower (GR - Rs. 2,57,480/ha; NR - Rs. 1,39,480/ha), Cabbage (GR - Rs. 2,45,160/ha; NR - Rs. 1,30,160/ha), and Chilli (GR - Rs. 2,41,050/ha; NR - Rs. 1,36,050/ha). In comparison to this, the farmers' practice earned a net return of Rs. 93,500/ha in case of tomato, which is below the least performing crop in this list (Cabbage earning Rs. 1,30,160/ha) by 39%. The net return difference between Tomato cultivated using Jalkund technology compared to that cultivated by farmers' practice comes to Rs. 72,500/ha. This implies an increase of profit per hectare by 77.5% despite the increase in cost of cultivation by just Rs. 1,10,000/ha against Rs. 98,500/ha under farmers' practice. This difference indicates that the additional investment involved in Jalkund construction and operation is recovered many-fold through the yield and income gains through Jalkund, which is a truly transformative agricultural technology.

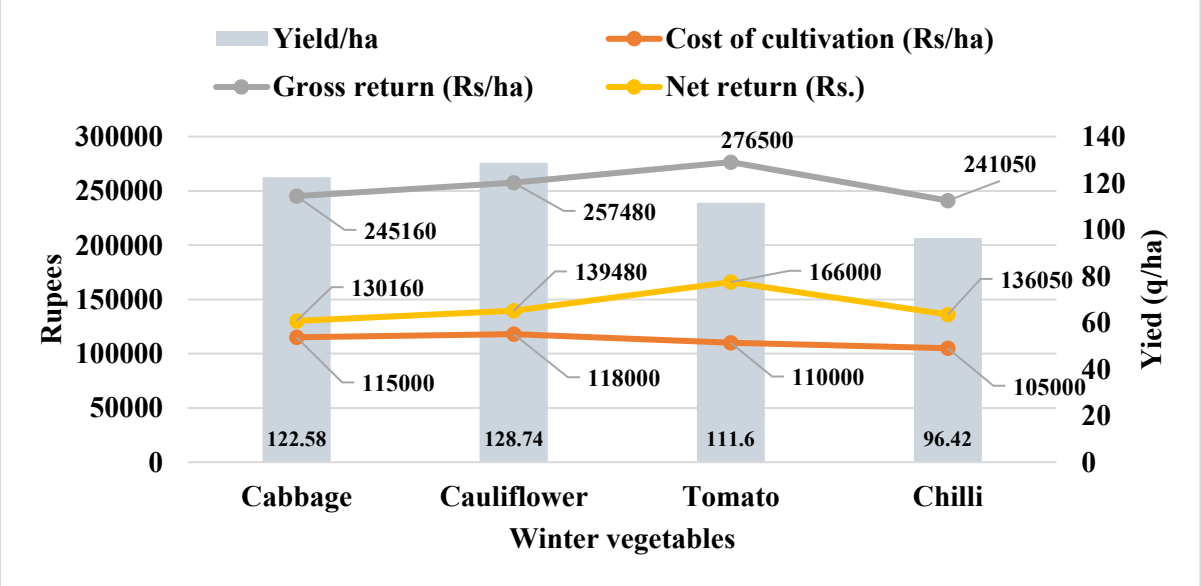


Fig. 1. Yield and Economics of winter vegetable production using Jalkund as an irrigation source

The benefit-to-cost ratio (BCR) analysis provides perhaps the most unambiguous insight into the impact of the Jalkund on the economy (Fig. 2). It can be observed that all four vegetable crops had BCR above 2 ranging from 2.13 (cabbage) to 2.51 (tomato), with chilli and cauliflower having 2.30 and 2.18, respectively. In all these cases, the ratio exceeded the farmers' practice B:C ratio of 1.94, implying that the system based on the use of the Jalkund was better at generating higher ROI, not just for one vegetable crop but for all four crops cultivated. The BCR of tomato stands out as being 29.40% better than the farmer's practice due to the superior quality, timing and availability of the irrigation water provided by the Jalkund. On the other hand, from the perspective of the farming system, the adoption of four rabi vegetables, facilitated by the increased irrigated area, would help distribute market and climatic risks across several streams of income. In conclusion, the above results confirm

that the Jalkund is more than just an irrigation system, rather, it is a basic infrastructure required for a viable and diversified rabi vegetable farming enterprise (Fig. 3).

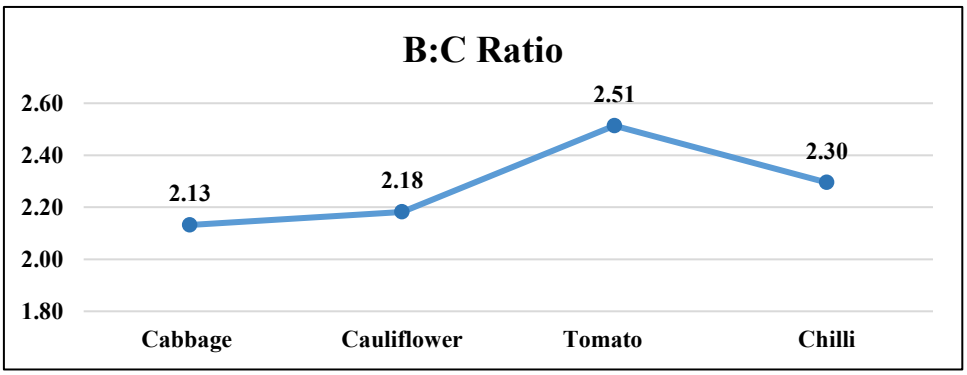


Fig. 2. Benefit – Cost ratio of Winter vegetable production using Jalkund as an irrigation source



Fig. 3. Winter vegetable production using Jalkund-based rainwater harvesting structure established on the farm of Mr. Tengseng Sangma, demonstrating improved irrigation access and diversified vegetable production in Bagugre village, West Garo Hills dist., Meghalaya

Spread of Innovation and Community Impact

One of the key characteristics of the success story of Mr. Tengseng Sangma is the diffusion of knowledge and technology from his farm to the rest of the farmers in the community. Seeing the results achieved in his farm, the ICAR-KVK, West Garo Hills, identified Mr. Sangma's farm as the location where learning could take place, as a place where farmers can learn through participation in technology transfer. Through planned on-farm demonstrations, peer-to-peer contacts and knowledge transfer facilitated through field days organized by ICAR-KVK, Mr. Sangma has successfully motivated the adoption of technologies by 12 neighbouring farmers. This peer-extension system has worked out well because of the results that have been achieved in the area through Mr. Sangma's own efforts rather than the recommended practices from outside, which would not have been easy for risk-averse small farmers without any access to extension services.

Summary

The success story of Mr. Tengseng Sangma stands as a perfect illustration of the transformative impact of Jalkund - a farm-level rainwater harvesting structure on smallholder farming systems in the West Garo Hills district of Meghalaya. The Jalkund has become a catchment of seasonal monsoon runoff otherwise wasted, effectively turning it into a perennial water source for the farm and thus ensuring irrigation of his 1.20 ha area during the rabi season. It has changed the mainly subsistence, water-limited agricultural system into a booming and commercially viable vegetable production. Besides increased farm yields, farm income, and environmental enhancements, the availability of assured irrigation triggered the cultivation of high-quality, high-priced vegetable crops. The farmer has been enjoying the resulting economic gains in terms of benefit-cost ratios, which have always been more than 2.00, and net earnings topping Rs. 1, 66, 000 lakh per hectare. Income generation by this initiative has not been the sole benefit: it has also contributed to mitigating production risks arising from water shortages during key crop growth stages. The outstanding success attained by Mr. Sangma did not only make him well-known but it has also led to his being honoured with the title of Best Innovative Farmer Award (2024-25) at the IX Foundation Day Celebration of ICAR, Agricultural Technology Application Research Institute (ATARI), Zone VII, Umiam, Meghalaya (Fig. 4). This high honour brings to light his outstanding use of climate-resilient technologies and his role in the sustainable agricultural development of the region. The fact that 12 other neighboring farmers spontaneously adopted the Jalkund-based production system indicates its replicability and acceptability. The dissemination of this technology from one farmer to another is an indicator of its practicality and efficiency in the local agroclimatic context. In light of all the above-mentioned facts, it becomes evident that the strategy for disseminating climate-resilient technologies undertaken by the ICAR-KVK, West Garo Hills is quite efficient and effective. The successful implementation of this technology by Mr. Sangma clearly shows its significance and replicability in increasing the water security of the region.



Fig. 4. Best Innovative Farmer Award received by Mr. Tengseng Sangma on IX Foundation Day Celebration of ICAR, ATARI, Zone VII, Umiam, Meghalaya

Acknowledgements

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COMMERCIAL CHILLI CULTIVATION UNDER POLYHOUSE: CONSTRUCTION, PRODUCTION TECHNOLOGY, CROP MANAGEMENT, HARVESTING AND ECONOMIC POTENTIAL OF ONE ACRE

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Abstract

Chilli (Capsicum annuum L.) is one of the commercially important vegetable and spice crops cultivated in India. It is marketed as fresh green chilli, ripe red chilli, dried chilli and processed chilli products. Its commercial value depends on fruit size, colour, pungency, quality, shelf life, market demand and the suitability of the harvested product for fresh consumption or processing. Polyhouse cultivation is a protected-cultivation approach that enables growers to manage irrigation, nutrient application, ventilation, crop sanitation and insect entry more systematically than in conventional open-field production. It can help reduce direct rainfall exposure and improve crop-management consistency. However, a polyhouse does not automatically guarantee higher yields or profits. The actual performance depends on variety selection, climate, plant population, irrigation-water quality, pest management, labour availability and market prices. For a one-acre project, the gross land area is approximately 4,046.86 m². A naturally ventilated galvanized iron (GI) polyhouse with UV-stabilized greenhouse film, insect-proof netting, drip irrigation and fertigation can be considered for commercial chilli cultivation. conventional field guidance provides a useful starting reference for plant spacing, nursery production, basal nutrition and fertigation. These practices must be adapted to the selected hybrid and protected environment rather than applied without adjustment. The project should integrate structural engineering, crop planning, irrigation design, nutrient management, integrated pest management, harvesting, grading, packaging and marketing. Its financial feasibility should be assessed using actual construction quotations, locally validated marketable yields, current farm-gate prices and a complete operating-cost estimate.

1. Introduction

Chilli belongs to the family Solanaceae and is scientifically known as Capsicum annuum L. It is widely cultivated for its fresh fruits and dried spice products. Depending on the variety and intended market, the crop may be harvested at the green stage or allowed to mature to red. Chilli production has commercial importance

in domestic vegetable markets, wholesale markets, food processing, spice trading and value-added product manufacturing. Fresh green chilli is generally sold according to fruit size, colour, freshness and pungency, whereas ripe red chilli and dried chilli may be evaluated using colour, moisture content, pungency and processing quality. Open-field chilli cultivation is exposed to rainfall, fluctuating temperatures, wind, soil-moisture variation and pest movement. A polyhouse provides a degree of protection from these external conditions and enables more organized crop management. Its primary purpose is to improve control over the production environment, not to eliminate every climatic or biological risk. The commercial success of a chilli polyhouse depends on coordinating the structure with the crop. A well-constructed structure with poor ventilation may experience excessive heat and humidity. Similarly, a good hybrid may perform poorly when planted at unsuitable spacing, supplied with excessive nutrients or exposed to inadequate irrigation. Therefore, one-acre chilli cultivation should be planned as an integrated agricultural enterprise covering construction, planting material, water management, crop protection, labour, post-harvest handling and marketing.

2. Importance of Chilli as a Commercial Crop

Chilli has a broad market because it can be sold in different forms and at different maturity stages. This creates opportunities for growers to select a production objective according to local demand.

2.1 Green Chilli Production

Green chilli is harvested before full fruit ripening. Commercial quality is influenced by fruit length, shape, colour, tenderness, pungency and freshness. Buyers may include vegetable wholesalers, retailers, hotels, restaurants and food-service businesses. The crop requires frequent harvesting when fruits reach the preferred commercial size. Timely harvesting is important because overmature fruits may not meet the buyer's specifications.

2.2 Ripe Red Chilli Production

Ripe red chilli is harvested after fruits develop the required mature colour. It may be sold fresh to particular buyers or dried for the spice market. The production system must consider maturity period, colour development, drying facilities and the buyer's quality requirements. Red chilli production may require a different harvest schedule and post-harvest process from green chilli production. Therefore, the market objective should be finalized before choosing the hybrid.

2.3 Role of Protected Cultivation

Protected cultivation can provide several management advantages:

- Reduced direct exposure to rainfall.
- More systematic drip irrigation and fertigation.
- Improved control over crop sanitation and selected insect pests.
- Better access for crop inspection and harvesting.
- More consistent management of root-zone moisture.
- Potential improvement in marketable quality when crop conditions are suitable.

These advantages must be evaluated against the higher initial investment, film and net replacement, maintenance, labour requirements and the possibility of poor returns during periods of low market prices

3. Objectives of One-Acre Polyhouse Chilli Production

The proposed project aims to establish a commercially manageable protected-cultivation system for producing marketable chilli fruits under a planned production and marketing programme.

The main objectives are:

1. To establish a structurally safe, naturally ventilated polyhouse over a one-acre site.
2. To select a chilli variety or hybrid suitable for the intended market.
3. To provide efficient drip irrigation and fertigation facilities.
4. To maintain suitable growing conditions through ventilation, sanitation and crop monitoring.
5. To reduce avoidable crop losses through integrated pest and disease management.
6. To produce fruits that meet buyer specifications for size, colour, freshness and quality.
7. To establish a reliable harvesting, grading, packing and marketing system.
8. To calculate investment requirements and operating profitability using verified local data.

The project should be evaluated through both agronomic and commercial performance. A high total yield alone is not sufficient if a large proportion of the harvest is rejected or sold at a low price.

4. Site Selection for One-Acre Polyhouse

Site selection is a major determinant of construction safety, irrigation efficiency and long-term operating cost. The land should be suitable for a protected structure and provide reliable access to water, electricity, labour and markets.

4.1 Land and Soil Requirements

The preferred site should be relatively level or gently sloping, with adequate drainage and sufficient space for the structure, water storage, fertigation equipment, packing area and vehicle access. Soil testing should be completed before construction. The test should cover soil pH, electrical conductivity (EC), texture, organic carbon and available nutrients. Additional testing may be required if salinity. Well-drained soil is important because prolonged waterlogging can reduce root function and increase the risk of root diseases. Where drainage is inadequate, the site should be corrected or an alternative location considered before construction.

4.2 Irrigation-Water Quality

Irrigation water should be tested for pH, EC, bicarbonate, chloride, sodium and other parameters relevant to the source. Suspended solids should also be evaluated because they can affect filter and emitter performance. Poor water quality may cause salt accumulation, nutrient imbalance and reduced plant growth. Filtration can remove suspended particles but cannot, by itself, remove dissolved salts. Water treatment should therefore be selected according to laboratory results.

5. Polyhouse Construction and Structural Design

At IGO Agri tech Farms, our objective is to develop a protected cultivation structure that supports healthy ginger growth, efficient water management, and consistent crop performance. The proposed one-acre project will focus on a suitable structure with adequate ventilation, rain protection, and proper drainage.

5.1 Structure Selection

A naturally ventilated polyhouse or a suitable rain-shelter structure can be evaluated based on local climatic conditions, construction cost, and crop requirements. Since ginger requires warm and humid conditions, the structure should prevent excessive heat accumulation while providing sufficient air circulation. A fully climate-controlled polyhouse should be considered only after evaluating its additional investment and operating costs.

5.2 Important Structural Components

- Frame and covering: A durable frame with suitable UV-stabilised covering material to provide protection from excessive rainfall.
- Ventilation: Side and roof ventilation, where applicable, to support air movement and reduce excessive humidity.
- Drainage: Peripheral drains and properly designed pathways to prevent water stagnation.
- Growing area: Raised beds with sufficient space for crop maintenance, irrigation, and harvesting.
- Irrigation system: A suitable water distribution system to maintain uniform soil moisture.

5.3 Construction Planning

Before construction, the site should be assessed for sunlight, wind exposure, water availability, soil drainage, and accessibility. Structural dimensions, material specifications, and costs should be finalised with a qualified supplier. The design must prioritise crop requirements and long-term operational efficiency rather than construction alone.

6. Soil Preparation and Planting

Healthy soil and quality planting material are essential for successful ginger production. At IGO Agritech Farms, soil preparation will focus on improving drainage, maintaining organic matter, and providing favourable conditions for rhizome development.

6.1 Soil Requirements

Ginger performs well in fertile, friable, well-drained loamy soil rich in organic matter. A soil pH of approximately 6.0–6.5 is a useful target. Soil testing should be completed before planting to determine nutrient availability, pH, and any necessary amendments.

6.2 Land Preparation and Bed Formation

The soil should be loosened and prepared into raised beds to support root and rhizome development. Well-decomposed farmyard manure (FYM) or compost can be incorporated according to soil-test results and crop requirements. Raised beds and drainage channels should be arranged to prevent waterlogging, as excess moisture can increase the risk of rhizome rot.

6.3 Seed Rhizome Selection

Healthy, disease-free ginger rhizomes should be selected from a reliable source. Planting material should be firm, free from visible rot, and suitable for the chosen variety. a conventional seed-rhizome requirement of approximately 1,500–1,800 kg per hectare, equivalent to about 607–728 kg per gross acre. The final quantity will depend on planting spacing, bed area, and rhizome size.

6.4 Planting Method

Planting should be carried out at the recommended spacing for the selected cultivation system. It approximately 40 × 20 cm spacing under irrigated cultivation, while other spacing options may be used for raised-bed systems. The final plant population should be calculated after accounting for pathways, drainage channels, and service areas.

7. Pest and Disease Management

Effective pest and disease management is essential for protecting crop health and reducing production losses. At IGO Agritech Farms, the proposed approach will prioritise prevention, regular monitoring, field sanitation, and timely corrective measures.

7.1 Major Crop Problems

- Rhizome rot: Often associated with infected planting material and poorly drained, waterlogged soil.
- Shoot borer: Can damage shoots and affect healthy crop development.
- Leaf spot and other foliar diseases: May affect leaves and reduce plant vigour under favourable disease conditions.

7.2 Preventive Management

Healthy planting material should be sourced from a reliable supplier. Raised beds, effective drainage, removal of severely affected plant material, and regular inspection can help reduce disease pressure. Excessive humidity and prolonged leaf wetness should be avoided wherever practical.

7.3 Monitoring and Corrective Action

The crop should be inspected routinely for yellowing, wilting, damaged shoots, leaf lesions, and rhizome deterioration. If a problem is identified, the affected area should be assessed promptly. Any biological or chemical control measure should be selected according to the identified pest or disease, current agricultural recommendations, and applicable label instructions.

8. Harvesting and Post-Harvest Management

Harvesting and post-harvest handling directly influence ginger quality, storage performance, and market value. IGO Agritech Farms will plan harvesting according to crop maturity and the intended market, ensuring that the produce is handled carefully from the field to dispatch.

8.1 Harvesting Time

Ginger grown for mature rhizomes is generally harvested around 8–9 months after planting, depending on the variety, growing conditions, and market requirement. Ginger intended for use as tender vegetable ginger may be harvested earlier. Crop maturity should be assessed before harvesting rather than relying only on a fixed date.

8.2 Marketing and Dispatch

Before harvest, the farm should identify potential buyers such as wholesalers, retailers, processors, and local produce markets. Harvesting volume, grading standards, packaging, transport arrangements, and expected selling prices should be planned in advance. This will help improve post-harvest coordination and reduce avoidable losses.

9. Conclusion

The Ginger Cultivation Under Polyhouse project proposed by IGO Agritech Farms aims to combine protected cultivation practices with scientific crop management to achieve consistent production and quality improvement.

By providing suitable growing conditions, maintaining proper irrigation and drainage, applying balanced nutrients, and implementing effective pest and disease management, the project seeks to support healthy crop development and efficient resource utilisation. Our approach focuses on selecting appropriate infrastructure, using quality planting materials, and following systematic crop management practices throughout the production cycle. Proper harvesting, grading, packaging, and marketing arrangements will further contribute to maintaining product quality and reducing post-harvest losses. At IGO Agritech Farms, we believe that successful agricultural development depends on the integration of technology, practical farm management, and sustainable resource utilisation. Through careful planning, continuous monitoring, and quality-focused production, this project aims to establish a reliable and commercially oriented ginger cultivation model with potential for long-term agricultural development.

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COMMERCIAL GINGER CULTIVATION UNDER POLYHOUSE
One-Acre Protected Cultivation Project Report

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ABSTRACT

Ginger (*Zingiber officinale* Roscoe) is an important commercial spice crop widely cultivated for its fresh rhizomes, dried ginger, and value-added products. It is used in food processing, traditional preparations, beverages, and several commercial applications. Successful ginger production depends on suitable growing conditions, healthy planting material, proper moisture management, balanced nutrient supply, and effective pest and disease control.

At IGO Agritech Farms, our approach to ginger cultivation focuses on scientific crop planning, efficient resource utilisation, and sustainable farm management. Protected cultivation may help improve control over rainfall exposure, irrigation, and growing conditions when the structure and production system are appropriately designed. However, ginger is traditionally grown in soil under open-field or shade-protected conditions, and the suitability of a polyhouse system must be evaluated according to local climate, ventilation, substrate, and production costs.

This project report presents a one-acre ginger cultivation concept covering site selection, polyhouse planning, soil preparation, planting, irrigation, nutrient management, crop protection, harvesting, and post-harvest handling. The objective is to establish a commercially organised production system that supports consistent rhizome quality, efficient farm operations, and market-oriented production.

1. INTRODUCTION

Ginger is a rhizomatous herbaceous crop belonging to the Zingiberaceae family. Its underground rhizomes are the primary economic produce and are marketed as fresh ginger, dried ginger, ginger powder, and processed products. Demand is supported by household consumption, spice trading, food processing, and other commercial uses. Ginger performs well in warm, humid environments with adequate soil moisture, good drainage, and partial shade. Waterlogging, excessive direct sunlight, poor-quality planting material, and unsuitable soil conditions can affect crop establishment and rhizome development. At IGO Agritech Farms, we consider ginger a potential commercial crop where suitable environmental conditions, reliable planting material, efficient irrigation, and appropriate market access are available. The proposed one-acre project will be planned around crop requirements rather than infrastructure alone, with emphasis on healthy growth, disease prevention, and efficient use of land and water.

2. IMPORTANCE OF GINGER AS A COMMERCIAL CROP

2.1 Fresh Ginger Production

Fresh ginger is harvested when the rhizomes reach the required maturity and size for the intended market. It is supplied to vegetable markets, wholesalers, retailers, and food-processing businesses. Commercial success depends on uniform rhizome development, good appearance, low damage during harvesting, and timely delivery. Proper grading and careful handling help maintain market quality.

2.2 Dry Ginger Production

Mature ginger rhizomes can be processed into dry ginger for spice markets and further processing. Dry ginger production requires appropriate cleaning, curing or preparation, drying, and storage practices. The suitability of fresh or dry ginger production should be decided according to buyer requirements, prevailing prices, processing facilities, and expected recovery after drying.

2.3 Role of Protected Cultivation

Protected cultivation can provide opportunities to manage rainfall exposure, irrigation, and certain environmental conditions. A properly designed structure may also support more organised crop monitoring and farm operations. However, ginger requires adequate moisture without waterlogging and generally benefits from partial shade. A fully enclosed polyhouse can create excessive temperature or humidity if ventilation is inadequate. Therefore, the structure must be designed with sufficient ventilation, drainage, and suitable shading where required. Before investing in a full-acre polyhouse, IGO Agritech Farms recommends evaluating a trial area to compare crop growth, rhizome yield, disease incidence, and production cost against an appropriate open-field or shade-grown system.

3. OBJECTIVES OF ONE-ACRE GINGER CULTIVATION

The primary objectives of the proposed project are:

1. To establish a commercially organised ginger production unit on one acre.
2. To select healthy, disease-free rhizome planting material suitable for local growing conditions.
3. To develop an efficient irrigation and drainage system that maintains adequate soil moisture.
4. To improve crop establishment through proper land preparation, spacing, mulching, and nutrient management.
5. To implement preventive pest and disease management practices.
6. To improve rhizome quality through suitable harvesting, cleaning, grading, and storage methods.
7. To evaluate the economic feasibility of protected ginger cultivation using actual construction quotations, input prices, and market data.
8. To develop a scalable production model based on field performance and commercial results.

4. SITE SELECTION FOR ONE-ACRE GINGER CULTIVATION

4.1 Land and Soil Requirements

Site selection is an important factor in ginger production. The selected land should have good drainage, suitable soil depth, access to quality irrigation water, and convenient transport access. Ginger performs well in fertile, friable, organic-matter-rich soil. Well-drained sandy loam or loam soil is generally preferred because it supports rhizome expansion and allows excess water to drain away.

The following factors should be assessed before project establishment:

- **Soil texture:** Friable soil that allows rhizome development.
- **Soil drainage:** No prolonged waterlogging or standing water.
- **Soil fertility:** Adequate organic matter and balanced nutrient availability.
- **Soil pH:** Soil conditions suitable for ginger growth, confirmed through soil testing.
- **Land slope:** Gentle slope or properly designed drainage to prevent water stagnation and erosion.
- **Previous crop history:** Avoid land with a history of serious rhizome rot or other persistent soil-borne diseases.

A soil test should be conducted before finalising fertiliser and soil-amendment requirements.

4.2 Irrigation-Water Quality

Reliable irrigation water is essential throughout ginger growth, especially during establishment and rhizome development. Water quality should be assessed before installing the irrigation system. The assessment should include pH, electrical conductivity (EC), and any relevant dissolved salts or contaminants. Water with excessive salinity may affect plant growth and soil conditions. The irrigation system should deliver water uniformly while avoiding excessive saturation. Drainage channels and field outlets should be provided to remove surplus water during heavy rainfall.

5. POLYHOUSE CONSTRUCTION AND STRUCTURAL DESIGN

5.1 Structure Selection

For a one-acre project, the proposed protected structure should be selected based on the local climate, wind conditions, rainfall, ventilation requirements, and available investment. A naturally ventilated polyhouse may be considered where protected cultivation is justified. However, ginger does not automatically require a fully enclosed polyhouse. An open-field system with suitable shade and mulch, or a rain-protected structure with adequate side ventilation, may be more economical depending on the site. The final choice should be based on a comparison of construction cost, operating expenses, crop performance, and expected market returns.

5.2 Important Structural Components

Where a polyhouse or rain-protection structure is adopted, the principal components may include:

- **Structural framework:** A suitably designed structure capable of withstanding local wind and weather conditions.
- **Roof covering:** UV-stabilised agricultural film where appropriate for the selected system.
- **Side ventilation:** Openable or adequately ventilated sides to reduce excessive heat and humidity.
- **Insect-proof netting:** Used where required, provided it does not restrict airflow excessively.
- **Irrigation system:** Drip or another suitable system designed for uniform moisture application.
- **Drainage arrangements:** Channels and outlets to remove excess rainwater and irrigation water.
- **Shading provisions:** Suitable shade management where local conditions require it.
- **Access and sanitation:** Entry paths and operational arrangements that support crop monitoring and disease prevention.

5.3 Construction Planning

Before construction, the one-acre layout should be prepared with the assistance of a qualified structural supplier. The layout should include growing beds, walking paths, irrigation lines, drainage, water storage, input handling, and harvesting access. The structure should not be finalised until local temperature, rainfall, wind exposure, and crop-management requirements have been evaluated. Construction quotations should separately identify structural materials, covering materials, installation, irrigation, drainage, and any automation.

6. SOIL PREPARATION AND PLANTING

6.1 Soil Requirements

Ginger requires loose, fertile, well-drained soil for healthy rhizome development. Compacted soil can restrict rhizome expansion, while waterlogged soil increases the risk of rhizome rot. The growing area should be tested before planting. Organic matter and soil amendments should be incorporated according to soil-test results and the production system being used. Where soil is unsuitable or has a history of serious soil-borne disease, a suitable alternative growing system should be evaluated before investing in large-scale cultivation.

6.2 Land Preparation and Bed Formation

Land preparation should create a loose and well-drained growing medium. Raised beds are useful where drainage is a concern, particularly during periods of heavy rainfall.

Recommended preparation practices include:

1. Remove weeds and unwanted crop residues.
2. Loosen the soil without creating excessive compaction.
3. Incorporate well-decomposed organic manure according to soil-test recommendations.
4. Form raised beds or ridges with suitable drainage channels.
5. Install and test the irrigation system before planting.
6. Apply mulch after planting where appropriate to conserve moisture and suppress weeds.

Bed dimensions and spacing should be finalised according to the selected planting method, variety, soil conditions, and machinery or labour access requirements.

6.3 Planting Material Selection

Ginger is commonly propagated through healthy rhizome pieces containing viable buds. Planting material should be obtained from a reliable source and selected for varietal identity, maturity, and freedom from visible rot or pest damage.

Before planting:

- Reject soft, discoloured, rotten, or damaged rhizomes.
- Select healthy rhizome pieces with viable buds.
- Follow appropriate seed-rhizome treatment recommendations from a qualified agricultural adviser.
- Use only approved products and follow their label instructions where chemical or biological treatments are required.
- Keep planting material in clean conditions and avoid prolonged exposure to excessive heat or drying.

The planting-material requirement per acre should be calculated after fixing the variety, bed layout, spacing, and seed-rhizome size.

6.4 Planting Method

Planting should be carried out when suitable soil moisture and local weather conditions support establishment. Rhizome pieces are placed at the recommended depth and spacing for the selected production system and covered with loose soil. Spacing should allow adequate plant development, air movement, field access, and rhizome expansion. Mulching may be applied to conserve moisture, moderate soil temperature, and reduce weed growth. Uniform planting depth, healthy planting material, and consistent moisture during establishment are important for achieving an even crop stand.

7. IRRIGATION AND NUTRIENT MANAGEMENT

7.1 Irrigation System

The irrigation system should maintain adequate moisture in the root and rhizome zone without causing waterlogging. Drip irrigation may be considered where it can provide uniform moisture and efficient water use. The system design should account for the area, bed layout, water source, flow rate, filtration requirements, and irrigation schedule. Filters and lines should be inspected regularly to prevent clogging and uneven water distribution.

7.2 Irrigation Scheduling

Irrigation frequency should be based on soil texture, weather, crop stage, rainfall, and moisture conditions in the growing beds.

- **Establishment stage:** Maintain sufficient moisture for sprouting and root development.
- **Vegetative growth stage:** Avoid prolonged drying of the soil.
- **Rhizome development stage:** Maintain consistent moisture while ensuring adequate drainage.
- **Maturity stage:** Adjust irrigation according to crop condition and the planned harvest.

Irrigation should be reduced or temporarily stopped when the soil is excessively wet. Fixed irrigation durations should not be prescribed without considering the actual water discharge and soil conditions.

7.3 Nutrient Supply

Ginger requires balanced nutrition to support foliage growth and rhizome development. Nutrient application should be planned using soil-test results, crop stage, expected yield, and the selected production system.

The nutrient-management programme may include:

- Well-decomposed organic manure.
- Balanced application of essential plant nutrients.
- Split nutrient applications according to crop growth.
- Suitable micronutrient correction where a deficiency is identified.
- Monitoring of crop growth and soil conditions to avoid excess nutrient application.

Fertigation may be adopted where the irrigation system and fertiliser compatibility permit it. Fertiliser quantities should be finalised only after the soil test and the selected production method are confirmed.

7.4 Monitoring and Records

Farm records should include planting date, variety, planting-material quantity, irrigation schedule, nutrient applications, crop-protection measures, labour, input expenses, disease observations, and harvest weight. Regular records help identify problems early and provide a reliable basis for calculating production cost, yield, and profitability.

8. PEST AND DISEASE MANAGEMENT

8.1 Major Crop Problems

Ginger production may be affected by rhizome rot, bacterial wilt, leaf spot, shoot borer, and other pests or diseases depending on local conditions. Rhizome rot and other soil-borne problems are particularly important because they can damage underground produce and reduce marketable yield. Disease risk may increase when drainage is poor, planting material is infected, or the same crop is repeatedly cultivated in affected soil.

8.2 Preventive Management

Preventive management should be the foundation of crop protection.

- Use healthy, disease-free planting material.
- Provide adequate drainage and avoid waterlogging.
- Maintain clean growing beds and remove severely affected plants appropriately.
- Clean tools and equipment used in crop operations.
- Avoid moving contaminated soil or plant material between growing areas.
- Follow a suitable crop-rotation plan where ginger is grown in soil.
- Use recommended planting-material treatments and biological products only where appropriate.

8.3 Monitoring and Corrective Action

The crop should be inspected regularly for yellowing, wilting, leaf spots, unusual shoot damage, and signs of rhizome deterioration. Affected areas should be identified early. The cause of the problem should be confirmed before applying a control measure, since water stress, nutrient deficiencies, and disease symptoms may appear similar. Where a pesticide, fungicide, or biological product is required, it should be selected according to the identified problem, local approval, product label, and recommended safety precautions.

8.4 Integrated Crop Protection

An integrated crop-protection programme combines prevention, regular monitoring, sanitation, appropriate biological measures, and need-based approved treatments. The aim is to reduce avoidable crop losses while maintaining safe production practices. All crop-protection applications should be recorded, and any applicable pre-harvest interval should be followed before harvesting.

9. HARVESTING AND POST-HARVEST MANAGEMENT

9.1 Harvesting Time

Harvesting time depends on the variety, planting date, crop condition, and intended market. Ginger grown for fresh consumption may be harvested earlier than ginger intended for mature rhizomes or dry-ginger processing. Crop maturity should be assessed through foliage condition, rhizome development, and the buyer's quality requirements. A fixed harvesting date should not be assumed for every production system.

9.2 Harvesting Method

Harvesting should be carried out carefully to avoid cutting, bruising, or breaking the rhizomes. The growing soil should be loosened before lifting the plants or rhizomes. Harvested ginger should be collected in clean containers and protected from direct exposure to excessive heat. Damaged and diseased rhizomes should be separated from healthy produce to maintain lot quality.

9.3 Cleaning and Grading

Harvested ginger should be cleaned according to the intended market. Excess soil and unwanted plant material should be removed without causing unnecessary damage to the rhizome surface. Grading may be based on rhizome size, shape, cleanliness, maturity, appearance, and the buyer's specifications. Diseased or severely damaged rhizomes should be excluded from marketable produce.

9.4 Packaging and Storage

Fresh ginger should be packed in clean, suitable containers that protect it from mechanical damage and contamination. Packaging type and quantity should be selected according to transport distance, buyer requirements, and expected storage duration.

Storage conditions should be appropriate for fresh ginger and the intended market. Excessive moisture, poor ventilation, and unsuitable temperatures can contribute to deterioration during storage and transportation. Where dry ginger is produced, the cleaning, drying, moisture control, and storage process should be planned separately to meet the requirements of the intended buyer.

9.5 Marketing and Dispatch

Marketing arrangements should be developed before the expected harvest. Potential channels include wholesale markets, retailers, spice traders, food processors, and direct commercial buyers. The project should record harvested weight, marketable yield, rejected quantity, grade-wise selling price, transport expenses, and realised revenue. These records are essential for evaluating the commercial performance of the crop.

10. CONCLUSION

At IGO Agritech Farms, we view ginger as a crop with commercial potential when its growing requirements, planting-material quality, water management, and market opportunities are carefully evaluated. A successful project requires more than the construction of a protected structure; it requires a production system designed around the crop's biological needs and the site's environmental conditions. The proposed one-acre ginger project provides a framework for planning land preparation, planting, irrigation, nutrient management, crop protection, harvesting, and post-harvest handling. Before full-scale implementation, a trial cultivation programme should be used to assess the performance of the selected variety and growing system under local conditions. Our objective is to develop a technically sound, resource-efficient, and commercially viable ginger production model supported by accurate farm records, appropriate infrastructure, and reliable market linkages. Final investment decisions should be based on actual construction quotations, input costs, trial results, expected marketable yield, and prevailing selling prices.