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INSECT THERMODYNAMICS



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Introduction

The study of how insects acquire, lose, control and use heat for movement, development, reproduction and survival is known as thermodynamics in insects. One of the most significant environmental variables affecting insect physiology and behavior is temperature. Insects are typically small bodied species, therefore temperature fluctuations have a significant impact on them. An exact balance between heat production, heat dissipation and energy consumption is necessary for insect flying. In contrast to bigger vertebrates, insects rely on a combination of ambient heat sources, specialized muscle activity and behavioral adaptations to reach and sustain the high thoracic temperatures required for continuous wing movement. Some species use evaporative cooling systems or external sources like sun radiation to control body temperature, while others produce heat internally through pre-flight shaking of the thoracic muscles. The shape and function of asynchronous flight muscles, the biochemical pathways involved in energy consumption and the physical constraints brought on by their small body size and high surface area to volume ratio all have an impact on flight performance. Diverse thermoregulatory adaptations that facilitate efficient feeding, dispersion and survival in shifting climatic conditions have been highlighted by recent research, which has improved our understanding of how these parameters interact across many insect taxa.

Ectotherms: Animals whose body temperature is mostly influenced by heat sources in their surroundings.

Endotherms: Animals that can generate heat through their own metabolism are known as endotherms.

Heterotherms: Animals that exhibit both endothermic and ectothermic behavior at different periods are known as heterotherms.

Poikilotherms: Poikilotherms are organisms whose body temperature changes based on their surroundings.

Homeotherms: Organisms that keep their body temperature comparatively constant are known as homeotherms.

Insects were once thought of as poikilothermic animals because their body temperature fluctuates in response to environmental factors. Nonetheless, studies have revealed that many insects have amazing thermoregulatory systems that enable them to sustain temperatures appropriate for their physiological functions.

Insects' Thermoregulation

The capacity of insects to maintain body temperatures that optimize survival and reproductive success is known as thermoregulation. Due to their small size, insects typically cannot produce enough internal heat. Larger insects and powerful flyers, on the other hand, can raise body temperatures by engaging in vigorous muscular activity.

Temperature Adaptation Examples

- ✚ Insects that live in glaciers, like *Diamesa* species, can withstand extremely low temperatures.
- ✚ When flying, sphinx moths keep their thoracic temperatures at about 46°C.
- ✚ The thoracic temperature of honeybees rises by about 15°C above room temperature.
- ✚ Before taking off, the thoracic temperature of the tobacco hornworm moth (*Manduca sexta*) must be close to 45°C.

Shivering Thermogenesis

Many moths quickly tense opposing flight muscles to warm their thoracic muscles before taking off. This technique produces heat without the use of wings and is similar to shivering in mammals.

Heat Loss Mechanisms

Insects lose heat through:

1. **Conduction** – direct transfer to cooler surfaces.
2. **Convection** – heat transfer to moving air.
3. **Radiation** – emission of infrared energy.
4. **Evaporation** – cooling through water loss.

Behavioral Thermoregulation

Temperature Preference

Many insects actively seek temperatures that maximize performance. Second-stage desert locust larvae (*Schistocerca*) prefer temperatures between 35°C and 45°C, with 40–41°C showing the strongest preference. This suggests that insects are able to recognize and choose ideal heat conditions.

Behavioral Adaptations

Insects regulate body temperature through:

- ✚ When it's cold, moving into the sun.
- ✚ Seeking cover when it gets too hot.
- ✚ Changing one's orientation with respect to the sun.
- ✚ Modifying one's stance to reveal more or less of one's body.

Grasshoppers and locusts are excellent examples of behavioral thermoregulation.

Basking Behavior

Many butterflies warm themselves through basking.

Lateral Basking

Butterflies partially open their wings to maximize solar radiation absorption.

Dorsal Basking

Butterflies expose the upper wing surfaces directly to sunlight while resting. These behaviors increase thoracic temperature sufficiently for flight.

Stilts and Parasols

Desert beetles of the family Tenebrionidae exhibit remarkable adaptations:

- ✚ The body is raised above the hot sand by long legs.
- ✚ Heat absorption is decreased by body position.
- ✚ Some species orient themselves to reduce the amount of heat from the sun.

Thermoregulation in Caterpillars

The sphinx moth caterpillar (*Hyles lineata*) regulates temperature through position and posture changes. As environmental temperatures rise:

- ✚ Caterpillars travel to plants from the ground.
- ✚ On stems, they take up vertical positions.
- ✚ These actions prevent overheating while permitting ongoing feeding.

Pipevine Swallowtail Larvae

Field observations revealed two thermoregulatory strategies:

1. Transition to microhabitats that are colder.
2. Red-colored larvae are more common in warmer climates.

The deeper hue exhibits phenotypic flexibility and influences heat absorption.

Physiological Thermoregulation

Heat Production During Flight

Flight muscles generate enormous quantities of heat. In many insects:

- ✚ 80–90% of energy used during flight is released as heat.
- ✚ Only a small proportion contributes directly to flight power.

Manduca sexta

The tobacco hornworm moth maintains thoracic temperatures between 38°C and 42°C over a wide range of environmental temperatures.

Thoracic Temperature Regulation

The figure illustrates that thoracic temperature remains relatively constant despite changes in ambient temperature. This demonstrates efficient physiological thermoregulation.

Bumblebee Thermoregulation

Thorax and gaster temperatures during flight:

- ✚ Thoracic temperature remains high for muscle activity.
- ✚ Abdominal temperature varies more widely.
- ✚ The abdomen functions as a heat radiator.

When thoracic temperature rises:

- ✚ Heartbeat rate increases.
- ✚ Hemolymph circulation accelerates.
- ✚ Heat is transferred to the abdomen.

Wing Beat Frequency Regulation

Some insects regulate heat production by altering wing movements. For example, the dragonfly *Anax*:

- ✚ Beats wings at about 35 Hz at 20°C.
- ✚ Reduces frequency to about 25 Hz at 35°C.

This decreases metabolic heat production.

Counter current Heat Exchange

Bumblebees and moths possess specialized circulatory systems that:

- ✚ Retain heat in the thorax during cold conditions.
- ✚ Transfer excess heat to the abdomen during warm conditions.

This system resembles heat conservation mechanisms found in birds and mammals.

Evaporative Cooling and Colony Thermoregulation

Evaporative Cooling

Some insects use water evaporation to lower body temperature.

Desert Cicadas

Cooling by evaporative water loss demonstrates shows how cicadas release water through specialized pores.

- ✚ Body temperature may become up to 5°C lower than ambient temperature.
- ✚ Effective only when humidity is low and water availability is high.

Honeybee Cooling

When head temperature reaches approximately 44°C:

- ✚ Worker bees regurgitate nectar droplets.
- ✚ Evaporation cools the head and thorax.

This mechanism protects bees during hot weather.

Slifer's Patches in Grasshoppers

Grasshoppers possess thin cuticular regions called Slifer's patches.

Functions:

- ✚ Increased water loss.
- ✚ Localized cooling.
- ✚ Protection of reproductive organs during extreme heat.

Colony Thermoregulation in Social Insects

Social insects regulate nest temperature collectively.

Ant Colonies

Ants move larvae within the nest:

- ✚ Near the surface during warm periods.
- ✚ Deeper underground during winter.

This ensures optimal developmental temperatures.

Honeybee Colonies

At high temperatures:

- ✚ Workers fan their wings at hive entrances.
- ✚ Air circulation removes excess heat.
- ✚ Water is transported into the hive for evaporative cooling.

At low temperatures:

- ✚ Bees cluster together.
- ✚ Metabolic heat maintains temperatures between 20–25°C.

Bumblebee Cell Temperature

The temperature within bumblebee cell clusters demonstrates how colony metabolism maintains a stable developmental environment for brood despite fluctuating external temperatures.

Cold Tolerance and Freeze Survival

Flight at Low Temperatures

Certain moths such as *Eupsilia* can fly at ambient temperatures near 0°C. Adaptations include:

- ✚ Thick insulating hair covering.
- ✚ Counter current heat exchange systems.
- ✚ Efficient shivering mechanisms.

Cold Hardiness

Many insects remain alive even when inactive. Examples:

- ✚ *Locusta* larvae survive near 0°C.
- ✚ Wax moth (*Galleria*) larvae survive extended periods at reduced temperatures.

Freeze Tolerance

Some insects can survive actual freezing.

Example: *Gynaephora groenlandica*

This Greenland caterpillar:

- ✚ Freezes around -7°C.
- ✚ Survives temperatures as low as -70°C.
- ✚ Remains frozen for months.

Cryoprotectants

Substances that prevent cellular damage include:

- ✚ Glycerol
- ✚ Ice nucleating proteins
- ✚ Lipoproteins

These compounds protect tissues during freezing.

Freeze Avoidance

Many insects prevent ice formation through:

- ✚ Gut emptying
- ✚ Removal of ice nucleation sites
- ✚ Seeking insulated habitats

Freeze-Susceptible Insects

Species such as aphids and flesh flies cannot tolerate freezing.

Acclimation

Acclimation refers to physiological adjustments that increase tolerance to new temperature conditions.

These changes include:

- ✚ Altered enzyme activity.
- ✚ Increased cryoprotectant production.
- ✚ Modified membrane composition.

Temperature Sensing, Morphological Adaptations and Applications

Temperature Receptors

Most insects detect temperature using specialized sensory organs.

Antennal Receptors

Honeybees possess approximately 50 antennal segments containing thermoreceptors.

Cockroaches may possess over 100 temperature-sensitive sensilla.

Additional Thermoreceptors

Temperature-sensitive structures occur on:

✚ Antennae, Tarsi, Arolium and Pulvilli

These receptors guide insects toward favorable thermal environments.

Nervous System Effects

Temperature affects:

✚ Nerve conduction, Sensory processing, Muscle activity and Behavioral responses.

Morphological Adaptations

Several structural features aid thermoregulation:

✚ Dense scales and hairs for insulation.

✚ Air sacs reducing heat loss.

✚ Dark wing surfaces increasing heat absorption.

✚ Long legs reducing heat gain from hot surfaces.

Seasonal Color Variation

The figure showing seasonal variation in black pigmentation of the butterfly *Colias eurytheme* demonstrates that darker individuals absorb more solar radiation and warm more rapidly in cool seasons.

Nature's Thermometer: Crickets

Cricket chirping rate changes predictably with temperature.

Temperature Calculation

Fahrenheit: Temperature = Chirps in 14 seconds + 40

Celsius: Temperature = (Chirps in 25 seconds ÷ 3) + 4

Conclusion

The amazing variety of tactics insects employ to withstand temperature extremes is demonstrated by insect thermodynamics. Insects can maintain body temperatures appropriate for life and activity in a variety of habitats, from glaciers to deserts, through behavioral adaptations, physiological processes, morphological changes, colony-level management, and complex sensing systems. Their global range and ecological success are largely attributed to these thermoregulatory modifications.

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The role of honey bees in sustainable agriculture and food security



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Introduction

Listen closely on a warm morning. That peaceful hum of a honey bee at work? That is the soundtrack of your breakfast, lunch, and dinner being made. These tiny insects rarely get mentioned in fancy farming conferences or agricultural innovation awards. But honestly? They might be the hardest workers any farmer could ask for. While we scramble to figure out how to feed more people on a hotter, more crowded planet, bees have been quietly doing their job for fifty million years. No grants. No research papers. Just work. And here is the thing, they do it for free.

But let us talk numbers for a moment, because the value of what bees do is staggering. The Food and Agriculture Organization (FAO) says that without pollinators, the world would lose nearly 8 percent of its total food production. That is about 577 billion dollars every single year. Gone. Not because of drought or war, but because no one showed up to do the pollination. Around 1.4 billion people mostly small farmers in Africa, Asia, and Latin America depend on pollination for their jobs and daily bread. So when bees struggle, real families hurt. Real children go hungry. This is not an environmentalist's far-off worry. This is a farmer's here-and-now reality.

The bad news? Bees are struggling. A major review back in 2010 by a researcher named Potts and his team found clear evidence that wild and domesticated bees are declining on almost every continent. Why? Lots of reasons tangled together: we keep taking their homes away, drenching fields in chemicals, and letting new diseases and parasites like the Varroa mite spread. Even climate change is messing with their internal calendars. But here is the hopeful part and there is hope of protecting bees and growing food well actually go hand in hand. The same things that help bees usually help the farm too. A recent study in West Bengal, India, found that fields with managed bee colonies produced 55 percent more pods per plant and 44 percent more seeds per pod compared to fields that just hoped wild bees would show up. In Indonesia, communities started keeping tiny stingless bees. The bees pollinated their vegetable gardens, and the honey paid for school fees. Two wins from one small creature. So let us dig in. What do honey bees actually do for your farm? What is threatening them? And most importantly what can you, as a farmer or someone who cares about food, actually do about it?

The Silent Workforce Behind Our Food

Imagine hiring a crew that never asks for a raise, never calls in sick, and works every single daylight hour of your growing season. That is a honey bee colony.

One hive holds between 50,000 and 80,000 bees. On a good day, that colony will visit over 100 million flowers. Each bee is a flying pollen delivery system, moving from blossom to blossom with a kind of mechanical precision that engineers still cannot replicate. The result? Fruits set. Seeds form. Yields climb.

Let me give you a real-world example. California almonds. That industry is worth over 5 billion dollars a year. And it exists entirely because of honey bees. No bees? No almonds. Period. Same story for apples in Washington, blueberries in Maine, pumpkins in Illinois. Even crops you might think are fine on their own tomatoes, eggplants, cucumbers produce 30 to 50 percent more when bees come by and give the flowers a good buzz.

Back in 2007, a researcher named Klein and his team looked at 115 of the world's most important food crops. Their finding was simple but stunning, 75 percent of those crops produce more food when bees visit. Three out of every four things in your field or on your plate.

Table 1: How different crops depend on animal pollination

Crop Type	Pollination Dependence	Without Bees, Yield Drop By	Examples
High dependence	80-100%	80-100%	Almond, cherry, apple, blueberries, pumpkin
Moderate dependence	40-80%	40-80%	Cucumbers, melons, sunflower
Low dependence	10-40%	10-40%	Coffee, coconuts, Soybeans, chickpeas
No dependence	0-10%	0-10%	Wheat, rice, corn (wind pollinated)

Source: Klein et al. (2017)

But do not just take old research. A 2025 study from West Bengal, India, put bees to the test on mustard fields. One group of fields got managed honey bee colonies. The other group just had to make do with whatever wild bees happened to fly by. The difference was not subtle. Fields with honey bees produced 55 percent more pods per plant. They grew 44 percent more seeds per pod. And those seeds were heavier nearly 18 percent heavier than the ones from fields without managed bees. Think about that. No new fertilizer. No expensive irrigation system. No fancy GMO seeds. Just bees. And yields jumped by half.

Bridging the Pollination Gap

Even in places where wild bees still buzz around, they are often not enough anymore. Not nearly enough. Farmers have started calling this the "pollination gap." Here is how it works, your crop might need a hundred bee visits per square meter to reach full yield. But the wild bees in your area can only manage sixty. That gap of forty missing visits? That is lost produce. Lost income. Lost food. For years, most farmers did not even know the gap was there. They planted seeds. They sprayed sprays. They hoped for the best. When yields were lower than expected, they blamed the weather. Or the soil. Or the seed company. Hardly anyone looked at the bees.

But science has caught up. A landmark global study in 2013 found that more than 40 percent of the world's insect pollinator species are facing extinction. And in many farming areas, wild pollinator populations have dropped below the level needed to fully pollinate the crops growing right there. The gap is real. And it is growing.

In Indonesia, farmers have started keeping stingless bees. These are tiny, gentle creatures that cost almost nothing to keep. They do not sting. They produce honey. And they turn a small backyard patch of cucumbers or tomatoes into a jungle of produce. In Tanzania, communities are bringing back native woodlands. Not just for timber or wildlife, but specifically for bees. More trees mean more flowers. More flowers mean more bees. More bees mean more food. A beautiful cycle that works without expensive foreign aid or complicated technology.

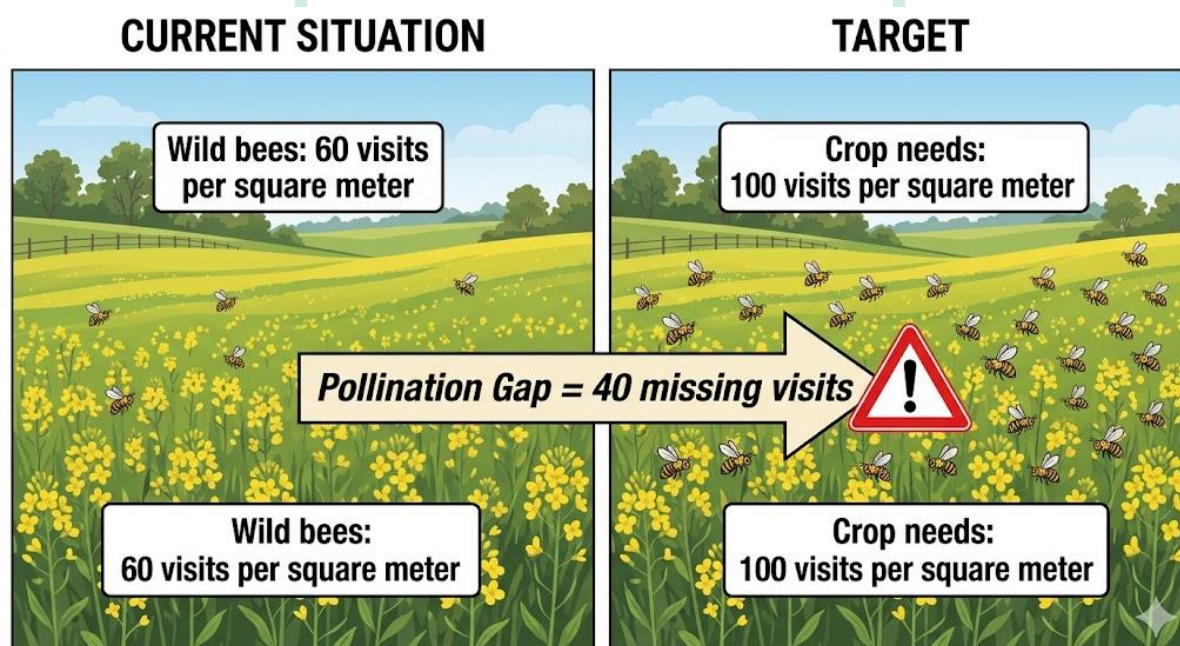


Diagram 1: The pollination gap

Table 2: Signs of a Pollination Gap on your Farm

If You Notice	It Might Mean	What to Check
Flower but no fruit	Not enough pollen transfer	Count bee visits per flower
Small or misshapen fruits	Incomplete pollination	Look for bee activity in the morning
Early fruit drop	Poor fertilization	Check if you have enough hives nearby
Low seed count in pods	Pollination was rushed	Observe if bees are avoiding your field

Source: Basak et al. (2025)

Here is what I want you to take away: you do not need to become a full-time beekeeper. You do not need fancy equipment or years of training. What you need to recognize is that pollination is not free anymore. Wild bees are struggling. The gap is real.

But the solution is simple. Bring bees to your crop. That might mean renting hives from a local beekeeper during bloom. In many places, the rental fee is surprisingly low often less than the value of the extra yield you will get. It might mean planting small patches of bee-friendly flowers along your field edges. It might mean simply leaving a few corners of your farm unmowed and unsprayed. One Indian farmer from that West Bengal study put it best. When someone asked why he started keeping bees on his farm, he just smiled and said: "I always thought bees were just for honey. Now I know they are for harvest."

A Species Under Threat

For all the good bees do, they are in real trouble. And the strange part? Most farmers do not even notice until it is almost too late. Before you think this is someone else's problem, ask yourself: who pollinates your crops? If you just said "nature takes care of it," please keep reading.

The Four Killers

Scientists have spent years trying to figure out what is wiping out the bees. The answer is not one thing. It is four things. And they are all getting worse.

The Four Killers – Threat Wheel

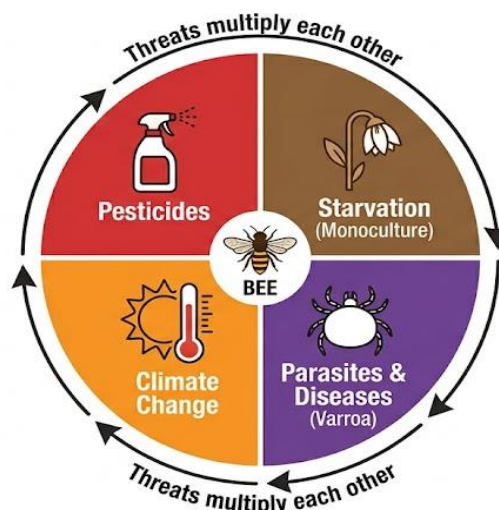


Diagram 2: The Four Killers – Threat Wheel

1. Killer Number One: Pesticides

You probably saw this coming. But the scale might surprise you. A single neonicotinoid seed treatment – applied once, at planting – can stay in plant tissues for months. When bees collect pollen or nectar from that plant, they do not drop dead immediately. Something worse happens. They get confused. They forget how to find their way home. Their babies develop deformities. The colony slowly weakens and dies.

2. Killer Number Two: Starvation

Walk through a modern farm landscape. What do you see? Corn. Soybeans. Wheat. Rice. Mile after mile of the same thing. To a bee, that is a desert. Bees need flowers from early spring through late fall. They need variety –

different shapes, different colors, different bloom times. A field of corn provides pollen for about two weeks. Then nothing. For the rest of the season, bees in that area are slowly starving. Farmers did not create this problem on purpose. Monoculture is efficient. It feeds the world. But efficiency has a cost, and the bees are paying it.

3. Killer Number Three: Parasites and Diseases.

The Varroa destructor mite is the single biggest threat to honey bees worldwide. It is a tiny red parasite about the size of a pinhead. Do not let the size fool you. Varroa mites suck the blood of developing bees, weaken their immune systems, and spread viruses. Without treatment, most infested hives die within two years.

4. Killer Number Four: Climate Change.

This one feels abstract until it is not. A honey bee is a creature of habit. It knows that apple trees bloom in April. It knows that clover flowers in June. For thousands of years, that timing worked perfectly. The weather is all over the place. Warm winters trick trees into blooming early. Then a late frost kills all the flowers. Rain arrives weeks late, and the bees have nothing to eat. A heatwave dries up the nectar before the bees can collect it. Climate change does not kill bees directly. It kills their food. Their shelter. Their sense of timing. And that kills them just as surely as any poison.

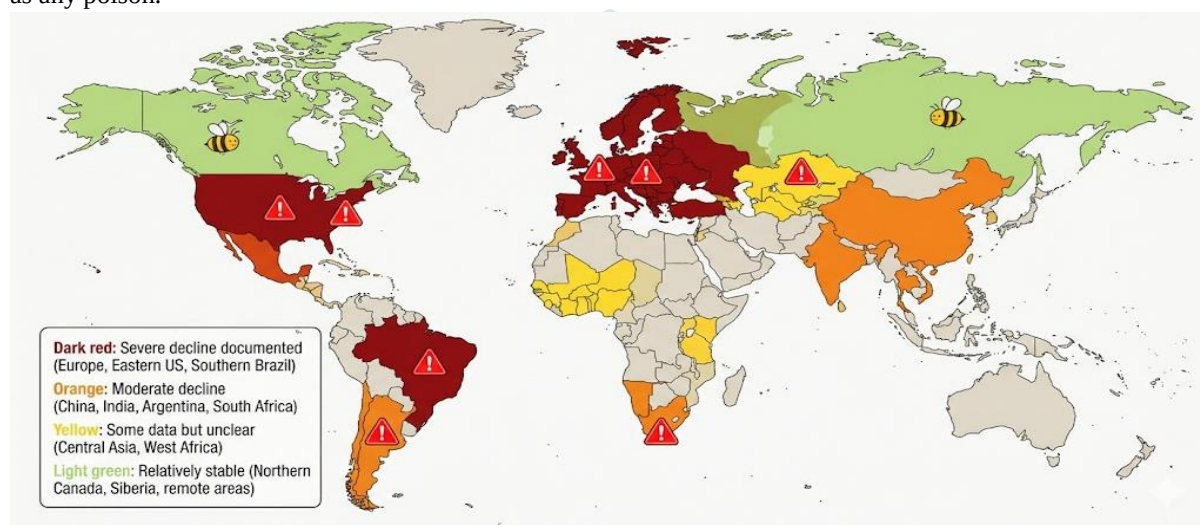


Diagram 3: World Map Showing Pollinator Decline Hotspots

Sustainable Solutions for Farmers and Policymakers

Enough bad news. Let me tell you what actually works. Here is the truth nobody tells you: protecting bees does not cost farmers money. It saves them money. And in many cases, it makes them more money. The research is clear. The field trials are done. The farmers who have tried these methods are not going back.

Table 3: Quick reference- What works, What Doesn't

Practice	Cost	Impact on Bees
Renting hives during bloom	Low to medium	High (adds pollinators)
Planting bee-friendly flowers	Low (seed cost only)	High (food source)
Spraying pesticides in evening	Zero cost change	High (save bees)
Leaving 5% of land wild	Low (opportunity cost)	High (nesting habitat)
Reducing pesticide use	Variable (savings possible)	Very high
Becoming a beekeeper	Medium (equipment)	High (managed colonies)

Source: Oktavia et al. (20205)

For Farmers: Five Things That Work

1. Rent hives during bloom.

This is the simplest, fastest fix. Find a local beekeeper. Pay them to put hives on your land when your crop is flowering. The cost is often just \$50 to \$150 per hive per season. The return? Studies show yield increases of 20 to 50 percent on crops that need pollinators.

2. Plant flowers that actually help

Not just any flowers. Bees need blooms across the whole season like spring through fall. They need flowers with accessible nectar and pollen. What works? Clover. Sunflowers. Buckwheat. Lavender. Native wildflowers like aster, goldenrod, and bee balm. Even flowering cover crops like mustard and phacelia. Where do you put them? Field edges. Road verges. Buffer strips along creeks. The corners of fields that are hard to farm anyway. You do not need a lot of land. You just need to use it wisely.

3. Stop spraying during bloom

This should be obvious, but it still happens all the time. Farmers spray insecticides on flowering crops because that is when the pest arrives. But that is also when bees arrive. The solution is simple: spray in the evening or at night. Most bees are back in their hives by dusk. A spray applied at 8 p.m. will dry by morning, and the bees will never know it was there.

4. Leave some land wild

You do not need to farm every square inch. A study from Germany found that farms with just 5 percent semi-natural habitat – hedgerows, wildflower strips, fallow land – had twice as many bees as farms with no wild habitat at all. Wild space is not wasted space. It is an investment in pollination.

5. Become a beekeeper yourself

This is not for everyone. But for small and medium farmers, keeping a few hives is surprisingly easy. The equipment is cheap. The learning curve is manageable. And the honey is a bonus crop you did not have before.

For Policymakers: What Governments Must Do

Farmers cannot solve this alone. They need help. First, subsidize pollination, not just production. Most farm subsidies pay for corn, wheat, and soybeans. Very few pay for healthy ecosystems. That needs to change. Governments can offer payments for planting pollinator habitat. Tax breaks for farmers who reduce pesticide use. Low-interest loans for beekeeping equipment. Second, ban the worst pesticides. The European Union banned three neonicotinoids back in 2018. Bee deaths dropped. It was not complicated. Third, restore public land for bees. Road verges. Power line corridors. Airport margins. Military bases. Millions of acres of public land that could be planted with wildflowers. Most of it is just mowed grass or bare dirt right now. France already requires roadsides to be managed for pollinators. The UK has a national pollinator strategy. Others are catching up. Fourth, fund research and extension. Farmers need practical advice. Which flowers work best in their region? When should they spray? How many hives per acre? Agricultural extension services should have pollinator experts on staff. They should run demonstration farms where farmers can see the results with their own eyes.

A Call to Action

A honey bee weighs less than a grain of rice. But this tiny creature, multiplied across millions of hives worldwide, holds up the global food system. And that army is retreating. Not because of some natural disaster. Because of our farming practices. Our chemicals. Our desire to control every single variable. The choice for farmers, policymakers, and the rest of us is simple: keep doing what we are doing and watch the pollination gap widen. Or change course with proven, affordable solutions. For farmers, change means renting hives, planting flowers along field edges, spraying in the evening instead of midday, leaving small corners of land wild, and maybe even becoming beekeepers themselves. Studies show these practices increase yields by 20 to 55 percent while reducing input costs. For policymakers, change means subsidizing pollinator habitat instead of just corn and soybeans, banning the pesticides that science has repeatedly linked to bee declines, planting public roadsides with wildflowers, and funding extension services that teach farmers what actually works. For the rest of us, change means planting a small pollinator garden in our backyard, buying honey from local beekeepers, asking our farmers how they protect bees, and voting for leaders who take this crisis seriously. That hum you hear, that is your harvest being made. Listen to it. Protect it. And pass it on.

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Apiculture: A Profitable Agribusiness for Rural Youth and Farmers



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Abstract

Apiculture, or beekeeping has emerged as a promising agribusiness enterprise with significant potential for rural livelihood generation particularly for smallholder farmers and unemployed rural youth. This article examines the economic viability, diversification opportunities, challenges, and government support structure associated with beekeeping in India, drawing upon peer-reviewed research, government programme data, and real-world case studies, the economic analysis reviewed analysis reveals that beekeeping profitability improves substantially with scale, with large scale operations managing upto 400 hives achieving a benefit cost ratio of 2.25. Group beekeeping under cooperative models yield 38% higher net income per 50 hives compared to individual operations. Beyond honey production, diversified product streams including beeswax, pollen, propolis, royal jelly, and pollination services offer multiple revenue source that enhance farm resilience. Real world case studies from Uttar Pradesh, Jammu and Kashmir, Andhra Pradesh, and other demonstrate that farmers with formal training and government support can transform modest beginnings into thriving thriving enterprises with one farmer scaling from a single hive to 600 boxes generating annual revenue of approximately 3 crore. Government initiatives including the Holistic Agriculture Development Programme (HADP), ICAR Tribal Sub Plan, CSIR Aroma Mission, and CSIR Floriculture Mission offer vital support in the form of financial aid, equipment distribution, and training. Significant obstacles still exist, nevertheless, including as exposure to pesticides, a lack of technical expertise, poor storage facilities, and barriers to market access mediated by middlemen. According to the article's conclusion, apiculture is a feasible, empirically supported strategy to improve rural livelihoods, especially if it is pursued with sufficient training, cooperative organization, government assistance, and strategic diversification. In order to fully realize apiculture's potential as a revolutionary agribusiness for rural India, the results highlight the significance of focused policy interventions, improved extension services, and farmer-centric value chain development.

Keywords Apiculture, beekeeping, rural livelihood, agribusiness, smallholder farmers, rural youth

1. Introduction

Beekeeping is one of the oldest agriculture practices known to humanity, yet it remains one of the most underutilized opportunity for rural livelihood generation in India today. For the young farmer struggling to make ends meet on a small plot of land, or the rural entrepreneur looking for a low cost, high return venture, apiculture offers a path worth serious consideration. Considering the story of Brajesh Kumar Verma from Lucknow. A few years ago, he was a farmer farming with just half a hectare of land, no significant financial backing, and limited opportunity for growth. His turning point came in the form of single bee box, provided free of cost under a government scheme. That modest beginning, which required little more than willingness to learn, has since transformed into as enterprise of six hundred bee boxes. Today, Brijesh employs over a thousand beekeepers, his organization generates annual revenues of nearly three crore rupees, and he has trained six thousand farmers at no cost to them. His journey from one box to a thriving agribusiness is not an anomaly. It is a testament to what apiculture can achieve when pursued with dedication and proper support.

The economic case for beekeeping is compelling. A study of beekeepers in Maharashtra's Kolhapur district found that large- scale operations those managing up to four hundred hives, achieved a benefit cost 2.25, meaning that every rupee invested returned two rupees and twenty- five paise. The average net annual return for such scale

beekeepers with as few as hives earned respectable profits that meaningfully supplemented their agriculture income.

What makes apiculture particularly attractive for rural youth and small farmers is its low barrier to entry. Unlike many agribusinesses that require substantial land, expensive machinery, or complex infrastructure, beekeeping demands relatively little. A few wooden boxes, access to flowering plants, and basic training are sufficient to begin. The bees themselves do most of the work, foraging freely and producing honey, wax, pollen, propolis, and royal jelly, each of which represents a distinct revenue stream. Furthermore, the pollination services provided by bees enhance the yield of neighbouring crops, creating additional value that often goes unmeasured but is very real.

In recent years, the government has greatly increased its support for apiculture. Aspiring beekeepers can receive bee boxes, training, and financial support through programs like the CSIR Aroma Mission, the Floriculture Mission, and other state-level efforts. The Holistic Agriculture Development Programme in Jammu and Kashmir has transformed local livelihoods by enabling 346 beekeepers to produce 5,000 quintals of honey. The ICAR Tribal Sub Plan has enabled families in Andhra Pradesh's tribal belts to generate an extra 19,000 rupees annually on average from a small number of hives.

This essay investigates the viability and profitability of apiculture as an enterprise for young people and farmers in rural areas. It uses data from government programs, peer-reviewed studies, and real-world case studies to provide an honest evaluation of opportunities, difficulties, and workable starting points. Instead of portraying beekeeping as a miraculous way to alleviate rural poverty, the objective is to provide an objective, fact-based perspective on an industry that has actually transformed thousands of lives.

2. The Economic Viability of Beekeeping: what the number Say

Before investing time and resources into any agribusiness, a farmer must ask a fundamental question that will this pay? In case of apiculture, the evidence from multiple studies across different regions of India suggests a clean and consistent answer yes, with proper management. A comprehensive study conducted in Kolhapur district of Maharashtra examined beekeeping operations across three scales and documented their profitability. The findings are presented in Table 1

TABLE 1: Profitability of Beekeeping at Different Scales in Kolhapur District, Maharashtra

Scale	Number of Hives	Benefit-cost Ratio	Average Net Annual Return
Small	Up to 10	1.17	Not separately reported
Medium	Up to 100	1.75	Not separately reported
Large	Up to 400	2.25	27,64000

Source: Patil et al (2025)

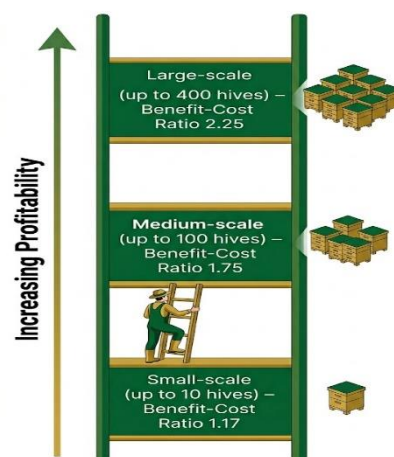
These figures show that beekeeping profitability increases dramatically with size. The benefit-to-cost ratio increases from 1.17 for small-scale operators to 2.25 for large-scale operators. In practical terms, this means that a farmer who invests one lakh rupees in large-scale beekeeping may expect to receive around two lakh twenty-five thousand rupees back. Few traditional crops provide this kind of return on investment.

A subsequent study conducted under the RKVY RAFTAAR scheme in Hamirpur district, Bundelkhand, Uttar Pradesh, yielded similar results. The average operational cost for fifty bee colonies was ₹25,017, with an average gross return of ₹83,112.

Table 2: Cost and Returns for 50 Bee colonies in Hamirpur District, Uttar Pradesh

Parameter	Amount
Average operational cost per unit	25,017
Average gross cost per unit	83,112
Net return range	51.780-72137
Benefit-cost range	2.0-2.5

Source: ICAR (2026)



3. Beyond Honey: Diversification and Value Addition

One of the most important lessons from successful beekeepers is that honey is only the beginning. A single hive produces multiple products each with its own market and profit margin. Farmers who understand this diversify their revenue streams and build more resilient businesses.

Table 4: Products from a Bee Colony and Their Uses

Products	Description	Primary Uses	Market Potential
Honey	Nectar processed by bees	Direct consumption, food processing, medicinal use	High
Bee pollen	Pollen collected by bees	Health supplement, protein source	Medium to high
Propolis	Resinous substance collected by bees	Natural medicine, cosmetics oral care	medium
Beeswax	Was secreted by worker bees	Candles, skincare products. Food wraps, polishes	Syable and consistent
Royal jelly	Secretion produced by worker bees	Hight value health supplement cosmetics	High
Pollination services	Rental of hives to farmers	Crop pollination from fruits, vegetables, nuts	growing

Source: Singh et al. (2025); Oktavia et al. (2025)

The financial logic behind diversification is simple. A farmer who only sells raw honey relies only on honey prices. A farmer who processes pollen into health drinks, transforms beeswax into candles and creams, and rents out hives to neighboring fruit producers during bloom has various revenue sources. When one market fluctuates, another may remain constant.

Jagtar Singh's experience in Punjab exemplifies this principle in action. By diversifying into value-added items, he was able to acquire margins previously held by processors and retailers. His beeswax creams, for example, command much higher prices than the raw beeswax he used to sell in bulk.



4. Challenges facing Beekeepers

No honest evaluation of apiculture would be complete without acknowledging the true obstacles that beekeepers encounter. These obstacles are considerable, but not insurmountable

4.1. Pesticide Exposure

Pesticide exposure, particularly neonicotinoid pesticides, poses the most serious hazard to bee populations. Bees do not usually die immediately after foraging on crops treated with these pesticides. Instead, they become bewildered, lose their ability to navigate, and transport tainted pollen back to the hive, where it spreads throughout the colony. A national study of beekeepers identified pesticide concerns as one of the three biggest barriers to sustainable beekeeping.

4.2. Limited technical Knowledge

Many farmers start beekeeping without receiving proper instruction in quality factors. Honey quality standards are stringent, and attaining them necessitates understanding of moisture content, storage conditions, and processing techniques. Without this expertise, growers risk producing honey that does not match market standards and hence cannot fetch top pricing.

4.3. Inadequate Storage Facilities

Honey is sensitive to temperature, light, and moisture. Improper storage causes fermentation, color changes, and loss of enzyme activity. Many small-scale beekeepers may not have access to adequate storage facilities, requiring them to sell their honey quickly often at lower prices, rather than saving it for better market possibilities.

4.4. Market Access and Middleman

Beekeepers in remote rural locations frequently rely on intermediaries to access metropolitan markets. These intermediaries generally receive a sizable portion of the ultimate retail price. According to a countrywide research, middlemen's margins accounted for almost 22% of individual beekeeper revenue (Mohanty et al., 2024). Cooperatives and direct marketing channels help to limit leakage, but not all farmers have access to these options.

5. Government Support for Apiculture

Farmers considering beekeeping do not need to navigate that path alone. Several government programmes provide financial support, training, equipment, and market linkages.

Table 5: Major Government Scheme Supporting Beekeeping in India

Scheme	Administering Body	Key Support provided	Impact
CSIR Aroma Mission	CSIR	Training, distillation unit, value addition support	1.22 lakh people trained, 110 entrepreneurs supported, 1 crore rural employments created (PIB 2025)
CSIR Floriculture Mission	CSIR	Apiculture, integration; honey bee box distribution	1,072 boxes distributed; 175 farmers benefited, combined earning of 262 crore from floriculture and apiculture (PIB, 20-25)
Holistic Agriculture Development Programme (HADP)	J&K Government	Modern equipment; technical training; financial assistance	346 beekeepers; 5000 quintals honey production
RKVY RAFTAAR	GOI	Project funding for agri-startups including apiculture	Benefit-cost ratio of 2.0-2.5 achieved in Bundelkhand (ICAR, 2026)
ICAR Tribal Sub Plan	ICAR	Hive boxes; training; handholding support	19000 average additional annual income per tribal family (Prasad et al., 2024)

6. Conclusion

Beekeeping is not a magic bullet for rural poverty, and it is not without risks. Pesticide exposure, climate variability, and market access issues are genuine difficulties that must be carefully managed. However, several studies and hundreds of successful beekeepers across India demonstrate that apiculture is a really viable agribusiness for those who approach it with correct training, realistic expectations, and a willingness to learn. The financial numbers are convincing. Large-scale beekeepers achieve benefit-cost ratios above 2.0, net annual returns of over 27 lakh rupees, and various revenue sources from a single group of hives. Even small-scale and tribal farmers generate significant additional revenue, transforming their home economies. The government has established extensive support infrastructure, ranging from training programs to equipment subsidies to marketing aid. And the experiences of farmers like Brajesh Kumar Verma, Mushtaq Ahmad Mir, and thousands more show how ordinary people with limited means can create amazing livelihoods via beekeeping.

Apiculture is a viable option for rural adolescents who have a tiny plot of land and low capital. For farmers wishing to diversify beyond traditional crops, beekeeping is a complementing activity that increases agricultural yields through pollination. A few bee boxes and good training can help an unemployed young person in a village with few career opportunities build a sustainable livelihood.

The bees do the majority of the job. They forage freely, pollinate nearby crops, and generate valuable goods without demanding pay or complaining about labor conditions. What they need from the farmer is knowledge, care, and protection from chemicals that threaten them. In exchange, they provide a relationship that has enabled human cultivation for thousands of years. One box. One colony. One season. That's how every successful beekeeper started. And for those who are eager to study, this is how they might start a new career.

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Nursery management and Softwood Grafting in Cashew



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Introduction

Cashew (*Anacardium occidentale* L.) is one of the most important plantation crops of tropical regions and is widely cultivated for its edible kernels, cashew apple, and industrial by-products. India is among the leading producers, processors, and exporters of cashew kernels, contributing significantly to employment generation and foreign exchange earnings. Successful commercial cultivation of cashew depends largely on the availability of healthy, vigorous, and true-to-type planting materials. Seed propagation results in high genetic variability; therefore, vegetative propagation techniques are recommended for maintaining the desirable characteristics of elite varieties. Among the various propagation methods, softwood grafting has emerged as the most reliable and commercially accepted technique due to its high success rate, simplicity, rapid multiplication, and production of uniform planting materials. Scientific nursery management combined with proper grafting techniques ensures better survival, early establishment, and enhanced productivity of orchards. The Directorate of Cashew Research (ICAR-DCR), Puttur, has standardized nursery and grafting technologies that are widely adopted throughout India for quality planting material production.

Nursery Management

The success of cashew propagation largely depends on efficient nursery management practices. Healthy nursery plants provide a strong foundation for establishing productive orchards. The first step is the selection of superior mother trees that are healthy, high-yielding, regular bearers, and free from insect pests and diseases. Mature nuts are collected from these selected trees during the harvesting season and are graded based on size, weight, and freedom from physical damage.

Fresh, fully mature seed nuts should be used because they exhibit better germination than stored seeds. Before sowing, the nuts are soaked in clean water for about 24 hours to improve moisture absorption and accelerate germination. Floating nuts should be discarded as they are generally of poor quality. Polybags of approximately 20 × 15 cm with adequate drainage holes are filled with a sterilized growing medium consisting of red soil, sand, and well-decomposed farmyard manure in the ratio of 2:1:1. This medium provides sufficient aeration, drainage, and nutrients for healthy root development.

Seed nuts are sown individually in polybags with the stalk end facing upward at a depth of about 3–5 cm. The nursery should be maintained under partial shade during the initial growth period to protect emerging seedlings from excessive sunlight. Regular irrigation is essential to maintain optimum soil moisture without causing waterlogging. Germination generally begins within 10–15 days and continues for about three weeks, with germination percentages often exceeding 85% when quality seeds are used.

Healthy seedlings are selected as rootstocks. Routine nursery operations include weeding, irrigation, removal of weak seedlings, and application of balanced nutrients when necessary. The nursery should be kept clean to minimize the incidence of damping-off, leaf spot, and insect pests. Appropriate plant protection measures should be adopted whenever required. Under proper management, seedlings attain a stem diameter of about 0.8–1.0 cm within 45–60 days and become suitable for softwood grafting.

Softwood Grafting Technique in Cashew

Softwood grafting is the most widely recommended vegetative propagation technique for cashew because it produces genetically identical plants with early bearing potential and high field establishment. The ideal period

for grafting varies with climatic conditions, although June to September is generally considered the most suitable season under Indian conditions due to favourable humidity and moderate temperatures. This is the most popular and the best method for commercial multiplication of improved cashew varieties and found to be suitable for propagation almost round the year. However, higher success rate of grafting can be achieved during June to October due to abundance of mature scion shoots, favourable temperature and higher relative humidity conditions. Various steps of softwood grafting technique are:

A. Raising of root stock:

- Potting mixture in the proportion of 1 part of red soil: 1 part of river sand: 1 part of Farm yard manure/compost has to be prepared with rock phosphate (40-50g/10kg mixture) added to it. This is filled in high density polythene bags of 25cm X 15cm size having thickness of 250-300 gauge, with holes punched on them for proper drainage for raising the root stock seedlings.
- Healthy and fully matured uniform sized seeds should be collected from the peak time in the season, preferably from a single variety and sun-dried for 2-3 days. Such selected seeds can be stored for about 6-8 months in gunny bags or plastic bags which can be further used for raising the root stocks. Such bags should be store in dry and cool place free from rodents.
- Heavy seeds screened by removing the seeds floating in water should be used for sowing. Such seeds, pre-soaked overnight have to dibbled with stalk-end upwards, 3-4 cm deep in the centre of the polythene bags filled with potting mixture and watered immediately. Seeds can be sown in fortnightly batches to ensure the availability of root stock seedlings continuously for grafting. Seeds, pregerminated in moist sand bed, can also be used for sowing to ensure the seedling in each polythene bag filled with growth medium.
- Watering should be done depending on the seasonal requirements (daily in summer) to ensure the proper germination which takes about 2-3 weeks. Healthy seedlings of 7-8 weeks old (50-60 days) after germination, are used for soft wood grafting. Collar rot or damping off disease during rainy season can be controlled by spraying Bordeaux mixture (1%) or Bavistin (1%) at fortnightly interval. Sucking pests like Tea Mosquito Bug (TMB) and Thrips can be controlled by spraying Monocrotophos or Quinolophos (1.5 ml/litre of water) during the growth of seedlings.

B. Preparation and Collection of scion sticks:

In the scion bank, healthy, nonflowering matured shoots of 4-5 months of current growth on desired variety are to be selected and precured by clipping off the leaves with part of petiole retained on the shoot, with help of a Secateur. Precuring should be done, batch wise at fortnightly interval, 10-12 days prior to grafting in order to stimulate the dormant buds on the shoots which will ensure the higher rate of graft take. Such pre-cured shoots of 15-20 cm length (scion sticks) which will be having bulged buds are to be collected early in the morning on the day of grafting.

C. Tying the graft:

Healthy root stock seedlings of 7- 8 weeks old (50-60 days) are selected for grafting. On the root stock seedling, very tender portion of terminal shoot is nipped off and all the lateral leaves except the lower most two pairs, are removed using the grafting knife. A transverse downward cut is given in the soft wood portion on the decapitated stem (15-20 cm above) to make a cleft of 5-6 cm deep. From the inner portion of cleft lips at the top, some portion of wood has to be removed to ensure smooth union at the grafting joint without any dead wood. • From the scions collected, a scion stick matching to the clefted root stock is selected and cut freshly at the bottom to reduce it to required length (10cm) and sharpened to wedge shape by giving smooth inward slant cuts at one stroke longitudinally downwards (up to 5-6 cm) on opposite sides on the scion stick so that the bark portion is intact on the other sides. • The wedge-shaped scion stick is inserted in to the cleft of the root stock and the cleft is closed in such a way that the cambial portion of both the scion stick and root stock comes in exact contact and the union portion is fastened firmly with polythene tape (100 gauge). The scion portion on the stock is covered with polythene bag to ensure the humid condition also to overcome the desiccation of the scion. Alternatively, all the grafted plants can be kept under poly house with mist facility to ensure the hot humid conditions required for faster callus growth in the joint region. The plants are maintained under nursery shed for 20-30 days to encourage the sprouting of the potential buds on the scion portion after which the polythene bags are removed and the grafts

are shifted to shade-net house (50%) and then to open condition for hardening. Depending on the season, about 70- 90 per cent graft success can be achieved by this method.

D. After care:

Polythene strip should be removed after five months to avoid girdling on graft union. The side shoots arising from the root stock region should be removed periodically. Striking of the tap root in to the nursery ground can be prevented by stacking the successful grafts on polythene sheet spread on the nursery ground. This also helps in sorting of the week grafts for special care. Grafts should be watered regularly depending on the season. Fungal diseases on young leaves can be controlled by spraying the Grafts should be sprayed with Bavistin (1%) to manage fungal diseases on young leaves and with monocrotophos (1.5ml/litre of water) against 'sucking pests and leaf minor, at 15-20 days interval. Flowering, if any, in the grafts in the nursery should also be removed.

In Situ Grafting: In this method of propagation also, softwood grafting technique is employed, but the entire exercise is carried out in the main field itself instead of the nursery practice. Various steps involved are:

- Layout the main field and dig-open the pits for curing during May. Fill the pits with top soil mixed Farm yard manure (FYM).
- Plant 2-3 selected seeds in the first week of June, in the centre of each pit filled with soil and FYM to raise the root stocks in the main field.
- Graft the desired pre-cured scion as described in 'soft wood grafting' on 3-4 months old, healthy root stock seedlings during September-October period and cover the scion with plastic cover. Other seedlings can be used if graft take is failed in the first attempt.
- Once the buds are sprouted, remove the plastic bag and remove the plastic strip January or February to avoid girdling. Remove the side shoot on the root stock below the grafting union. Advantages: Tap root system is intact unlike in field planted grafts, therefore, supports the extensive growth of lateral roots and withstands the onslaught of uprooting by stormy winds. In situ grafting may induce precocity, because, minimum size of canopy required for first harvesting is achieved in advance of one year. If root stocks are standardized, this method offers scope for taking advantage of positive stionic effect for specific varieties. In situ grafting is cost effective.

Conclusion

Scientific nursery management and softwood grafting are indispensable components of quality planting material production in cashew. Proper selection of mother trees, use of healthy seed nuts, suitable nursery media, efficient seedling management, and standardized softwood grafting techniques ensure high graft success and vigorous plant growth. Adoption of these technologies not only produces true-to-type planting materials but also promotes early bearing, higher productivity, and uniform orchard establishment. The technologies standardized by ICAR– Directorate of Cashew Research have significantly contributed to improving cashew cultivation in India and have enhanced the profitability of nursery enterprises. Wider dissemination of these improved propagation practices through farmer training, extension programmes, and entrepreneurship development will further strengthen sustainable cashew production and support the long-term growth of the cashew industry.



Figure 1: Seed germination in nursery (ICAR)

- A - Germination of seeds in sand bed
- B - Sowing of pre-germinated seeds in poly bags
- C - Uniform growth of seedlings
- D - Healthy seedlings becoming ready for root stock



Role of Veterinary Microbiology in Sustainable Livestock Production Systems



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Abstract

The escalating global demand for animal-derived protein necessitates a paradigm shift from intensive conventional livestock production to truly sustainable systems that balance economic viability, environmental stewardship, and social responsibility. Sustainable livestock production has become an essential component of global food security, environmental conservation, and public health protection. Within this context, veterinary microbiology is emerging as a cornerstone discipline, moving beyond its traditional diagnostic and therapeutic roles to become integral to improving livestock productivity, disease management, animal welfare, and food safety. This discipline encompasses bacteriology, virology, mycology, immunology, and molecular diagnostics, which collectively contribute to the prevention, diagnosis, and control of infectious diseases. This article synthesizes current knowledge on how veterinary microbiology contributes to sustainability through four key pathways: (1) enhancing microbial disease surveillance and precision diagnostics, alongside robust antimicrobial stewardship, to reduce antimicrobial use and combat antimicrobial resistance (AMR); (2) promoting gut microbiome modulation for improved feed efficiency, enhanced animal resilience against diseases, and reduced greenhouse gas emissions; (3) developing next-generation probiotics, vaccines, and competitive exclusion strategies as effective alternatives to antimicrobial growth promoters; and (4) enabling closed-loop biosecurity and waste management through microbial risk assessment and beneficial bioremediation. By integrating advanced genomic tools, metagenomics, and a One Health framework, veterinary microbiology provides the evidence base for interventions that simultaneously improve animal health, reduce the environmental footprint of livestock, lower environmental emissions, and safeguard public health. This review highlights recent innovations and future prospects for integrating these microbiological tools into climate-smart and economically viable livestock systems. We conclude that embedding microbiological principles into livestock management is not an option but a prerequisite for achieving the United Nations Sustainable Development Goals in animal agriculture.

Keywords: Veterinary microbiology; sustainable livestock production; One Health; antimicrobial resistance (AMR); gut microbiome modulation; next-generation probiotics; biosecurity; microbial diagnostics; greenhouse gas emissions; United Nations Sustainable Development Goals (SDGs)

1. Introduction

Livestock production contributes significantly to global agriculture, rural livelihoods, nutrition, and economic development. According to global agricultural estimates, the sector contributes nearly 40% of agricultural GDP worldwide and supports the livelihoods of billions of people. However, modern livestock production faces an unprecedented trilemma: it must increase productivity to feed a growing population, reduce its substantial environmental impact accounting for an estimated 14.5% of anthropogenic greenhouse gas emissions and curb the rising threat of antimicrobial resistance. Additional serious challenges include infectious diseases, environmental pollution, climate change, and increasing consumer demand for safe, ethically produced animal products. Traditional approaches focused on maximizing output through intensive confinement, routine antimicrobial use, and high-density stocking are now recognized as ecologically and epidemiologically unsustainable.

Veterinary microbiology, the study of microorganisms affecting animal health and their interactions with hosts, environments, and humans, has historically been reactive primarily diagnosing outbreaks and guiding treatment. However, a new paradigm is emerging. With the advent of high-throughput sequencing, microbiome science, systems biology, and advanced molecular diagnostics, veterinary microbiology is becoming a proactive,

predictive, and preventive force for sustainability. The growing concern over zoonotic diseases, including avian influenza, brucellosis, salmonellosis, and bovine tuberculosis, has further emphasized the importance of microbiological interventions in livestock management.

Sustainable livestock production systems require efficient disease prevention strategies, responsible antimicrobial use, improved animal immunity, and environmentally friendly management practices. Veterinary microbiology provides the scientific tools and technologies to achieve these goals. Advances in molecular biology, genomics, microbiome research, and biotechnology have expanded the role of veterinary microbiology beyond traditional disease diagnosis to encompass precision livestock farming, ecosystem sustainability, and One Health approaches.

This review article discusses the major contributions of veterinary microbiology to sustainable livestock production systems by focusing on four key pathways: disease control without overreliance on antimicrobials, enhanced feed conversion through gut microbiome modulation, reduction of environmental emissions, and resilient biosecurity. It also explores future opportunities for improving animal health and agricultural sustainability within a climate-smart and economically viable framework.



Figure 1: Conceptual framework of veterinary microbiology contributions to sustainable livestock production.

Figure Description (for legend): Central circular diagram connecting the four key pathways around Sustainable Livestock Production, with one Sustainable Livestock Production, One Health arc, anawoms of the bottom and SDG icons are bottom.

2. Sustainable Livestock Production: Principles and Microbial Surveillance

2.1. Concept of Sustainable Livestock Production

Sustainable livestock production refers to systems that are economically profitable, environmentally safe, socially acceptable, and capable of maintaining animal health and welfare over time. Such systems aim to achieve multiple interconnected objectives: enhance productivity without degrading natural resources; minimize greenhouse gas emissions; reduce disease burden and associated economic losses; improve food safety and protect public health; ensure animal welfare; and reduce dependence on chemical drugs and antibiotics. Microbial management has become central to achieving these objectives because microorganisms directly influence animal health, digestion, immunity, and environmental interactions. Consequently, veterinary microbiology provides a scientific foundation for transitioning from conventional intensive production to truly sustainable livestock systems.

Table 2.1: Projected Impact of Predictive Microbiology on Antimicrobial Use

Production System	Baseline Antimicrobial Use (mg/kg live weight)	Estimated Use After Genomic Surveillance	Reduction (%)
Swine (finishing)	150	90–105	30–40%
Broiler chickens	80	48–56	30–40%
Dairy cattle	40 (<i>per lactation</i>)	20–28	30–50%
Beef feedlot	120	60–84	30–50%

2.2. From Reactive Diagnosis to Predictive Surveillance

One of the greatest drivers of unsustainability in livestock production is the overuse of broad-spectrum antimicrobials, often administered prophylactically to compensate for poor or delayed diagnostics. Veterinary

microbiology is revolutionizing this paradigm through real-time genomic surveillance, enabling a shift from reactive to predictive disease management.

Metagenomic shotgun sequencing applied to on-farm samples such as feces, dust, and drinking water can now detect all bacteria, viruses, and fungi, including emerging pathogens, within 24 hours. This rapid, comprehensive profiling allows for early intervention before clinical disease manifests. Furthermore, whole-genome sequencing of microbial isolates enables precise source tracking, differentiating an environmental *Escherichia coli* from a pathogenic strain, or identifying a silent reservoir of *Salmonella* within a herd. Such precision permits targeted culling or sanitation measures instead of blanket antimicrobial medication. Advanced microbial risk assessment models now integrate multiple variables, including weather patterns, stocking density, and prior pathogen loads, to predict high-risk periods for diseases such as bovine respiratory disease. These predictive tools allow preemptive management changes for example, adjusting ventilation or bedding rather than relying on post-infection treatments. By replacing “just-in-case” antimicrobials with “just-in-time” microbial data, farms can reduce total antimicrobial use by an estimated 30–50% without compromising animal health or productivity. This approach not only mitigates the selection pressure for antimicrobial resistance but also aligns directly with the core principles of sustainable livestock production.

Table 2.2: Turnaround Time from Sample Collection to Actionable Result

Diagnostic Method	Turnaround Time	Pathogen Identification	Source Tracking	AMR Profile
Culture & biochemical testing	3–7 days	Yes	No	Partial
PCR (targeted)	4–24 hours	Limited (known targets)	No	No
Metagenomic shotgun sequencing	24–48 hours	Full (all microbes)	Yes (strain-level)	Yes (genotypic)

3. Veterinary Microbiology and the Gut Microbiome: The Engine of Feed Efficiency

3.1. Veterinary Microbiology: An Overview

Veterinary microbiology is the branch of science dealing with microorganisms that affect animals. It encompasses several core subdisciplines: bacteriology (study of bacteria causing diseases), virology (study of animal viruses), mycology (study of fungi), parasitic microbiology (study of protozoal pathogens), immunology (study of immune responses), and molecular microbiology (genetic and molecular analysis of pathogens). Together, these fields support livestock sustainability through diagnostics, surveillance, vaccine development, therapeutics, and microbial ecosystem management. Among these, the study of the gut microbiome has emerged as a critical focus, given its profound influence on feed efficiency, environmental emissions, and overall animal health.

3.2. The Gut Microbiome as a Master Regulator of Feed Efficiency

Feed production requiring land, water, and fertilizer represents the largest environmental footprint of most livestock systems. Veterinary microbiology has revealed that the gut microbiome is a master regulator of the feed conversion ratio, directly linking microbial ecology to sustainability outcomes.

Microbial contribution to digestion: In ruminants, the rumen microbiome degrades cellulose into volatile fatty acids, which serve as the primary energy source for the animal. Advanced characterization of this microbiome allows for the selection of cattle harboring “high-efficiency” microbial consortia. By breeding animals that naturally host such consortia, producers can achieve lower methane emissions per kilogram of milk or meat, thereby reducing the greenhouse gas footprint of ruminant production.

Microbiome-directed nutrition: Traditional feeding relies on fixed feed formulas. However, precision feeding based on an individual animal’s or herd’s microbial profile is emerging as a transformative approach. For example, supplementing diets with specific fibrolytic enzymes or exogenous microbes can unlock otherwise indigestible components of low-cost feedstuffs, such as agricultural by-products. This strategy reduces direct competition for human-edible grains and improves the overall resource efficiency of livestock systems.

Reducing nitrogen excretion: In monogastric animals such as pigs and poultry, a poorly balanced hindgut microbiome leads to excess nitrogen excretion in the form of ammonia, a potent environmental pollutant. Probiotic strains of *Bacillus* or *Lactobacillus* have been shown to improve protein utilization, reducing nitrogen

output by up to 20%. This not only mitigates air and water pollution but also enhances the economic efficiency of protein conversion. By integrating veterinary microbiological principles with gut microbiome management, sustainable livestock systems can achieve higher feed efficiency, lower environmental emissions, and reduced reliance on external inputs advancing the core goals of sustainable production.

4. Disease Diagnosis, Surveillance, and Antimicrobial Resistance Management

4.1. Conventional Diagnostic Methods

Early disease diagnosis is one of the most important contributions of veterinary microbiology to sustainable livestock systems. Traditional diagnostic methods include microscopy, culture techniques, biochemical tests, and serological assays. These methods help identify pathogens responsible for diseases such as mastitis, brucellosis, salmonellosis, and anthrax. While foundational, these approaches are often time-consuming and may lack sensitivity for subclinical infections.

4.2. Molecular Diagnostic Techniques

Modern molecular tools have improved diagnostic accuracy and speed. Important techniques include polymerase chain reaction (PCR), real-time PCR, enzyme-linked immunosorbent assay (ELISA), next-generation sequencing (NGS), and CRISPR-based diagnostics. These technologies allow rapid detection of pathogens even before clinical symptoms appear, reducing disease spread and economic losses. Metagenomic shotgun sequencing, in particular, enables comprehensive pathogen profiling from a single sample within 24 hours.

4.3. Epidemiological Surveillance

Veterinary microbiology contributes to disease surveillance systems by monitoring outbreaks, identifying emerging pathogens, and tracking antimicrobial resistance (AMR) patterns. Surveillance programs are critical for transboundary animal diseases and zoonoses (e.g., avian influenza, brucellosis). By integrating genomic data with epidemiological models, veterinarians can predict high-risk periods and implement targeted interventions.

4.4. Antimicrobial Resistance: Causes and Control

Antimicrobial resistance is one of the greatest threats to livestock sustainability and public health. The main causes of AMR in livestock include overuse of antibiotics, subtherapeutic antibiotic feeding (e.g., growth promoters), poor farm hygiene, and incomplete treatment regimens. Veterinary microbiologists contribute to AMR control by conducting antimicrobial sensitivity testing, developing antibiotic stewardship programs, monitoring resistant bacterial strains, and promoting alternative therapies. Microbiological surveillance helps farmers select targeted treatments instead of indiscriminate antibiotic use, thereby preserving the efficacy of existing drugs.

4.5. Alternatives to Antibiotics

Sustainable livestock systems increasingly rely on non-antibiotic microbial solutions. Key alternatives include:

- **Probiotics and next-generation probiotics:** Strains such as *Faecalibacterium prausnitzii* or *Butyricicoccus pullicaecorum* produce short-chain fatty acids that directly inhibit enteric pathogens like *Clostridium perfringens* in broilers, improving growth as effectively as conventional growth promoters without resistance risk.
- **Prebiotics and synbiotics:** Non-digestible substrates that selectively stimulate beneficial gut bacteria, often combined with probiotics for synergistic effects.
- **Bacteriophages:** Phage therapy for specific pathogens (e.g., *Salmonella* in swine, *Staphylococcus aureus* in dairy mastitis) offers a self-replicating, narrow-spectrum alternative. Phage cocktails can be applied in water or as sprays, reducing pathogen load without disrupting the broader commensal microbiome.
- **Competitive exclusion cultures:** Administering a defined culture of non-pathogenic gut bacteria to day-old chicks or newborn piglets quickly colonizes the gut, creating “colonization resistance” against *Campylobacter* and *Salmonella*. Competitive exclusion products are now standard in many organic poultry systems.
- **Herbal antimicrobials:** Plant-derived compounds (e.g., essential oils, tannins) with antimicrobial properties, used as feed supplements.

These approaches reduce antibiotic dependency while maintaining animal health and productivity.

5. Biosecurity, Waste Valorization, and Environmental Management



Sustainability requires closing nutrient loops. Veterinary microbiology provides tools to both detect hazards and create value from waste.

5.1. Pathogen Monitoring in Recycled Water and Bedding

As livestock systems recycle lagoon water or composted bedding, microbial monitoring (e.g., qPCR for *E. coli* O157, *Listeria*) ensures safety, enabling water reuse and reducing freshwater withdrawal. Regular testing of environmental samples prevents the re-introduction of pathogens into the herd.

5.2. Anaerobic Digestion and Microbiome Management

Managing the microbial community in biogas digesters that process manure can optimize methane yield while simultaneously reducing pathogen load. For example, thermophilic digestion (50–60°C) achieves up to 99% reduction in *Ascaris* eggs and *Salmonella*. This transforms a waste liability into renewable energy (biogas) and a sanitized biofertilizer rich in nutrients.

5.3. Bioremediation of Antimicrobial Residues

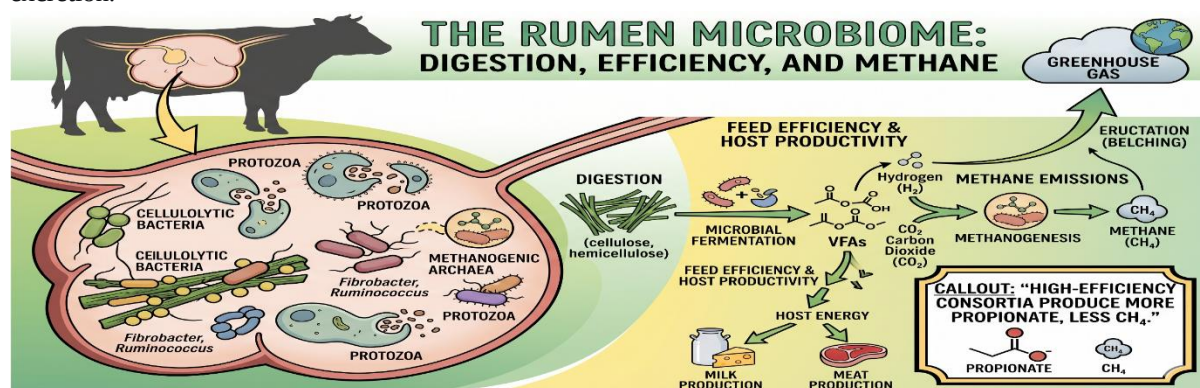
Certain soil bacteria (e.g., *Pseudomonas* spp.) can degrade residual antimicrobials and disinfectants present in manure, preventing their entry into the environment and reducing selection pressure for environmental AMR. Bioaugmentation of manure storage pits with such degraders is an emerging practice.

6. Gut Microbiome and Animal Productivity

The gastrointestinal microbiome plays a major role in digestion, immunity, metabolism, and feed conversion efficiency. Veterinary microbiology has revealed that managing this microbial ecosystem is central to sustainable production.

6.1. Importance of Gut Microbiota

Beneficial microbes improve nutrient absorption, enhance immunity (e.g., stimulating regulatory T cells), prevent pathogen colonization through competitive exclusion, and improve growth performance. Ruminants rely heavily on rumen microorganisms (bacteria, protozoa, fungi, and methanogenic archaea) for cellulose digestion and volatile fatty acid production. In monogastrics, the hindgut microbiota influences protein utilization and nitrogen excretion.



6.2. Probiotics in Livestock

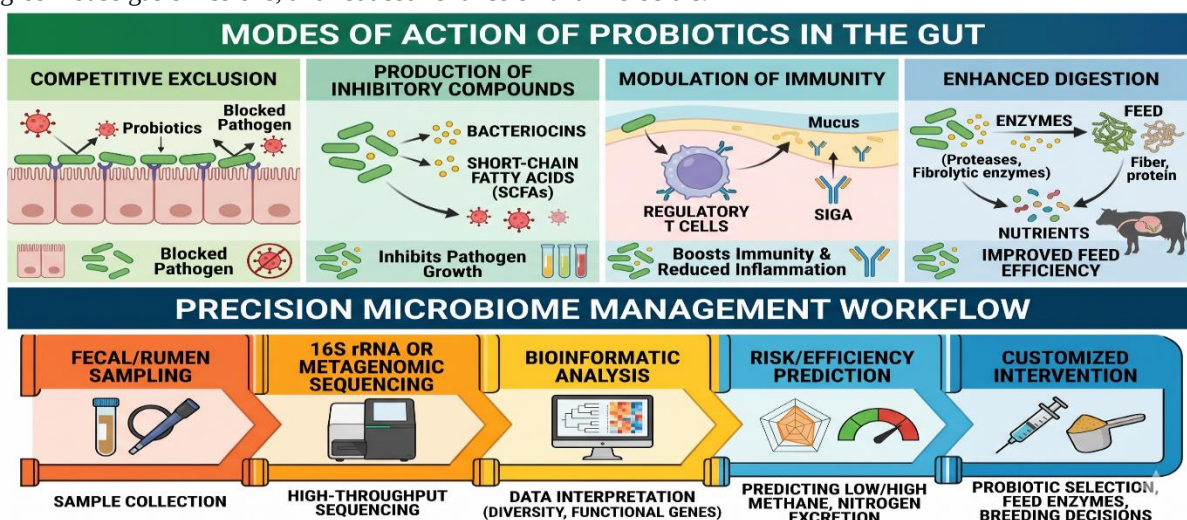
Probiotics are live beneficial microorganisms administered to improve intestinal microbial balance. Common probiotic organisms include *Lactobacillus* spp., *Bifidobacterium* spp., *Bacillus* spp., and *Saccharomyces cerevisiae* (yeast). Documented benefits include improved feed conversion ratio, better weight gain, reduced diarrhea (especially in young animals), enhanced immunity, and lower methane production in ruminants. For instance, probiotic strains of *Bacillus* or *Lactobacillus* have been shown to improve protein utilization, reducing nitrogen output by up to 20%.

6.3. Precision Microbiome Management

Advanced microbiome sequencing technologies (e.g., 16S rRNA amplicon sequencing, shotgun metagenomics) help design customized feeding and microbial management strategies for different livestock species. This includes:

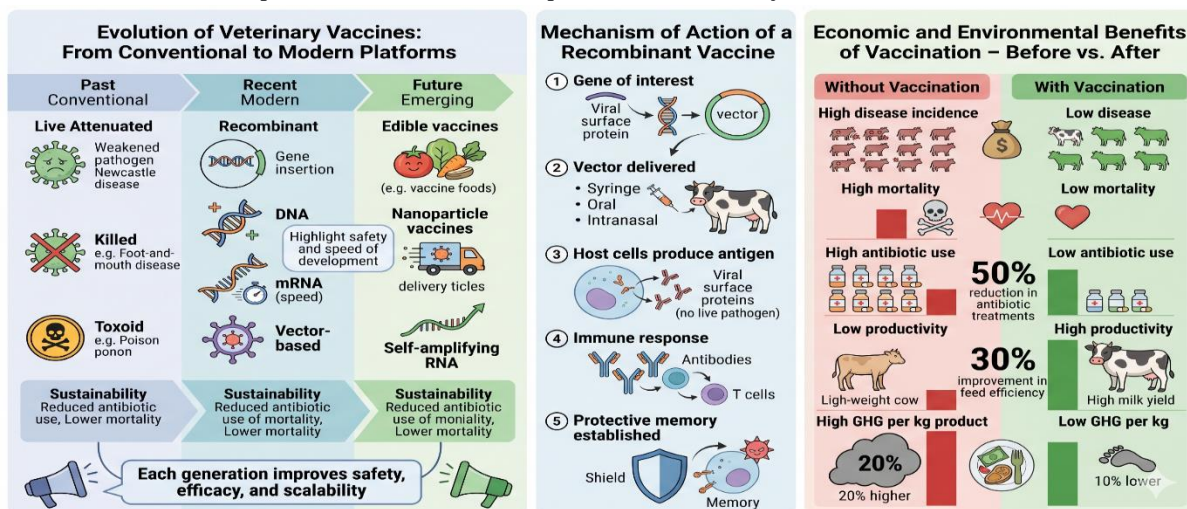
- Selecting animals with “high-efficiency” microbial consortia for breeding.
- Formulating precision feeds based on individual or herd microbial profiles.
- Supplementing with specific fibrolytic enzymes or exogenous microbes to unlock otherwise indigestible feed components (e.g., agricultural by-products), reducing competition for human-edible grains.

By integrating these approaches, sustainable livestock systems can achieve higher feed efficiency, lower greenhouse gas emissions, and reduced reliance on antimicrobials.



7. Vaccine Development and Immunization

Vaccination is one of the most sustainable disease prevention strategies in livestock production, as it reduces the need for antimicrobials, prevents outbreaks, and improves herd immunity.



7.1. Conventional Vaccines

Traditional vaccines have been widely used for decades and include live attenuated vaccines, killed (inactivated) vaccines, and toxoid vaccines. These are commonly applied against major livestock diseases such as foot-and-mouth disease, Newcastle disease, and haemorrhagic septicaemia. While effective, conventional vaccines may have limitations in safety (e.g., reversion to virulence in live vaccines) or duration of immunity.

7.2. Modern Vaccine Technologies

Recent microbiological advancements have led to the development of next-generation vaccine platforms, including recombinant vaccines, DNA vaccines, mRNA vaccines, vector-based vaccines, and edible vaccines. These modern technologies offer improved safety profiles, enhanced efficacy, and the potential for long-term immunity. For example, recombinant vaccines express specific immunogenic proteins without the need for live pathogens, while mRNA vaccines allow rapid design and production against emerging strains. Edible vaccines, expressed in plants, provide a low-cost, non-injectable delivery method suitable for large-scale livestock vaccination campaigns.

7.3. Economic and Environmental Benefits

Widespread vaccination reduces disease outbreaks, mortality rates, antibiotic use, and production losses (e.g., reduced weight gain, milk drop, and reproductive failure). By lowering the reliance on therapeutic antimicrobials, vaccination directly contributes to antimicrobial stewardship and reduces the selection pressure for antimicrobial resistance. Thus, vaccination supports both economic sustainability (higher productivity, lower veterinary costs) and environmental protection (fewer emissions per unit of product due to improved health and survival).

8. Veterinary Microbiology and Food Safety

Microbial contamination of animal products (meat, milk, eggs) poses a significant threat to human health. Veterinary microbiology plays a critical role in detecting, controlling, and preventing foodborne pathogens along the entire production chain.

8.1. Foodborne Pathogens

Important zoonotic pathogens that originate from livestock include *Salmonella* spp., pathogenic *Escherichia coli* (e.g., O157:H7), *Listeria monocytogenes*, and *Campylobacter* spp. These organisms can contaminate carcasses during slaughter, raw milk, or eggs, leading to human foodborne outbreaks. Veterinary microbiological surveillance in live animals helps identify carriers and subclinical shedders, enabling pre-harvest interventions.

8.2. Milk and Meat Hygiene

Microbiological testing ensures quality control and hygiene in dairy farms, slaughterhouses, poultry industries, and food processing units. Routine monitoring includes total bacterial counts, coliform counts, and specific pathogen detection (e.g., *Salmonella* enrichment, PCR for *Listeria*). Proper microbial monitoring improves consumer confidence, facilitates compliance with international food safety standards (e.g., Codex Alimentarius), and enhances export potential for animal products. Furthermore, whole-genome sequencing of isolates from food and animals enables precise source tracking during outbreak investigations, linking human cases back to farm or processing plant origins.

9. Environmental Sustainability and Waste Management

Livestock farming contributes significantly to greenhouse gas emissions (methane, nitrous oxide) and environmental pollution (ammonia, nitrate run-off, antimicrobial residues). Veterinary microbiology offers science-based solutions for eco-friendly livestock management.

9.1. Biogas Production

Anaerobic microorganisms, when managed in biogas digesters, convert livestock waste (manure, slurry) into biogas – a renewable energy source composed mainly of methane and carbon dioxide. The process reduces the organic load of waste, lowers odour emissions, and generates a nutrient-rich digestate that can be used as biofertiliser. By replacing fossil fuels, biogas production also mitigates climate change.

9.2. Microbial Decomposition and Composting

Microbial composting, carried out by aerobic bacteria, actinomycetes, and fungi, converts solid animal waste into stable, nutrient-rich organic manure. Proper composting reduces pathogen loads (e.g., *Salmonella*, *E. coli*),

kills weed seeds, and minimises greenhouse gas emissions compared to untreated manure storage. The resulting compost improves soil health, reduces the need for synthetic fertilisers, and closes nutrient loops on the farm.

9.3. Methane Reduction Strategies from Rumen Microbiomes

Enteric methane from ruminants is a major contributor to agricultural greenhouse gas emissions. Veterinary microbiology enables methane reduction through manipulation of the rumen microbiome. Strategies include:

- Dietary supplementation with probiotics (e.g., *Propionibacterium*, *Lactobacillus*) that redirect hydrogen away from methanogenesis toward propionate production.
- Use of methane inhibitors (e.g., 3-nitrooxypropanol, seaweed-derived bromoform) that specifically target methanogenic archaea.
- Breeding animals that naturally harbour low-methane microbial consortia.

These approaches help combat climate change while maintaining or even improving feed efficiency.

Section 9: Environmental Sustainability and Waste Management

Figure 1: Integrated Microbial Waste Valorization in Livestock Farms



Figure 2: Rumen Methanogenic Production and Mitigation Strategies

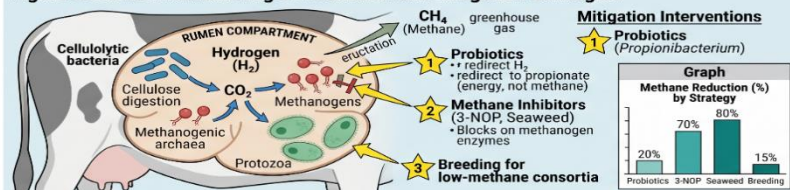


Figure 2: Rumen Methane Production and Mitigation Strategies

Figure 3: Comparative Greenhouse Gas Footprint: Conventional vs. Microbiologically-Optimized Manure Management

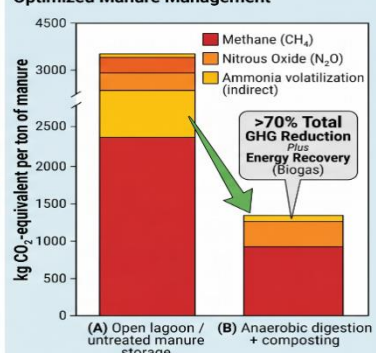


Figure 3: Comparative Greenhouse Gas Footprint: Conventional vs. Microbiologically-Optimized Manure Management

10. One Health Approach and Zoonotic Disease Control

The One Health concept recognizes the intrinsic interconnection between animal health, human health, and environmental health. This holistic framework is particularly relevant to sustainable livestock production, as the majority of emerging infectious diseases are zoonotic in origin. Veterinary microbiology contributes to the One Health approach through multiple pathways: monitoring zoonotic pathogens at the human–animal–environment interface, preventing disease transmission through early detection and biosecurity, supporting public health surveillance systems, and enhancing food safety systems to reduce foodborne zoonoses.

Emerging diseases such as avian influenza (e.g., H5N1, H7N9) and coronavirus-related infections (including SARS-CoV-2, which has been documented in farmed mink and deer) highlight the critical importance of integrated microbial surveillance systems that span human and animal health sectors. Veterinary microbiologists collaborate with public health agencies to detect spillover events, characterize pathogen genomics, and implement control measures. By embedding veterinary microbiology within a One Health framework, livestock systems can reduce zoonotic risks, protect farm workers and surrounding communities, and contribute to global health security.

11. Biotechnology and Advanced Innovations

Modern veterinary microbiology increasingly integrates biotechnology and digital tools to drive sustainable livestock improvement. These innovations enable more precise, rapid, and data-driven interventions.

11.1. Genomics and Metagenomics

High-throughput sequencing technologies have transformed veterinary microbiology. Genomics and metagenomics help identify disease-resistant breeds by linking specific genetic markers (e.g., major histocompatibility complex alleles) with resilience to infections. They also allow comprehensive analysis of microbial diversity in production environments, including the gut, rumen, and farm facilities. Furthermore, genomic surveillance enables scientists to understand pathogen evolution in real time, tracking the emergence of

new strains and antimicrobial resistance genes. These insights guide breeding programs, vaccine design, and biosecurity updates.

11.2. Nanotechnology

Nanotechnology offers novel solutions for livestock health and disease management. Nanoparticles are being used in drug delivery systems to improve the bioavailability and targeted release of antimicrobials or antiparasitics, thereby reducing the required dose and minimizing environmental residues. In vaccine enhancement, nanoparticles serve as adjuvants or delivery vehicles, improving immune responses and enabling mucosal administration (e.g., oral or intranasal). Additionally, nanoparticle-based biosensors provide rapid, field-deployable diagnosis of pathogens, allowing real-time detection of diseases such as mastitis or foot-and-mouth disease directly on the farm.

11.3. Artificial Intelligence and Digital Diagnostics

Artificial intelligence (AI) is revolutionizing microbial diagnostics and surveillance. Machine learning algorithms can analyse complex genomic, metagenomic, and epidemiological data to predict disease outbreaks before clinical cases appear. AI-based image recognition is being applied to interpret microbiological culture plates, Gram stains, and even electron microscopy images. When integrated with digital livestock farming platforms (e.g., sensor-based health monitoring), AI enables precision livestock farming where individual animals or groups receive tailored interventions based on real-time microbial risk assessments. These digital tools reduce diagnostic turnaround times, lower laboratory costs, and empower veterinarians and farmers to make evidence-based decisions that enhance both productivity and sustainability.

12. Challenges in Veterinary Microbiology for Sustainable Livestock Systems

Despite the significant advances and promising applications of veterinary microbiology, several challenges remain that limit its full integration into sustainable livestock production. Addressing these obstacles is essential for realizing the discipline's potential.

12.1. Infrastructural and Economic Barriers

Limited diagnostic infrastructure in rural and resource-limited areas constrains access to modern microbiological services. Many farms, particularly in low- and middle-income countries, lack nearby laboratories capable of performing PCR, sequencing, or even routine culture. The high cost of advanced technologies including metagenomic sequencers, bioinformatics platforms, and CRISPR-based diagnostic kits further restricts adoption, especially for smallholder farmers. Without affordable, field-deployable tools, the benefits of precision microbiology remain unevenly distributed.

12.2. Emerging Biological Threats

The continuing emergence of antimicrobial resistance (AMR) poses a dual challenge: it reduces the efficacy of existing treatments and accelerates the need for alternatives. Additionally, climate change is altering disease patterns, with rising temperatures and shifting precipitation facilitating the emergence and spread of novel pathogens (e.g., vector-borne diseases into previously temperate zones). Veterinary microbiology must therefore constantly adapt to new microbial threats.

12.3. Human and Social Factors

There is a notable lack of skilled manpower – including veterinary microbiologists, bioinformaticians, and farm-level technicians – in many regions. Coupled with poor awareness among farmers about the value of microbial diagnostics and alternatives to antibiotics, this hampers the uptake of sustainable practices. Overcoming these barriers requires interdisciplinary collaboration between microbiologists, veterinarians, agricultural economists, and extension services, as well as sustained government support and investment in veterinary research and education.

13. Future Prospects and Strategic Priorities

Veterinary microbiology has transcended its traditional diagnostic role to become a strategic enabler of sustainable livestock production. The evidence is clear: microbiome management, advanced diagnostics, phage therapy, and microbial waste treatment can concurrently improve animal welfare, reduce antimicrobial use, lower greenhouse gas emissions, and enhance profitability. To fully realize this potential, future research and policy should focus on the following priority areas.

13.1. Next-Generation Microbial Tools

- **Development of next-generation probiotics and precision microbiome engineering** (e.g., using synthetic biology to design microbial consortia with defined functions).
- **Rapid field diagnostic kits** including portable PCR devices, lateral flow assays, and smartphone-compatible biosensors that bring laboratory capabilities directly to the farm.
- **Bacteriophage therapy** as a mainstream alternative, with regulatory frameworks that recognize phages and next-generation probiotics as biologicals rather than chemical drugs, thereby accelerating approval and commercialisation.

13.2. Data-Driven and Climate-Resilient Systems

- **Climate-resilient disease surveillance systems** that integrate weather, landscape, and microbial data to predict emergence risks under changing climatic conditions.
- **AI-integrated microbial analytics** machine learning models that interpret metagenomic data in real time, providing actionable recommendations for feeding, biosecurity, and treatment.
- **Affordable, on-farm metagenomic tools** that democratise access to microbial insights for smallholders in low- and middle-income countries, closing the technology gap.

13.3. Standardisation and One Health Networks

- **Standardised microbiome-based indices** for feed efficiency and methane emission potential, integrated into breeding values and carbon credit schemes.
- **One Health microbial surveillance networks** that link human, animal, and environmental AMR data in real time, enabling early detection of resistance spillover and coordinated responses.

13.4. Sustainable Vaccine and Bioproduct Technologies

- **Sustainable vaccine production technologies** including plant-based (edible) vaccines, mRNA platforms, and cell-free synthesis that reduce production costs and environmental footprints.
- **Biorefinery approaches** for valorising livestock waste into high-value products (e.g., microbial protein, bioplastics) alongside biogas and fertiliser.

13.5. A Vision for 2040

The sustainable livestock system of 2040 will be managed not only by veterinarians and agronomists but also by microbial ecologists. Routine microbial profiling will be as common as temperature taking, and decisions on feed, breeding, and treatment will be guided by real-time metagenomic data. Investing in veterinary microbiology today through research funding, capacity building, and supportive regulation is the most cost-effective pathway to a resilient, low-carbon, and humane animal agriculture sector.

14. Conclusion

Veterinary microbiology plays a transformative role in sustainable livestock production systems by improving animal health, reducing disease burden, enhancing food safety, minimizing antibiotic dependence, and supporting environmental sustainability. Advances in microbial diagnostics, vaccines, microbiome research, and biotechnology have strengthened disease prevention and productivity enhancement strategies. Sustainable livestock production cannot be achieved without efficient microbial management and surveillance systems. Future research and policy support should prioritize microbiological innovations that align with One Health principles and climate-smart agriculture. By integrating veterinary microbiology into livestock management practices, the agricultural sector can ensure long-term productivity, public health safety, and environmental conservation.

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El Nino: Understanding Its Impact on Agriculture and Strategies for Climate Resilience



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Introduction

Climate variability has become one of the greatest challenges to global agriculture, directly influencing crop production, water resources, food security, and rural livelihoods. Among the various climatic phenomena that affect weather patterns worldwide, El Nino is one of the most significant. It is a naturally occurring ocean-atmosphere interaction in the tropical Pacific Ocean that alters rainfall distribution, temperature patterns, and atmospheric circulation across many parts of the world. Although El Nino originates thousands of kilometres away from India, its effects are felt across the Indian subcontinent through changes in the southwest and northeast monsoons, increased temperatures, prolonged dry spells, and greater climatic uncertainty.

India, where agriculture is largely dependent on seasonal rainfall, is particularly vulnerable to El Nino events. Variability in monsoon rainfall directly affects crop planning, sowing schedules, irrigation availability, and farm income. In states such as Tamil Nadu, where agriculture depends on both the Southwest Monsoon and the Northeast Monsoon, El Nino may disrupt agricultural activities in different ways. Understanding El Nino and adopting appropriate adaptation strategies are therefore essential for ensuring agricultural sustainability and food security.

What is El Nino?

El Nino is a climate phenomenon characterized by the abnormal warming of sea surface temperatures in the central and eastern equatorial Pacific Ocean. Under normal conditions, trade winds blow from east to west across the Pacific Ocean, pushing warm surface water toward Indonesia and Australia while allowing cold, nutrient-rich water to rise near the western coast of South America.

During an El Nino event, these trade winds weaken or even reverse. As a result, warm ocean water shifts eastward toward the central and eastern Pacific. This change alters atmospheric circulation, particularly the Walker Circulation, leading to significant changes in rainfall and temperature patterns across the globe.

El Nino usually develops every two to seven years and generally lasts between nine months and one year, although some events persist longer. Its intensity may be weak, moderate, or strong depending on the extent of ocean warming.

Difference Between El Nino and La Nino

El Nino represents the warm phase of the El Nino–Southern Oscillation (ENSO), whereas La Niña represents the cool phase. During El Nino, rainfall generally decreases in many parts of India, temperatures rise, and drought conditions become more likely. In contrast, La Nino is associated with cooler Pacific Ocean temperatures and often brings above-normal monsoon rainfall to India, although regional variations always exist.

Both phases significantly influence agriculture, but El Nino generally poses greater challenges because of its association with moisture stress and reduced water availability.

Impact of El Nino on Global Weather

The influence of El Nino extends far beyond the Pacific Ocean. It affects weather systems across Asia, Africa, Australia, and the Americas. Some regions experience droughts, while others receive excessive rainfall and floods. Increased frequency of heat waves, forest fires, cyclones, and changing storm tracks have also been linked to strong El Nino events.

These global impacts demonstrate the interconnected nature of Earth's climate system and highlight the importance of international climate monitoring.

Influence of El Nino on the Indian Monsoon

India receives nearly seventy percent of its annual rainfall from the Southwest Monsoon, which is crucial for agricultural production. Many historical droughts in India have coincided with El Nino years because the weakening of atmospheric circulation reduces monsoon rainfall over the Indian subcontinent.

Reduced rainfall delays sowing, lowers groundwater recharge, decreases reservoir storage, and limits irrigation water availability. Rain-fed crops become particularly vulnerable, while irrigated agriculture also faces challenges due to declining water resources.

However, the relationship between El Nino and the Indian monsoon is not absolute. Other climate systems, including the Indian Ocean Dipole (IOD), Madden-Julian Oscillation (MJO), and regional weather patterns, may strengthen or weaken El Nino's influence.

Impact on Agriculture

Agriculture is one of the sectors most severely affected during El Nino years. Delayed onset of monsoon rains often postpones sowing operations, shortening the effective growing season. Moisture stress during critical growth stages reduces germination, flowering, grain filling, and ultimately crop yield.

Crops such as rice, maize, pulses, sugarcane, cotton, and oilseeds may experience varying degrees of yield reduction depending on rainfall distribution and irrigation availability. Horticultural crops, plantation crops, and vegetables may also suffer due to increased evapotranspiration and water stress.

Livestock production is indirectly affected through reduced fodder availability, declining pasture productivity, heat stress, and limited drinking water. Fisheries may also experience changes in productivity because ocean warming alters marine ecosystems.

Impact on Coconut Cultivation

Coconut is highly sensitive to prolonged moisture stress. During El Nino years, reduced rainfall and increased temperatures decrease soil moisture availability, leading to reduced leaf production, button shedding, poor nut development, and lower nut yield. Severe drought conditions may weaken palms, making them more susceptible to pests such as rhinoceros beetle and red palm weevil, as well as diseases.

Intercrops cultivated under coconut gardens may also experience water stress unless efficient irrigation and mulching practices are adopted. Long-term drought can affect the economic sustainability of coconut-based farming systems.

Impact on Tamil Nadu Agriculture

Tamil Nadu presents a unique situation because it depends significantly on the Northeast Monsoon for agricultural production. El Nino may influence both monsoon seasons, although the effects vary from year to year. Reduced rainfall affects irrigation tanks, reservoirs, groundwater recharge, and river flows. Major crops such as paddy, millets, pulses, cotton, sugarcane, coconut, banana, and vegetables may experience reduced productivity under prolonged dry conditions. Farmers relying on rain-fed agriculture are particularly vulnerable.

Climate-Resilient Agricultural Practices

Climate-smart agriculture provides practical solutions for reducing the adverse impacts of El Nino. Crop diversification, drought-tolerant crop varieties, short-duration cultivars, efficient irrigation systems, and improved soil management enhance resilience against rainfall variability. Mulching, conservation tillage, rainwater harvesting, farm ponds, contour bunding, and watershed development improve soil moisture conservation and groundwater recharge. Integrated farming systems further reduce production risks by diversifying income sources.

Balanced fertilizer application based on soil testing, combined with organic manures and biofertilizers, improves soil structure and water-holding capacity, enabling crops to better withstand moisture stress.

Role of Government Institutions

The Government of India has implemented several programmes to strengthen climate resilience in agriculture. The Pradhan Mantri Krishi Sinchayee Yojana (PMKSY) promotes efficient irrigation through the principle of "Per Drop More Crop." The Pradhan Mantri Fasal Bima Yojana (PMFBY) provides crop insurance against weather-related losses. The National Mission for Sustainable Agriculture (NMSA) encourages resource conservation technologies, integrated farming systems, and climate-resilient agricultural practices.

The India Meteorological Department (IMD) continuously monitors El Nino conditions and provides seasonal monsoon forecasts, while the Indian Council of Agricultural Research (ICAR) develops drought-tolerant crop varieties and climate-resilient technologies through its network of research institutes.

State Agricultural Universities, Krishi Vigyan Kendras (KVKs), and the Department of Agriculture disseminate location-specific advisories, weather-based crop management practices, and farmer training programmes to enhance preparedness during El Nino years.

Role of Farmers

Farmers play a central role in adapting to climate variability. Adoption of weather-based crop planning, efficient irrigation techniques, integrated nutrient management, integrated pest management, and conservation agriculture reduces production risks. Crop diversification, agroforestry, and livestock integration further strengthen resilience and improve farm income under uncertain climatic conditions.

Regular monitoring of weather forecasts, timely sowing, use of certified drought-tolerant seeds, and participation in crop insurance schemes enable farmers to minimize climate-related losses.

Way Forward

Managing the impacts of El Nino requires coordinated efforts involving scientists, policymakers, extension agencies, and farming communities. Continued investment in climate research, improved seasonal forecasting, digital advisory services, resilient infrastructure, and sustainable natural resource management will be essential for strengthening agricultural resilience.

Promotion of precision agriculture, remote sensing, artificial intelligence, and decision-support systems can further improve climate risk management. Community participation in water conservation and sustainable land management will also play a vital role in adapting to future climate variability.

Conclusion

El Nino is a recurring global climate phenomenon with profound implications for agriculture, water resources, and food security. Although its occurrence cannot be prevented, its impacts can be minimized through scientific planning, climate-resilient agricultural practices, efficient water management, and timely dissemination of weather advisories. Strengthening the collaboration between research institutions, government agencies, extension services, and farmers will be critical for enhancing resilience against climatic uncertainties. By integrating modern technologies with sustainable farming practices, agriculture can continue to remain productive even under changing climatic conditions, ensuring food security and improved livelihoods for future generations.

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Climate-Smart Farming: Adapting Cropping Patterns for a Resilient Future

"Farming no longer follows the calendar—it follows the climate."



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Abstract

Agricultural stability depends directly on consistent climatic conditions. However, the rapid pace of climate change is disrupting traditional farming systems across the world. Global Warming, irregular rainfall, prolonged droughts, unexpected floods, and increasing incidences of pests and diseases are altering cropping patterns and threatening food security. In India, where millions of livelihoods depend on agriculture, climate variability is emerging as one of the most significant challenges posing for farming community. Karnataka, with its extensive rainfed agricultural areas, is particularly vulnerable to these changes. Farmers are increasingly modifying crop choices, sowing schedules, irrigation practices, and farm management strategies to cope with climatic uncertainty. This article examines the impact of climate change on cropping patterns, highlights emerging adaptation strategies, and discusses the role of climate-smart agriculture in ensuring sustainable agricultural development. It argues that while climate change presents unprecedented challenges, it also offers opportunities for innovation, resilience, and transformation within the agricultural sector.

Keywords: Climate Change, Cropping Patterns, Climate Resilience, Sustainable Agriculture, Climate-Smart Agriculture, Food Security

Introduction: Agriculture at a Crossroads

Agriculture has traditionally been guided by the predictable rhythms of nature. Farmers relied on seasonal cycles, established rainfall patterns, and local ecological knowledge of crop selection and appropriate cultivation timing. These patterns remained relatively stable for generations, enabling farming communities to develop production systems suited to their local environments. Agricultural calendars were passed from one generation to the next, and farmers could generally predict the onset of monsoon rains, the duration of growing seasons, and the timing of harvests.

Today, however, this predictability is rapidly disappearing. Climate change has emerged as one of the most significant threats to agriculture, disrupting long-established farming practices and creating new uncertainties for farmers. Scientific evidence suggests that the Earth's average temperature has increased considerably over the last century, primarily due to anthropogenic interventions such as deforestation, industrialization, and extensive fossil fuels emissions. This warming trend has triggered changes in precipitation patterns, increased the frequency of extreme weather events, and altered ecological systems worldwide.

Agriculture in India is not merely an occupation but a lifeline, supporting close to half of the nation's people directly or indirectly, the implications are profound. Agriculture contributes significantly to food security, rural employment, and economic development. Yet it remains highly sensitive to climatic conditions. A slight delay in rainfall, an unexpected heatwave, or excessive rainfall during harvest can significantly reduce crop yields and farmer incomes. As climate variability intensifies, agriculture is increasingly becoming a high-risk enterprise.

In Karnataka, the situation is particularly challenging. The state encompasses diverse agro-climatic zones ranging from coastal regions to arid inland areas. More than two-thirds of Karnataka's cultivated area depends on rainfall rather than assured irrigation. Consequently, fluctuations in weather patterns have direct and often severe consequences for agricultural productivity. Farmers who once relied on traditional knowledge are now finding that historical weather patterns no longer provide reliable guidance. As a result, climate change is forcing a fundamental rethinking of agricultural practices and cropping patterns across the state.

Understanding Climate Change and Its Agricultural Implications

Climate change refers to long-term alterations in temperature, precipitation, wind patterns, and other climatic variables. While climate has naturally varied throughout Earth's history, the current rate of change is unprecedented and largely driven by human activities. The accumulation of greenhouse gases such as carbon dioxide, methane, and nitrous oxide in the atmosphere has intensified the greenhouse effect, causing global temperatures to rise.

Agriculture is uniquely vulnerable to these changes because crop growth depends directly on environmental conditions. Temperature influences photosynthesis, flowering, and grain development. Rainfall determines soil moisture availability and irrigation requirements. Humidity affects pest and disease dynamics, while extreme weather events can destroy crops within hours.

The agricultural impacts of climate change are multifaceted. Rising temperatures accelerate crop development, shortening the growing period and reducing yields. Increased evaporation leads to greater water demand, placing additional pressure on already scarce water resources. Changes in rainfall distribution affect planting schedules and crop establishment. Furthermore, extreme weather events such as droughts, floods, cyclones, and heatwaves are becoming more frequent and severe, increasing production risks for farmers.

The consequences extend beyond crop production. Livestock systems are also affected by heat stress, reduced fodder availability, and changing disease patterns. Fisheries face challenges due to warming water temperatures and altered aquatic ecosystems. Together, these impacts threaten farming livelihoods, food security, and economic stability.

The Changing Face of Rainfall: When Monsoons Become Unpredictable

Among the most visible manifestations of climate change is the increasing unpredictability of rainfall. The Indian monsoon, often described as the lifeline of Indian agriculture, has traditionally provided the water necessary for crop cultivation across vast areas of the country. For generations, farmers have synchronized their agricultural activities with the arrival and progression of monsoon rains.

Recent decades, however, have witnessed significant changes in monsoon behavior. Rainfall is becoming increasingly erratic, characterized by delayed onset, early withdrawal, prolonged dry spells, and intense rainfall events. Instead of receiving moderate rainfall spread over several weeks, many regions now experience heavy downpours concentrated within short periods. Such rainfall often leads to runoff and flooding rather than effective soil moisture recharge.

For farmers, this variability creates substantial challenges. Delayed monsoon onset can postpone sowing operations, reducing the effective growing season. Excessive rainfall during crop establishment may damage seedlings and increase disease incidence. Conversely, dry spells during critical growth stages can lead to moisture stress and yield reduction. Heavy rainfall near harvest can damage mature crops and reduce grain quality.

In Karnataka, rainfall variability has become increasingly evident. Districts that previously experienced relatively stable rainfall patterns are now facing greater uncertainty. Rainfed farmers often struggle to decide when to sow crops, as traditional indicators are becoming unreliable. This uncertainty increases production risks and affects investment decisions, particularly among small and marginal farmers.

Rising Temperatures and Their Impact on Crop Productivity

While rainfall receives considerable attention, increasing temperatures are equally important in shaping agricultural outcomes. Global average temperatures have risen significantly over the past century, and projections indicate further increases in the coming decades.

Temperature influences virtually every aspect of crop growth and development. Most crops have specific temperature ranges within which they perform optimally. When temperatures exceed these thresholds, physiological processes are disrupted, resulting in reduced productivity.

High temperatures accelerate crop maturation, reducing the duration available for grain filling. Although crops may reach maturity more quickly, the resulting grains are often smaller and lighter, leading to yield reductions. Heat stress during flowering is particularly damaging, as it can reduce pollination success and increase flower abortion.

In crops such as wheat, rice, maize, and pulses, elevated temperatures have been associated with substantial yield losses. Heatwaves occurring during critical growth stages can devastate entire fields within days. Horticultural crops are similarly affected, with high temperatures reducing fruit quality, causing sunburn, and affecting marketability.

Farmers across Karnataka increasingly report experiencing unusually high temperatures during both kharif and rabi seasons. These conditions not only affect crop growth but also increase irrigation requirements, production costs, and labor challenges.

Climate Change and the Transformation of Cropping Patterns

One of the most significant responses to climate change has been the transformation of cropping patterns. Cropping patterns refer to the proportion of area allocated to different crops within a region. Traditionally, these patterns evolved in response to climatic conditions, soil characteristics, water availability, and market demand. As climatic conditions change, farmers are reassessing the suitability of various crops. In many regions, traditional cropping systems are becoming increasingly difficult to sustain. Water-intensive crops such as paddy and sugarcane face growing challenges in drought-prone areas. Farmers are therefore shifting towards crops that require less water and exhibit greater tolerance to climatic stress.

The revival of millets represents one of the most notable examples of this transformation. Once considered "coarse grains" and often neglected in favor of rice and wheat, millets are now gaining renewed attention. Crops such as ragi, jowar, bajra, foxtail millet, and little millet are naturally adapted to dry conditions and can produce reasonable yields under moisture stress.

In Karnataka, the renewed interest in millets reflects both necessity and opportunity. Farmers recognize that these crops offer greater resilience under uncertain climatic conditions. Additionally, increasing consumer demand for nutritious and climate-resilient foods has created new market opportunities. The promotion of millets through government programs and international initiatives has further strengthened their importance within climate adaptation strategies.

Pest and Disease Dynamics in a Warming World

Climate change is also reshaping pest and disease dynamics in agricultural systems. Rising temperatures and changing humidity levels create favorable conditions for many insects, pathogens, and weeds.

Warmer temperatures often accelerate pest development and reproduction, enabling populations to increase more rapidly. Some pests are expanding their geographical range, appearing in regions where they were previously absent. Similarly, changing environmental conditions influence the prevalence and severity of plant diseases.

Farmers increasingly encounter pest outbreaks that are difficult to predict and manage. New pest species are emerging, while traditional control measures may become less effective under changing climatic conditions. Increased pesticide use raises production costs and environmental concerns, further complicating agricultural sustainability.

The challenge is particularly acute for smallholder farmers who may lack access to timely information, resistant varieties, and integrated pest management technologies.

Climate-Smart Agriculture: Building Resilience for the Future

In response to growing climatic challenges, climate-smart agriculture has emerged as a comprehensive framework for sustainable agricultural development. Climate-smart agriculture seeks to enhance productivity, strengthen resilience, and reduce greenhouse gas emissions simultaneously.

The approach emphasizes efficient resource use, diversified farming systems, and adaptive management practices. Farmers are encouraged to adopt technologies and practices that improve their ability to cope with climatic variability while maintaining productivity.

Integrated farming systems, agroforestry, conservation agriculture, precision farming, and water-efficient irrigation technologies all form important components of climate-smart agriculture. These approaches not only reduce vulnerability to climatic shocks but also contribute to environmental sustainability.

In Karnataka, climate-smart agriculture is gaining momentum through research initiatives, extension programs, and government interventions. Demonstrations conducted by agricultural universities, Krishi Vigyan Kendras, and development agencies are helping farmers understand and adopt resilient farming practices.

Farmers as Innovators: Adaptation from the Ground Up

Perhaps the most encouraging aspect of climate adaptation is the ingenuity demonstrated by farmers themselves. Across Karnataka and India, farmers are developing innovative solutions to address climatic challenges.

Many farmers are adjusting sowing dates based on weather forecasts rather than traditional calendars. Others are adopting drought-tolerant varieties, diversifying crop portfolios, constructing farm ponds, and investing in micro-irrigation systems. Some have integrated livestock, horticulture, and agroforestry into their farming enterprises to reduce dependence on a single source of income.

These adaptations illustrate that farmers are not passive victims of climate change. Rather, they are active agents of change who continuously experiment, learn, and innovate in response to emerging challenges.

Conclusion: The Future of Farming in a Changing Climate

Climate change is fundamentally altering the agricultural landscape. Traditional cropping patterns, long-established farming practices, and historical climatic assumptions are increasingly being challenged by new environmental realities. Rising temperatures, erratic rainfall, and frequent extreme weather events have introduced unprecedented uncertainty into agricultural systems.

Yet the story of agriculture under climate change is not solely one of vulnerability. It is also a story of resilience, adaptation, and innovation. Farmers across Karnataka and India are responding by modifying cropping patterns, adopting climate-resilient crops, embracing new technologies, and implementing sustainable farming practices.

The future of agriculture will depend on the collective efforts of farmers, researchers, policymakers, extension agencies, and consumers. Investments in climate-resilient technologies, improved weather services, sustainable water management, and farmer-centered extension systems will be essential. Equally important is the recognition and support of local innovations that emerge from farming communities themselves.

As the climate continues to change, agriculture must evolve accordingly. The farms that thrive in the future will not necessarily be the largest or most mechanized, but those that are most adaptable, resilient, and capable of learning from a changing environment. Climate change may have altered the rules of farming, but with knowledge, innovation, and collective action, farmers can continue to feed the world while safeguarding the environment for future generations.

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From Traditional to Smart Farming: A Review of the Role of ICT in Agricultural Transformation



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Abstract

The integration of Information and Communication Technologies (ICTs) has emerged as a cornerstone for modernizing global agriculture, offering transformative potential to address food security and environmental sustainability. This review article synthesizes current advancements in smart farming, focusing on the role of the Internet of Things (IoT), Artificial Intelligence (AI), and Unmanned Aerial Vehicles (UAVs) in optimizing agricultural production. By analyzing recent research, this study highlights how these technologies enhance resource management, increase crop yields, and foster economic empowerment for smallholder farmers. However, the review also critically examines persistent barriers to widespread adoption, including infrastructural deficits, the digital skills gap, and socio-technical misalignment. The article concludes that achieving a sustainable digital agricultural transformation requires not only technological innovation but also policy-driven, context-specific interventions that prioritize inclusivity and the development of resilient, low-power digital ecosystems.

Keywords: ICT in Agriculture; Smart Farming; Precision Agriculture; Digital Transformation; Internet of Things (IoT); Artificial Intelligence (AI); Unmanned Aerial Vehicles (UAVs); Agricultural Sustainability; Smallholder Farmers; Digital Divide.

Introduction

Global agriculture is currently at a crossroads. By 2050, the agricultural sector must increase output significantly to feed a growing global population while simultaneously reducing its environmental footprint under the pressures of climate change. Traditional farming methods, often characterized by manual labor and suboptimal resource utilization, are proving insufficient to meet these complex demands. Consequently, the adoption of Information and Communication Technologies (ICTs) has initiated a paradigm shift toward "Smart Farming" a data-driven, precision-oriented approach to cultivation. ICTs in agriculture encompass a broad spectrum of digital tools, including mobile applications, sensor-based monitoring, satellite imagery, and advanced data analytics. These technologies facilitate the move from "gut-feeling" farming to precision agriculture, where interventions are applied with spatial and temporal accuracy. While developed nations have made strides in high-tech farming, the narrative is evolving in developing regions where mobile-based "e-extension" services are bridging the gap between farmers and critical information on weather, market prices, and pest control. This review explores the technological drivers of this transformation, analyzes the empirical impact of ICTs on farm-level outcomes, discusses the persistent socio-economic barriers to adoption, and outlines a future agenda for equitable digital development.

Key Technological Drivers

Modern "Smart Farming" relies on a synergetic integration of several core technologies:

- **Internet of Things (IoT):** IoT provides the backbone of connectivity by utilizing networks of sensors, actuators, and cloud platforms to monitor soil moisture, crop health, and climate conditions in real-time (Dhanaraju et al., 2022; Miller, 2025).
- **Artificial Intelligence (AI) and Machine Learning (ML):** AI algorithms, including Convolutional Neural Networks (CNNs) and Support Vector Machines (SVMs), process vast quantities of agricultural data to provide predictive insights, such as early disease detection, optimized fertilization, and yield forecasting (Miller, 2025).
- **Unmanned Aerial Vehicles (UAVs):** Drone technology has revolutionized precision agriculture, particularly in pesticide application and large-scale land monitoring, leading to a "low-carbon" reduction in chemical inputs (Deng et al., 2024).

Impact on Agricultural Outcomes

The adoption of ICT-based "e-extension" services has demonstrated significant positive impacts across diverse farming landscapes:

1. **Productivity and Efficiency:** By bridging the information gap, ICTs facilitate the adoption of good agricultural practices (GAP). A systematic review indicates that approximately 74% of evaluated studies observed higher yields among ICT users (Mulungu *et al.*, 2025).
2. **Resource Management:** Precision irrigation and site-specific nutrient management—powered by sensor networks—allow for the drastic reduction of water and energy waste (Dhanaraju *et al.*, 2022; Miller, 2025).
3. **Economic Empowerment:** Digital platforms help smallholder farmers reduce information asymmetry, enabling better access to market prices and financial services, which directly contributes to increased income (Mulungu *et al.*, 2025; Xaba, 2025).

Barriers to Adoption

Despite these advancements, widespread adoption remains uneven, particularly in developing regions:

- **Infrastructure and Cost:** High costs of devices and data, coupled with unreliable electricity and internet connectivity (load-shedding), remain primary barriers in Sub-Saharan Africa and other rural regions (Nyakudya *et al.*, 2024; Xaba, 2025).
- **Digital Skills Gap:** Low literacy levels and limited digital competency prevent many farmers from navigating complex mobile applications and data-driven interfaces (Dhehibi *et al.*, 2023; Xaba, 2025).
- **Socio-Technical Constraints:** Technology must be "contextualized." A lack of compatibility between generalized ICT tools and local cropping systems, farming styles, or socio-economic realities often leads to low adoption rates (Dhehibi *et al.*, 2023; Mulungu *et al.*, 2025).

Future Outlook

The path forward requires moving beyond simple technology dissemination toward the development of inclusive, low-power, and resilient systems. Future research must prioritize "low-power AI models" and hardware that can withstand harsh, off-grid environmental conditions (Miller, 2025). Furthermore, policymakers must focus on targeted interventions that bridge the digital divide, ensuring that even small-scale farmers have the training and infrastructure required to participate in the modern digital agricultural ecosystem.

Conclusion

The digital transformation of agriculture represents a powerful mechanism to increase productivity and sustainability, yet its full potential remains untapped. The current evidence base confirms that ICT tools—ranging from IoT-enabled sensor networks to AI-driven predictive analytics—are highly effective in reducing waste, increasing efficiency, and connecting farmers to essential markets. Despite these tangible benefits, the disparity in adoption rates between regions underscores that technology alone is not a panacea.

The primary constraints to scaling these innovations remain rooted in inadequate rural infrastructure, the high cost of entry, and the need for localized, user-centric interfaces that cater to diverse literacy and farming levels. Moving forward, the agricultural sector must pivot toward the development of "low-power," cost-effective, and highly resilient technologies designed for the unique challenges of off-grid rural environments. Ultimately, the successful integration of ICTs will depend on a multi-stakeholder approach where governments, the private sector, and research institutions collaborate to bridge the digital divide, ensuring that the fruits of the technological revolution are accessible to all farmers, regardless of their scale of operation or geographic location.

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Economics of AI (Artificial Intelligence)



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Abstract

Artificial Intelligence is transforming economic systems by enhancing productivity, enabling innovation and reshaping how resources are allocated. Artificial Intelligence influences production efficiency, labour markets, pricing strategies and global competitiveness. The economics of Artificial Intelligence focuses on understanding these impacts while addressing challenges such as inequality, job displacement, ethical concerns and environmental sustainability. With rapid technological advancements, Artificial Intelligence is becoming a key driver of economic growth and structural transformation. This article provides a comprehensive analysis of Artificial Intelligence and its economic role, including its impact on productivity, employment, market structures, infrastructure, governance and future development pathways.

Introduction

Artificial Intelligence has become a significant driver of economic development by improving productivity, efficiency, and innovation across various sectors. It enables businesses to automate routine tasks, optimize resource utilization, reduce operational costs, and enhance decision-making through advanced data analysis. Artificial Intelligence contributes to economic growth by increasing competitiveness, creating new business opportunities, and promoting technological advancement. As the adoption of Artificial Intelligence continues to expand, it is transforming industries, influencing labor markets, and encouraging governments and organizations to develop policies that maximize its economic benefits while addressing challenges such as job displacement, skill development, and income inequality.

Artificial Intelligence refers to the simulation of human intelligence in machines that can learn, reason, and make decisions. In recent years, Artificial Intelligence has evolved from a theoretical concept into a practical tool widely used in everyday life and business operations. Its applications range from voice assistants and recommendation systems to advanced robotics and predictive analytics. In economic terms, Artificial Intelligence is considered a transformational technology that can significantly increase efficiency and output. It allows firms to analyse vast amounts of data quickly, improve the accuracy of decision-making, and reduce human errors. Artificial Intelligence-driven systems also enable faster innovation cycles, allowing businesses to adapt quickly to changing market conditions. Moreover, Artificial Intelligence contributes to economic development by improving public services such as healthcare diagnostics, traffic management, and agricultural planning. However, the uneven distribution of Artificial Intelligence technologies across regions may widen the gap between developed and developing economies, making inclusive access to Artificial Intelligence a critical issue.

Artificial Intelligence as a Factor of Production

Artificial Intelligence is increasingly recognized as a fifth factor of production, alongside land, labor, capital and entrepreneurship. It enhances the productivity of all other factors by improving efficiency and reducing wastage. For example, Artificial Intelligence can optimize land use in agriculture, enhance labor productivity through automation and improve capital utilization by reducing downtime in machines. A key feature of Artificial Intelligence is its dependence on data as an input. Data has become a valuable economic asset, often referred to as “the new oil.” Companies that possess large datasets and advanced Artificial Intelligence capabilities gain a competitive advantage in the market. However, this also raises concerns about data monopolies, where a few large firms dominate the market due to their control over data and technology. To address this, governments must ensure fair competition and promote open access to data where appropriate.

Artificial Intelligence, Productivity, and Economic Growth

Artificial Intelligence plays a significant role in enhancing Total Factor Productivity (TFP), which measures the efficiency of all inputs in the production process by automating repetitive tasks and improving decision-making. Artificial Intelligence reduces production costs and increases output. In addition to efficiency gains, Artificial Intelligence drives innovation-led growth by enabling the development of new products and services. For instance, AI-powered healthcare solutions can detect diseases early, while financial technologies improve risk assessment and fraud detection. Artificial Intelligence also supports resource optimization ensuring that inputs such as energy, water and raw materials are used efficiently. However, the benefits of productivity growth may be concentrated in specific industries leading to unequal economic development.

Artificial Intelligence and Labor Market Transformation

Artificial Intelligence is reshaping the labour market by change the nature of work. Routine and repetitive tasks are increasingly being performed by automated systems. In contrast, jobs requiring creativity, critical thinking, and technical skills are expanding rapidly. This leads to job polarization, where demand increases for high-skilled and low-skilled jobs, but declines for middle-skilled jobs. Artificial Intelligence also encourages the rise of the gig economy, where workers engage in short-term, flexible jobs through digital platforms. While this provides opportunities for income generation, it may also lead to job insecurity and lack of social protection. Governments and institutions should prioritize investments in education, training, and skill development to overcome these challenges. Continuous learning and digital literacy are crucial for helping workers adapt to the changing demands of an AI-driven economy.

Cost Structures and Market Dynamics in Artificial Intelligence Economy

Artificial Intelligence changes traditional cost structures by involving high fixed costs and low marginal costs. Developing Artificial Intelligence systems requires substantial investment in research, software, and infrastructure, but once low marginal cost. This creates to economies of scale, allowing large firms to dominate the market. As a result, Artificial Intelligence markets often exhibit winner-takes-all dynamics, in which a small number of companies control a significant share of the market. Artificial Intelligence also enables dynamic and personalized pricing by adjusting prices based on consumer behaviour, preferences, and demand patterns. While this enhances market efficiency, it also raises concerns regarding consumer privacy and fairness in pricing.

Artificial Intelligence Infrastructure and Digital Economy

The growth of Artificial Intelligence depends on strong digital infrastructure, including cloud computing, data centers, high-speed internet, and advanced hardware. These components enable the storage, processing, and analysis of large datasets required for Artificial Intelligence systems. Artificial Intelligence has accelerated the expansion of the digital economy, which includes e-commerce, online services, digital payments, and platform-based businesses. These platforms lower transaction costs, enhance market accessibility, and facilitate more efficient connections between producers and consumers. However, the digital divide continues to be a significant challenge, as areas with inadequate infrastructure may not fully benefit from these technologies. Addressing this gap is essential to promote inclusive and sustainable economic growth.

Ethical, Social, and Environmental Implications

Artificial Intelligence raises important ethical issues, including data privacy, algorithmic bias, and accountability. Artificial Intelligence systems may be trained biased outcomes if trained on biased data, leading to discrimination in areas such as employment and finance. Socially concerns include the potential for increased inequality, as those with access to Artificial Intelligence technologies benefit more than others. Ensuring fairness and inclusivity in Artificial Intelligence development is therefore essential. From an environmental perspective, Artificial Intelligence systems require significant energy for data processing and storage, promoting area artificial intelligence through energy efficient algorithms and the use of renewable energy can help make artificial intelligence more sustainable.

Policy, Regulation, and Governance of Artificial Intelligence

Effective governance is essential to maximize the benefits of artificial intelligence while minimizing risk. Governments should develop policies that encourage innovation while ensuring ethical and responsible use of Artificial Intelligence. Key policy areas include data protection laws, cyber security regulations, and competition

policies. Governments should also support research and development through funding and incentives. International cooperation is necessary to addressing global challenges such as cross-border data governance Artificial Intelligence standards and the responsible use of Artificial Intelligence worldwide.

Future Trends and Economic Outlook of Artificial Intelligence

The future of Artificial Intelligence economics is shaped by continuous innovation and integration across sectors. Emerging trends include autonomous vehicles, smart cities, Artificial Intelligence-powered healthcare and intelligent manufacturing systems. Advanced technologies such as edge computing, quantum computing and artificial general intelligence (AGI) are expected to further transform economic systems. Artificial Intelligence will also play a significant role in addressing global challenges such as climate change, food security and public health. Ensuring a just and inclusive transition to an Artificial Intelligence -driven economy is essential. Policymakers must focus on reducing inequality, supporting displaced workers and promoting equitable access to Artificial Intelligence technologies.

India Artificial Intelligence Impact (2026)

In 2026, Artificial Intelligence is expected to play an increasingly important role in India's economic growth by improving productivity, innovation and public service delivery. Artificial Intelligence adoption is expanding across agriculture, healthcare, manufacturing, finance and education, enabling better decision-making and resource utilization. Government initiatives promoting digital infrastructure and Artificial Intelligence research are accelerating technology adoption. As a result, Artificial Intelligence is strengthening India's digital economy and creating new opportunities for skilled employment.

India's Strategic Edge with Artificial Intelligence

India possesses a strong strategic advantage in Artificial Intelligence due to its large skilled workforce, expanding digital infrastructure, and globally recognized information technology sector. The availability of vast digital data, increasing startup activity, and supportive government policies has further accelerated Artificial Intelligence development. By investing in research, innovation, and workforce up skilling, India is well positioned to become a global leader in Artificial Intelligence-driven economic transformation. This strategic advantage is expected to enhance competitiveness and support long-term sustainable growth.

Conclusion

The economics of artificial intelligence provides valuable insights into how Artificial Intelligence is transforming modern economies. It enhances productivity, drives innovation and creates new opportunities, but also presents challenges related to employment, inequality and ethical concerns. A balanced approach that combines technological advancement with effective policies, education and sustainability measures is essential for maximizing the benefits of Artificial Intelligence. By promoting responsive innovation inclusive growth and strong governance, societies can harness the full potential of Artificial Intelligence to achieve long-term economic development social welfare and sustainable progress.

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Agriculture Graduates in Karnataka: Between Dreams and Reality



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Abstract

Agriculture has long been portrayed as a foundational sector for economic development and food security, yet agriculture graduates in Karnataka face a paradox between aspirational career ideals and practical realities. Every year, agricultural universities across the state produce thousands of graduates equipped with scientific knowledge, practical skills, and aspirations to contribute to agricultural development. Most students enter agricultural education with dreams of becoming agricultural officers, scientists, extension professionals, or successful agripreneurs. However, the reality after graduation often presents a different picture. Limited government employment opportunities, increasing competition, skill gaps, and changing industry demands create significant challenges for many graduates. At the same time, agriculture is undergoing a remarkable transformation driven by technology, agribusiness, digital innovations, climate-smart farming, and entrepreneurship. These developments are opening new avenues for educated youth. This article examines the current situation of agriculture graduates in Karnataka, explores the challenges they face, discusses emerging opportunities, and highlights the role of education, policy, and innovation in shaping their future. The article argues that agriculture graduates are not merely job seekers but potential drivers of rural transformation and sustainable agricultural development.

Keywords: Agriculture graduates, Karnataka, agricultural education, agribusiness, employability, entrepreneurship, digital agriculture, rural development, agricultural careers.

Introduction

Agriculture has always occupied a special place in Karnataka's economy, culture, and society. From the paddy-growing regions of southern Karnataka to the millet-producing drylands of the north, agriculture shapes the lives of millions of people. The state is also recognized for its achievements in horticulture, sericulture, coffee cultivation, dairy farming, and plantation crops. Despite rapid urbanization and industrial growth, agriculture continues to provide livelihoods to nearly half of the state's population.

Behind Karnataka's agricultural progress stands a large network of educational institutions dedicated to developing skilled human resources for the sector. Universities such as the University of Agricultural Sciences (Bengaluru, Dharwad, and Raichur) and Keladi Shivappa Nayaka University of Agricultural and Horticultural Sciences-Shivamogga have played a crucial role in producing agricultural professionals who contribute to farming, teaching, research, extension, agribusiness, and rural development.

Over the last decade, agricultural education has become increasingly popular among youth. Growing concerns about climate change, food security, environmental sustainability, and agricultural modernization have enhanced the importance of agriculture as a professional discipline. Students across rural and urban areas increasingly choose agricultural studies not only to enhance their own economic prospects but also to contribute knowledge, innovation, and services that uplift farming families and rural communities.

However, the journey after graduation is often filled with uncertainty. While agriculture graduates possess valuable scientific knowledge and practical skills, they frequently encounter difficulties in securing suitable employment. Government jobs remain the most preferred career option, but vacancies are limited and competition is intense. At the same time, private-sector opportunities are expanding but require a different set of skills and expectations. This contrast between aspiration and reality defines the contemporary experience of many agriculture graduates in Karnataka.

The Growing Attraction of Agricultural Education

A decade ago, agriculture was often considered a second-choice option by many students. Today, the situation has changed significantly. Agricultural courses attract large numbers of applicants every year, particularly from rural areas. Reports indicate that more than one lakh students compete annually for a limited number of seats available in State Agricultural Universities (SAUs).

Several factors have contributed to this growing interest. Increasing awareness about climate change and environmental sustainability has highlighted the importance of agriculture in addressing global challenges. Government initiatives promoting farming, food security, and rural development have also improved the visibility of agricultural professions. Furthermore, advancements in biotechnology, precision farming, digital agriculture, and food processing have broadened career opportunities beyond traditional farming.

Agricultural education today covers a wide range of disciplines, including Agronomy, Horticulture, Soil Science, Genetics & plant breeding, Agricultural Engineering, Agricultural Economics, Extension Education, Biotechnology, and Food Technology. Students gain practical exposure through laboratory work, field visits, Rural Agricultural Work Experience (RAWE) Programme, Internship attachments in Agro - Industries, Experiential Learning Programme and Study Tours. These experiences help them empathise the realities of agricultural production and rural development.

Yet, despite this growing demand for agricultural education, employment opportunities have not expanded at the same pace. This mismatch between the number of graduates and available jobs has emerged as a major concern.

Government Jobs: The Dream That Drives Thousands

For most agriculture graduates, securing a government job remains the ultimate goal. Positions such as Agriculture Officer, Assistant Agriculture Officer, Horticulture Officer, Extension Officer, and Research Scientist are widely regarded as prestigious and stable career options.

The attraction is understandable. Government jobs offer regular salaries, job security, pension benefits, and opportunities to work directly with farmers. In rural communities, government employment is often associated with social prestige and financial stability. Families frequently encourage graduates to prepare for competitive examinations rather than pursue private-sector opportunities or entrepreneurship.

However, the reality is far more challenging, while agricultural universities produce thousands of graduates every year, government departments recruit only a limited number of candidates. Recruitment processes are often delayed, and vacancies may remain unfilled for extended periods. As a result, thousands of graduates compete for a relatively small number of positions.

Many students spend several years preparing for examinations conducted by agencies such as the Karnataka Public Service Commission, Karnataka Examination Authority, SAUs, and various government departments. Some eventually succeed, but many remain caught in a cycle of repeated examinations, uncertainty, and financial dependence on their families.

This dependence on government employment has created a situation where many talented graduates overlook alternative opportunities available in the rapidly changing agricultural sector.

The Challenge of Employability and Skill Gaps

One of the most frequently discussed issues in agricultural education is the gap between academic training and industry requirements. Agricultural universities provide students with strong scientific knowledge in areas such as crop production, soil fertility, pest management, genetics, and plant breeding. These foundations are essential, but modern employers increasingly seek additional skills.

Today's agricultural sector requires professionals who can communicate effectively, manage businesses, understand markets, analyze data, and adapt to technological innovations. Agribusiness companies often recruit graduates for roles involving sales, marketing, technical consultancy, customer support, and product development. Success in these positions depends not only on technical expertise but also on communication and managerial abilities.

Digital agriculture is further transforming the employment landscape. Technologies such as drones, artificial intelligence, remote sensing, geographic information systems, mobile advisory platforms, and precision farming

tools are becoming increasingly important. Graduates who lack exposure to these technologies may struggle to meet industry expectations.

Another concern is limited practical exposure to commercial agriculture and agribusiness operations. Although students participate in field training and internships, many graduate without sufficient understanding of market dynamics, entrepreneurship, value chains, and agribusiness management. Strengthening industry linkages and practical learning opportunities is therefore critical.

Higher Education as a Career Strategy

Constrained employment opportunities have led to increased postgraduate enrollment in agriculture-related specializations. For some, higher education is a pathway towards research, teaching and extension careers. For others, it represents an opportunity to improve employability and gain specialized knowledge. Competitive examinations for organizations such as ICAR, NABARD, and agricultural universities also encourage students to pursue advanced degrees.

While higher education offers numerous benefits, it is not without challenges. Additional years of study often place financial burdens on families and delay economic independence. In some cases, students pursue postgraduate education not because of academic interest but because they are uncertain about employment opportunities after graduation.

Nevertheless, advanced education continues to play an important role in producing skilled professionals capable of contributing to agricultural innovation, policy development, and scientific research.

New Opportunities in Agribusiness

Agriculture is no longer limited to crop production. It has evolved into a complex system involving production, processing, marketing, logistics, finance, and technology. This transformation has created significant opportunities for agriculture graduates.

Private-sector companies involved in seeds, fertilizers, pesticides, irrigation systems, farm machinery, and food processing require trained professionals who understand agricultural systems. Graduates work as field officers, technical advisors, quality analysts, procurement specialists, and sales executives.

The food processing sector, in particular, has emerged as a major source of employment. As consumer demand for processed and value-added food products increases, industries require professionals capable of ensuring quality, safety, and efficiency throughout the supply chain.

Agribusiness management has become one of the fastest-growing career options for agriculture graduates. Professionals who understand both agriculture and business are increasingly valued by companies operating in domestic and international markets.

Agri-Startups: A New Generation of Opportunities

One of the most exciting developments in recent years has been the emergence of agri-tech startups. Karnataka, particularly Bengaluru, has become a leading hub for agricultural innovation and entrepreneurship.

Startups are addressing challenges related to market access, supply chains, precision farming, climate resilience, farm mechanization, and digital advisory services. Many of these companies actively recruit agriculture graduates because they possess both technical knowledge and an understanding of farmers' needs.

The startup ecosystem is changing perceptions about agricultural careers. Instead of waiting for government jobs, many young graduates are choosing to work in innovative enterprises that offer dynamic learning opportunities and professional growth.

Some graduates are even establishing their own startups focused on organic farming, hydroponics, precision agriculture, food processing, and e-commerce platforms for agricultural products. These ventures demonstrate that agriculture can be both profitable and innovative when combined with technology and entrepreneurial thinking.

From Job Seekers to Job Creators

Perhaps the most encouraging trend among agriculture graduates is the growing interest in entrepreneurship. Increasing numbers of young professionals are returning to rural areas and establishing successful agricultural enterprises.

Organic farming, mushroom cultivation, nursery management, dairy farming, beekeeping, protected cultivation, and integrated farming systems are becoming popular among educated youth. Many graduates are adding value to agricultural products through processing, branding, and direct marketing.

Government programmes such as RKVY-RAFTAAR, Startup Karnataka, PMFME, and NABARD-supported initiatives are encouraging entrepreneurial ventures by providing financial assistance, training, and mentorship. Agricultural universities have also established incubation centres that help students convert innovative ideas into viable businesses.

The rise of Farmer Producer Organizations (FPOs) has created additional opportunities for graduates to work in management, marketing, and capacity-building roles. These organizations require skilled professionals who can connect farmers with markets and improve the efficiency of agricultural value chains.

Challenges That Still Need Attention

Despite encouraging developments, several challenges continue to affect agriculture graduates. Unemployment and underemployment remain significant concerns, particularly in rural areas. Many graduates accept low-paying jobs because better opportunities are unavailable.

Social expectations also influence career choices. Families often view entrepreneurship and farming as less secure than government employment. As a result, graduates may hesitate to pursue innovative ventures despite having the necessary skills and knowledge.

Climate change presents another challenge. Unpredictable rainfall, droughts, pest outbreaks, and market fluctuations create risks that discourage investment in agriculture. Access to finance remains a major obstacle for young entrepreneurs who wish to establish agricultural enterprises.

Mental stress associated with prolonged job searches and competitive examination preparation is also becoming increasingly common. Addressing these issues requires stronger career guidance, counselling services, and institutional support.

Conclusion

Agriculture graduates in Karnataka represent one of the state's most valuable resources for rural development and agricultural transformation. They possess scientific knowledge, technical skills, and a deep understanding of farming systems. Yet many continue to face challenges arising from limited employment opportunities, intense competition, and changing industry expectations. At the same time, agriculture is entering a new era characterized by technology, innovation, sustainability, and entrepreneurship. Agribusiness, food processing, digital agriculture, climate-smart farming, and startup ecosystems are creating opportunities that were unimaginable a generation ago.

The future belongs to graduates who are willing to adapt, innovate, and embrace new possibilities. Educational institutions must strengthen practical training and industry engagement, policymakers must support entrepreneurship and employment generation, and graduates themselves must move beyond traditional career expectations. The future of Karnataka's agriculture will not depend solely on farmers. It will also depend on the thousands of agriculture graduates who bring scientific knowledge, innovation, and entrepreneurial energy to the fields, markets, and institutions that shape rural India.

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ENERGY ECONOMICS



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Abstract

Energy economics is an essential resource that drives economic growth, industrial development and improvements in human welfare. Every sector of the economy, including agriculture, manufacturing, transportation, healthcare and communication, depends on a reliable and affordable energy supply. Energy economics is a specialized branch of economics that examined the production, distribution, pricing, consumption and management of energy resources while considering economic efficiency, environmental sustainability and social welfare. Rapid industrialization, population growth, urbanization, climate change and fluctuations in global energy prices have increased the importance of energy economics in recent decades. Currently, many countries are working to improve energy security, increase energy efficiency, promote renewable energy and develop sustainable energy policies for long-term economic growth. Modern technologies such as smart grids, digital energy management systems, artificial intelligence, and energy storage are also transforming the global energy sector. This review article discusses the concepts, importance, energy demand and supply, energy markets, governance, major challenges, and future perspectives of energy economics. It highlights how efficient energy management contributes to sustainable economic development while balancing environmental protection and energy security.

Introduction

Energy is one of the most essential resources for economic and social development because it supports nearly every productive activity in modern society. Agriculture depends on energy for irrigation, mechanization, fertilizer production, harvesting and food processing. Industries require electricity and fuel for manufacturing, while transportation, healthcare, education and communication systems rely on a continuous energy supply. Therefore, the availability of affordable, reliable and sustainable energy directly influences economic productivity, employment and the quality of life. Over the last few decades, global energy demand has increased rapidly due to population growth, urbanization, industrial expansion and technological advancement. However increase dependence on fossil fuels has created serious environmental challenges, including greenhouse gas emissions, climate change and air pollution.

Fluctuations in international oil and gas prices, geopolitical conflicts, and disruptions in global supply chains have also increased concerns about energy security and economic stability. These developments have made energy economics an important area of study for governments, industries, and researchers. Energy economics is an interdisciplinary field that combines economics, engineering, environmental science and public policy. It analyses how energy resources are produced, distributed, traded, priced and consumed while ensuring efficient resource allocation and sustainable development.

The discipline also evaluates the economic impacts of energy policies, investment decisions, technological innovations and environmental regulations. In recent years, the global energy, improvements in energy efficiency and the development of digital energy technologies have expanded the scope of energy economics, making it one of the most dynamic fields in modern economics.

Concept of Energy Economics

Energy economics is a branch of economics that focuses on the efficient production, distribution, pricing, consumption and management of energy resources. It examines the relationship between energy and economic development by analysing how energy influences production, trade, investment, employment and national

income. Unlike conventional economics, energy economics specifically considers the unique characteristics of energy resources, such as limited availability, price volatility, infrastructure requirements, environmental impacts and government regulation. Energy is considered as a strategic economic resource because every sector depends on it for efficient operation. Farmers require fuel and electricity for irrigation, machinery and post-harvest processing. Industries consume energy during manufacturing, while households depend on electricity for lighting, cooking, heating and cooling. Reliable energy supply also supports banking, healthcare, education, transportation and digital communication. Consequently, efficient management of energy resources contributes directly to national productivity and economic competitiveness. Energy economics also examine the interaction between energy producers, consumers, governments and international markets. It is analysed, how energy demand changes over time, how investment decisions are made how government policies influence energy production and consumption. The discipline also evaluates the effectiveness of policies designed to improve energy efficiency, promote the renewable energy, reduce greenhouse gas emission and encourage sustainable resource utilization.

Importance of Energy Economics

1. Promotes Economic Growth

Energy economics plays an important role in promoting sustainable economic growth and improving living standards. Efficient energy management increases productivity, supports industrial development, creates employment opportunities and contributes to higher national income. Reliable energy systems also improve industrial competitiveness.

2. Ensures Energy Security

Energy economics helps strengthen energy security by reducing dependence on imported fossil fuels. It supports policies that diversify energy sources, increase domestic energy production and promote renewable energy to reduce the risks of price fluctuations and supply disruptions.

3. Supports Environmental Sustainability

Energy economics promotes energy conservation, energy efficiency and the use of renewable energy sources such as solar, wind, hydropower and biomass. It also encourages investments in smart grids and battery storage systems to improve the efficiency and reliability of energy systems.

4. Supports Better Decision-Making

Energy economics provides useful information for policymakers, investors, industries and researchers. It helps evaluate energy projects, forecast future energy demand, assess environmental impacts and develop effective pricing policies for sustainable economic development.

Energy Demand and Supply

Energy demand and supply are key components of energy economics because they determine how energy is produced, distributed and consumed. Their balance influences energy prices, investment, productivity and economic growth. An efficient energy system provides a reliable and affordable energy supply for households, industries, agriculture and transportation.

Energy demand is the amount of energy required by different sectors over a specific period. It is affected by population growth, industrialization, urbanization, income levels, technology, weather and government policies. In developing countries, energy demand is increasing due to economic growth, improved living standards and the growing use of electric vehicles and digital technologies.

Energy Markets and Pricing

Energy markets are systems where producers and consumers buy and sell energy such as electricity, crude oil, natural gas, coal and renewable energy. These markets help allocate energy resources efficiently, promote competition, encourage investment and ensure a reliable energy supply. Well-managed energy markets also support economic stability by improving market transparency and reducing supply disruptions. Energy markets are mainly divided into electricity, petroleum, natural gas and renewable energy markets. Electricity markets involve power generation and distribution, while petroleum and natural gas markets include production, transportation and trade. Renewable energy markets focus on energy generate from solar, wind, hydropower, biomass and geothermal sources. As countries adopt clean energy technologies, renewable energy markets continue to grow.

Energy pricing is an important part of energy economics because it affects production costs, transportation, inflation and household expenses. Energy prices are influenced by supply and demand, production and transportation costs, taxes, government policies and global market conditions. They may also change due to geopolitical conflicts, natural disasters, supply disruptions, seasonal demand and technological developments. Stable and transparent pricing helps maintain market confidence and encourages long-term investment in the energy sector.

Energy Governance

Energy governance refers to the policies, regulations and institutions that manage the production, distribution, pricing and use of energy resources. It ensures that energy systems are efficient, transparent and sustainable while supporting economic growth and environmental protection. Governments develop energy policies, regulate energy markets, promote renewable energy, improve energy efficiency and protect consumer interests. Regulatory authorities ensure fair competition and support innovation, while international organizations provide guidance for sustainable energy development.

Effective energy governance promotes clean energy, improves energy conservation, reduces greenhouse gas emissions, attracts investment, strengthens energy infrastructure and supports long-term sustainable development.

Current Issues and Challenges in Energy Economics

Despite significant progress in the global energy sector, several challenges continue to affect energy production, distribution and consumption. These challenges influence economic growth, energy security and environmental sustainability.

1. Energy Price Volatility

Energy prices often fluctuate due to changes in global supply and demand, geopolitical conflicts, trade restrictions, exchange rates and natural disasters. Rising energy prices increase production and transportation costs, contribute to inflation and affect economic growth.

2. Energy Security

Energy security means ensuring a reliable and affordable energy supply. Many countries depend on imported fossil fuels, making them vulnerable to supply disruptions. Diversifying energy sources, increasing domestic energy production and investing in renewable energy can improve energy security.

3. Environmental Sustainability

The heavy use of fossil fuels has increased greenhouse gas emissions, air pollution and climate change. Energy economics supports energy-efficient technologies and renewable energy to reduce environmental impacts while promoting sustainable development.

4. Growing Energy Demand

Population growth, urbanization, industrialization and digital technologies continue to increase global energy demand. Meeting this demand while keeping energy affordable and environmentally sustainable remains a major challenge.

5. Investment and Infrastructure

The energy sector requires major investments in power generation, transmission networks, energy storage and modern technologies. Developing countries often face financial and technological challenges, making government support and public-private partnerships essential for improving energy infrastructure.

Future Perspectives in Energy Economics

The future of energy economics will be driven by technological innovation, digital transformation and sustainable energy development. Technologies such as artificial intelligence, smart grids and digital energy management are improving energy efficiency, electricity distribution and system reliability. Renewable energy sources, including solar, wind, hydropower, biomass and geothermal energy, are expected to play a larger role in global electricity generation. Government policies, financial support and technological progress continue to encourage clean energy development. Advanced battery storage, electric vehicles and green hydrogen technologies are also supporting the transition to a low-carbon economy by improving energy reliability and reducing dependence on fossil fuels. In the future, energy economics will continue to focus on economic growth, energy security, affordability and

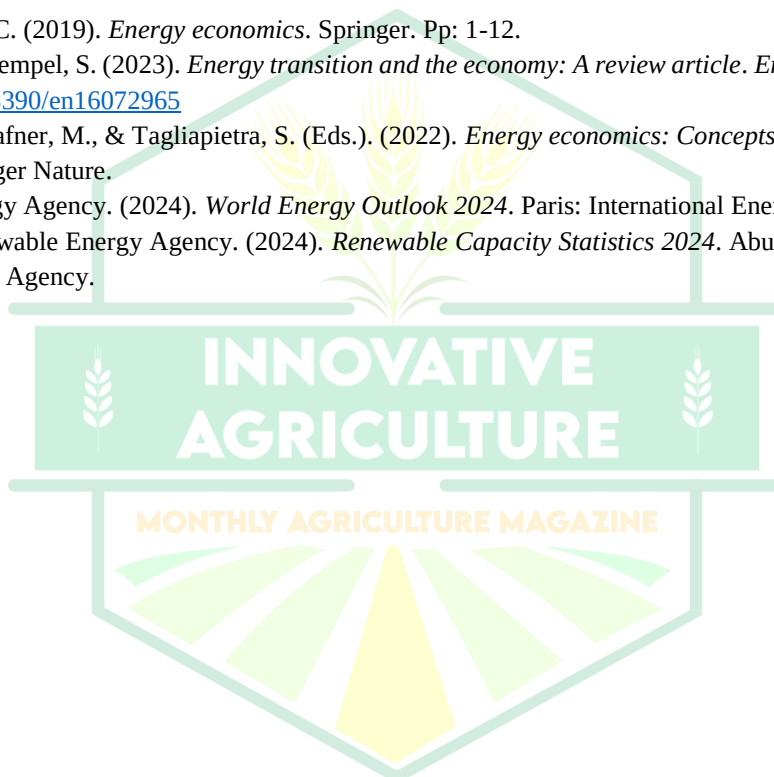
environmental sustainability. Strong governance, innovation, efficient resource management and international cooperation will be essential for developing sustainable and reliable energy systems.

Conclusion

Energy economics is an important field that studies the relationship between energy resources and economic development. It helps improve energy production, distribution, pricing, governance and policy while addressing energy security and environmental sustainability. Efficient energy management supports industrial growth, employment and improved living standards. As global energy demand continues to grow, countries need sustainable energy policies that promote efficient resource use, renewable energy and technological innovation. Technologies such as artificial intelligence, smart grids, battery storage and digital energy management are improving energy systems and supporting economic growth. The future of energy economics depends on balancing economic growth, energy security, affordability and environmental sustainability. Strong governance, innovation and international cooperation will help build reliable and sustainable energy systems for future generations.

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THE IMPACT OF EL NIÑO ON INDIAN AGRICULTURE



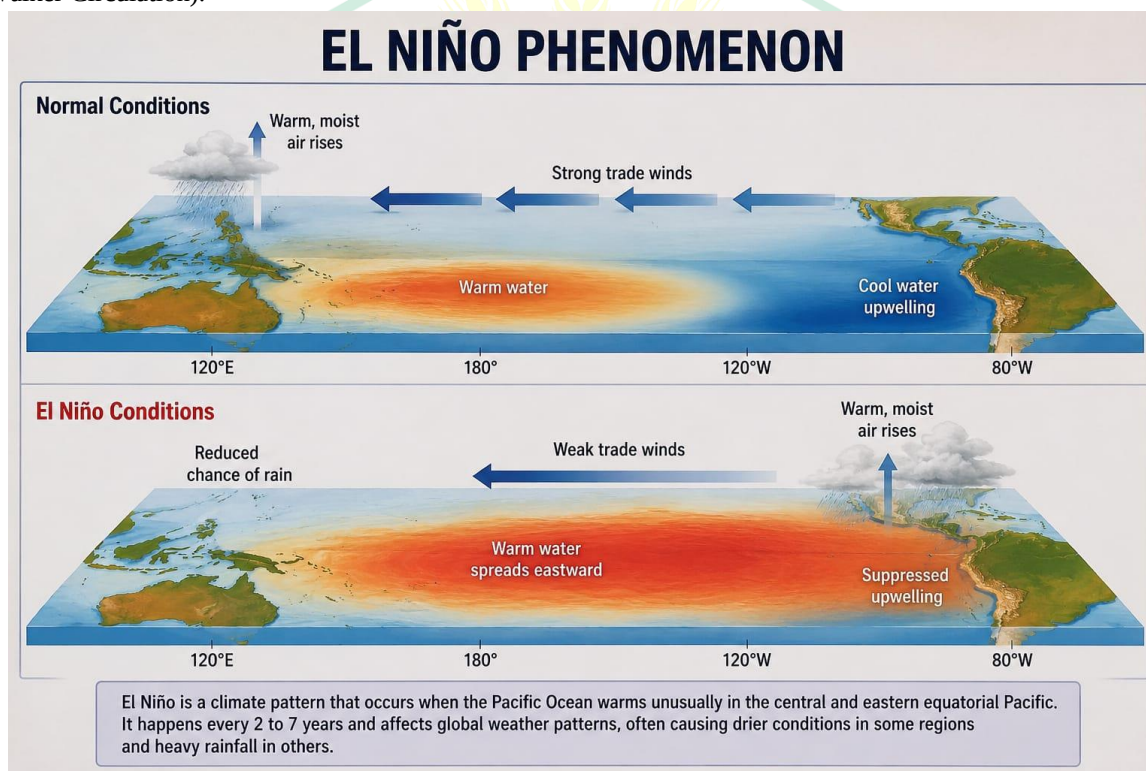
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Indian agriculture is often described as a "gamble on the monsoon." With over 50% of the country's net sown area lacking permanent irrigation, the livelihood of millions of farmers depends heavily on the Southwest Monsoon (June to September). When the global climate phenomenon known as El Niño develops, this delicate agricultural balance is severely disrupted.

Understanding the El Niño Phenomenon

El Niño—meaning "The Little Boy" in Spanish—refers to the abnormal warming of sea surface temperatures (SST) in the central and eastern equatorial Pacific Ocean. Under normal conditions, trade winds blow from east to west, pushing warm water toward Asia. During an El Niño event, these trade winds weaken or reverse. The warm water shifts back eastward toward South America, disrupting global atmospheric circulation patterns (the Walker Circulation).



Source: earthobservatory.nasa.gov

As seen in the scientific model above, when warm ocean water accumulates near South America during an El Niño year, it pulls moisture-heavy air systems away from the Indian subcontinent. Consequently, the Indian monsoon mechanism loses its strength, frequently causing delayed, deficit, or poorly distributed rainfall across major agricultural belts.

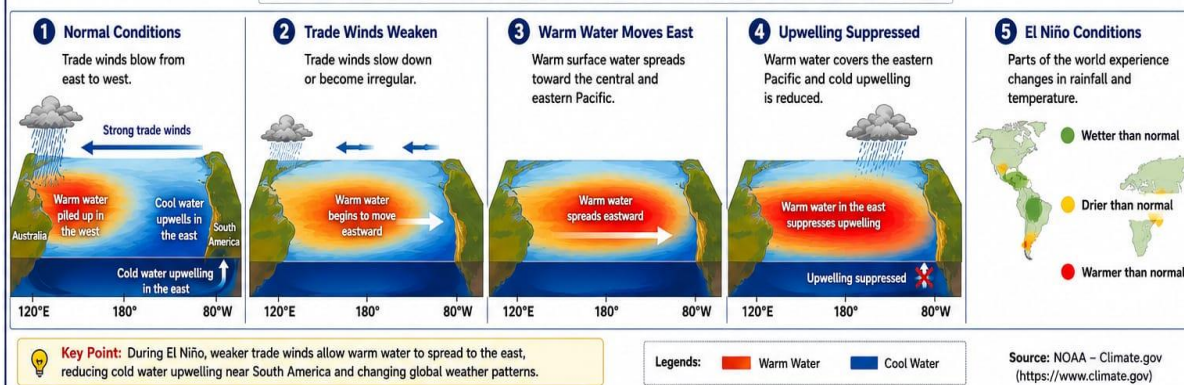
Major Risks to Indian Agriculture

1. Monsoon Deficits and Severe Droughts

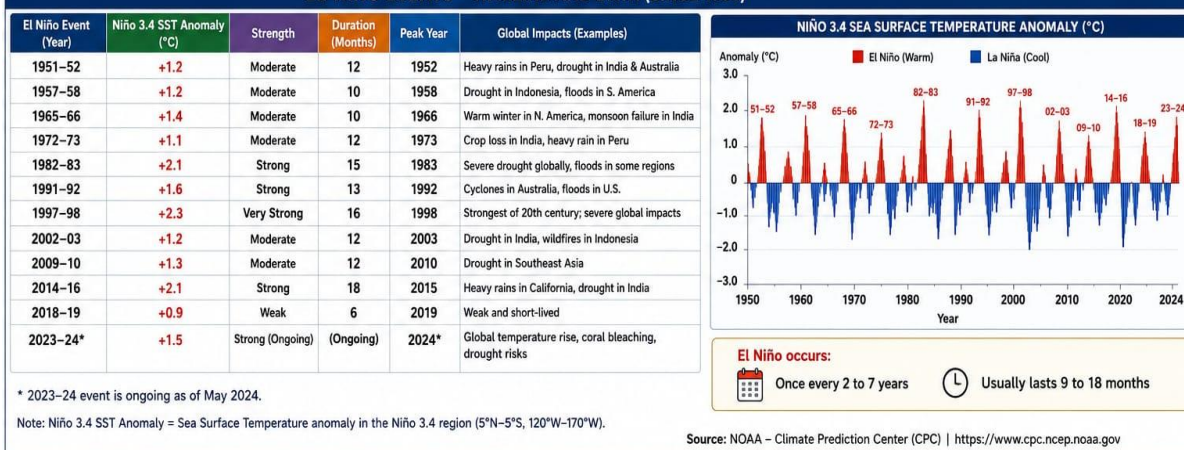
The historical correlation between El Niño and deficient Indian monsoons is remarkably strong. Out of all the major drought years recorded in India since 1950, a vast majority occurred during recognized El Niño phases. The direct consequences manifest as dry spells during critical crop lifecycle stage.

EL NIÑO – HOW IT FORMS

El Niño occurs when the central and eastern equatorial Pacific Ocean becomes warmer than normal.



EL NIÑO EVENTS – TIMELINE AND DATA (SINCE 1950)



Source: NOAA Climate Prediction centre

2. Contraction of Kharif Crop Acreage

The Kharif season (sown in June-July and harvested in October-November) bears the immediate brunt of the phenomenon. Key crops are heavily impacted:

Rice: Delayed monsoons stall nursery preparation and transplanting, leading to reduced yields.

Pulses & Oilseeds: Crops like tur (pigeon pea), urad, and soybean suffer from lack of early vegetative moisture.

Coarse Cereals: Maize and bajra fields witness lower germination rates due to dry topsoil.

3. Depletion of Ground Water and Reservoir Levels

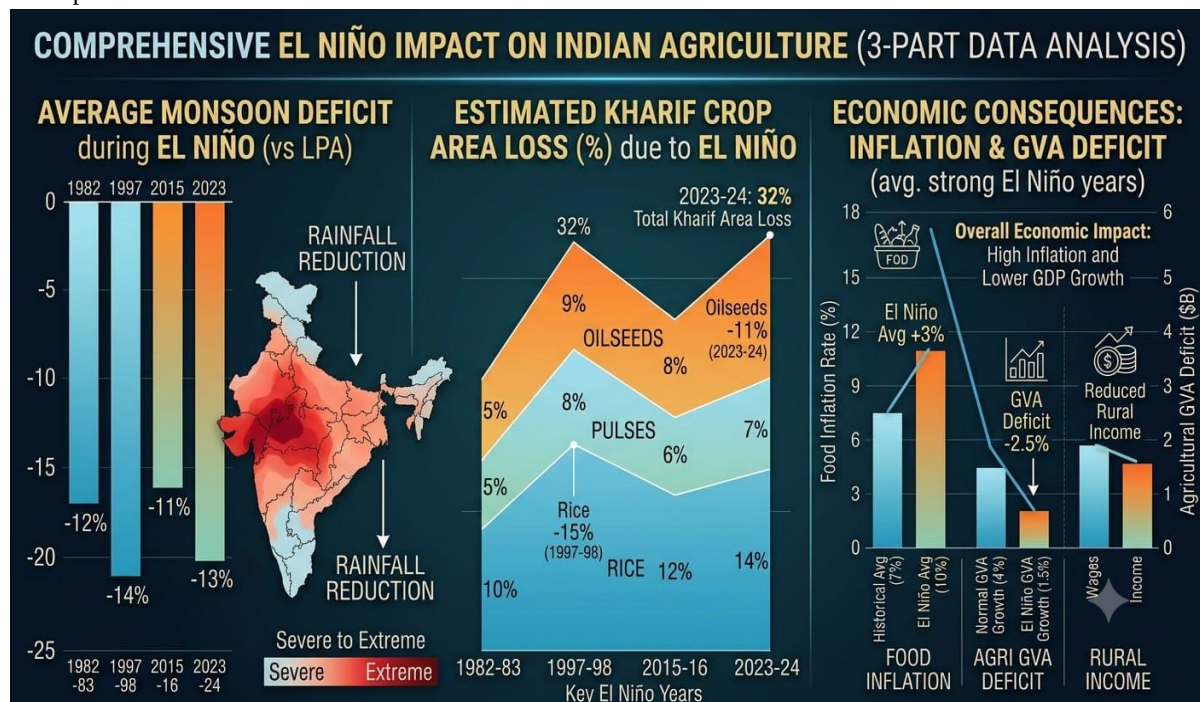
When monsoon rainfall falls short, water levels in the nation's major reservoirs drop drastically. This creates a dangerous cascading effect: it starves the subsequent Rabi season (winter crops like wheat and mustard) of crucial supplementary irrigation water and strains local groundwater tables.

The Pacific Threat: How El Niño Reshapes Indian Agriculture

El Niño has a direct inverse relationship with Indian rainfall. According to data from the India Meteorological Department (IMD) and the Food and Agriculture Organization (FAO), a strong El Niño event can suppress monsoon rains to well below 92% of the Long Period Average (LPA). Since rain-fed irrigation accounts for nearly 50% of India's net sown area and drives 40% of its total food production, a delayed or weak monsoon instantly disrupts the farming cycle.

The immediate impact is visible in the drastic reduction of Kharif (summer-sown) crop acreage. Historical data reveals that during intense El Niño cycles, overall crop sowing can plummet by over 20%. Water-intensive and essential crops bear the brunt of this deficit: paddy (rice) cultivation traditionally drops by up to 25%, while pulses and cotton face a decline of 30% to 35%. The hardest-hit sector is often oilseeds (like soybean and

groundnut), where delayed rains can slash acreage by over 50%, forcing India to rely heavily on expensive edible oil imports.



- ❖ **Economic Implications: Food Inflation and Rural Distress:** When agricultural output drops, the economic shocks ripple quickly through the broader Indian economy:
The Inflation Cycle: Lower yields lead to a supply crunch in essential commodities. Prices of staples—particularly rice, pulses, sugar, and milk—climb rapidly. This forces the Reserve Bank of India (RBI) to keep interest rates high to counter supply-side inflation.
Rural Income Compression: Reduced crop yields directly translate to lower incomes for small and marginal farmers.
- ❖ **Decreased FMCG Demand:** Because rural households must spend more of their limited income on basic food survival, discretionary spending on tractors, two-wheelers, and fast-moving consumer goods (FMCG) drops sharply, slowing down the broader industrial economy.
- ❖ **Mitigation and Adaption Strategies:** To reduce vulnerability to Pacific Ocean warming trends, India is actively transitioning toward climate-resilient agricultural practices:
Promoting Short-Duration & Climate-Resilient Crops: Agricultural universities are introducing drought-tolerant varieties of rice and pulses that can mature early even under moisture-stress conditions.
Expanding Micro-Irrigation Infrastructure: Moving away from flood irrigation to drip and sprinkler systems reduces water use by up to 50% while sustaining optimal crop yields.
Shifting to Climate-Smart Agriculture: Encouraging farmers in low-rainfall zones to switch from water-guzzling crops like sugarcane and paddy to nutritious, resilient alternatives like millets (Sorghum, Pearl Millet, Ragi).
- ❖ **Conclusion:** El Niño is a significant climatic phenomenon that strongly influences the Indian monsoon and agricultural production. It often leads to below-normal rainfall, drought conditions, water scarcity, and reduced crop yields, particularly in rainfed farming regions. Major crops such as rice, pulses, sugarcane, and oilseeds are highly vulnerable to its impacts. However, effective water management, climate-resilient agricultural practices, drought-tolerant crop varieties, and accurate weather forecasting can help farmers minimize losses. Strengthening adaptation strategies and sustainable farming practices is essential to enhance the resilience of Indian agriculture against future El Niño events.

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RED MUD AND ITS IMPACT ON ENVIRONMENT



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ABSTRACT

Red mud is a by-product produced in the process of extraction of alumina from bauxite by Bayer's Process. It is an insoluble product and is generated after bauxite digestion with sodium hydroxide at elevated temperature and pressure is known as red mud. Large quantity of red mud is generated worldwide every year posing a very serious and alarming environmental problem. Red mud contains high quantities of alkali-generating minerals and metal ions, which cause significant environmental damage. Many valuable components such as rare-earth elements such as Aluminium and Iron in Red mud are difficult to be utilized owing to their particle size and alkalinity. Thus, developing an economical and efficient technology to consume a large amount of Red mud can efficiently solve Red mud disposal issues. Red mud is an industrial solid waste rarely utilized and often disposed in landfills, resulting in resource waste and environmental pollution. However, due to its high pH and abundance of iron and aluminum oxides and hydroxides, red mud has excellent adsorption properties which can effectively remove heavy metals through ion exchange, adsorption, and precipitation.

Keywords: Red Mud, Bauxite, Pollution, Heavy Metals, Sustainability.

INTRODUCTION

Red mud is a strongly alkaline by product generated from the extraction of alumina from bauxite, which is rich in iron [Fe (III)] oxides. On average, producing 1t alumina generates about 1.5 t red mud. The annual world alumina yield is estimated to be over 130 million tons, which creates more than 200 million tons of red mud. However, the reuse of red mud is less than 5%, and most existing red mud remains in storage at disposal pits. Because of the high pH (10–12.5) and the content of toxic elements, such as Th, Zr, Cr, Ni, Ce, V, Nd, Mn, La, Sc and As, the storage of red mud causes a series of environmental issues. These issues include heavy metal contamination in surface water and groundwater, soil Salinisation, and air pollution. The large generation of red mud posing a very serious and alarming environmental problem. Considerable research and development work for the storage, disposal and utilization of red mud is being carried out all over the world. The global production of red mud is mainly distributed in China (28.2%), Oceania region (22.4%), South America (14.6%), Europe (12.9%), North America (8.8%) and others (13.10%), which is more than 90% of the worldwide production. The observed red mud poses several challenges due to its high alkalinity, minor amounts of heavy metal, and large amounts produced, such as red mud disposal. It is disposed of in several ways, such as by dumping it into the sea, storing it in lagoons, stacking it dry, or using other dry disposal methods. Aluminum industries disposal of red mud into the sea can harm marine environment.

CHEMICAL COMPOSITION

The composition of red mud is varies with the type of bauxite used and the alumina production process in Bayer's process (Fig.1). The mineral and chemical constituents of red mud, which showed different physical characteristics, were determined by the XRD analyzer. The red mud contains non-crystalline materials in about 70

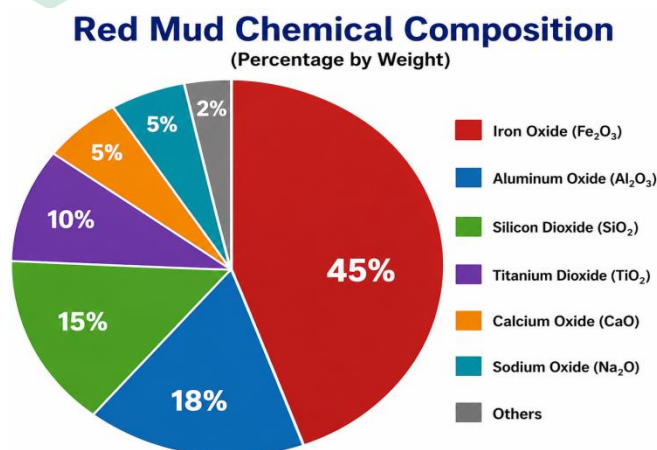


Fig 1. Red Mud Chemical Composition

percent due to the presence of cancrinite and hematite minerals. The white precipitates were identified as 100% calcite, and the hard, thin plates from the surface of the disposal are almost entirely of aluminium hydroxide minerals.

PHYSICAL CHARACTERISTICS OF RED MUD

The physical characteristics of red mud vary depending on its source and processing method. The colour of red mud is reddish-brown due to its high iron oxide content. It has a fine, powdery texture, although coarser particles may also be present. The bulk density of red mud ranges from 2.7 to 3.5 g/cc, indicating its considerable heaviness. The pH of red mud lies between 10 to 13, which shows its alkaline in nature when sodium hydroxide is used in alumina extraction. The moisture content varies widely, generally between 20 - 30%, influenced by the dewatering and storage processes. Red mud also has a high specific surface area, usually 20–30 m²g⁻¹, due to its fine particle size, which affects its reactivity and contaminant absorption its high porosity allows it to retain significant amounts of water, presenting challenges and opportunities for handling and application. These characteristics are crucial for effective management and potential reuse in various applications, including environmental remediation and as construction materials.

ENVIRONMENTAL CONCERNS OF RED MUD

Red mud is disposed as dry or semidry material in red mud pond or abandoned bauxite mines and as slurry having a high solid concentration of 30- 60% with high ionic strength. The environmental concern related to two aspects: very large quantity of red mud generated and its causticity. Problems associated with the disposal of red mud waste include:

- High pH (10.5 to 12.5)
- Alkali seepage into the underground water.
- Instability of storages.
- Alkaline air borne dust impact on plant life.
- Up to 2 ton of liquid with a significant alkalinity of 5 to 20 g/l caustic (As Na₂CO₃) accompany every ton of red mud solids.

ENVIRONMENTAL IMPACTS OF RED MUD

1. Soil Contamination

Due to its high pH, red mud is highly caustic in nature. When disposed of on land, it can severely alter the soil's composition, making it infertile. The high alkaline content disrupts the soil's pH balance, leading to the degradation of soil quality and loss of vegetation. Over time, this contamination can extend to nearby agricultural lands, affecting crops and surrounding ecosystems.

2. Water Pollution

Red mud can be particularly harmful to water bodies when it leaches into rivers, lakes, or groundwater. The chemicals in red mud, including toxic heavy metals and alkalis, contaminate water sources, making them unsafe for both human consumption and aquatic life. Aquatic ecosystems are especially vulnerable, as the change in pH and introduction of pollutants can result in the destruction of biodiversity and the degradation of habitats.

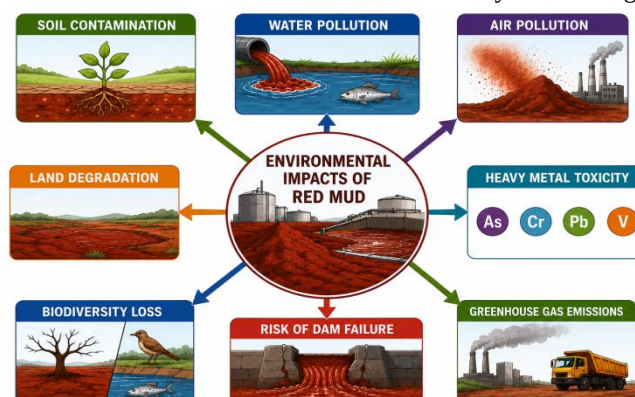


Fig 2. Impacts of Red mud on environment

3. Air Pollution

When red mud is stored improperly, such as in open air storage ponds or landfills, dust particles can be carried by the wind. This airborne red dust can pose health risks to nearby communities, causing respiratory problems and eye irritation. Additionally, the fine particles are prone to contaminating the surrounding air, which could contribute to long-term health problems for humans and animals living in their vicinity.

4. Health Risks

Long-term exposure to red mud, particularly through inhalation of dust or skin contact, poses several health risks. The high alkaline content can lead to skin burns, irritation, and other dermatological conditions. Respiratory issues, such as asthma and bronchitis, are also common among workers who are regularly exposed to red mud dust. Moreover, the heavy metals in red mud can accumulate in the human body over time, potentially leading to serious health concerns like cancer, kidney damage, or neurological disorders.

REMEDIATION METHODS FOR RED MUD

Red mud disposal methods include traditional closed cycle disposal (CCD) methods and modified closed cycle disposal (MCCD). A new class of dry stacking (DS) technology has requires much less land. Safe treatment and storage of high-volume industrial waste streams pose unique waste management challenges. Seawater discharge, lagooning, dry stacking and dry disposal are the methods currently in use for the disposal of bauxite residue. The disposal of red mud remains one of the biggest environmental challenges in the aluminum industry. Currently, red mud is mostly stored in tailings ponds or landfills, often in large quantities, creating the risk of spills, leaks, and contamination of nearby areas. Some regions have implemented containment strategies, such as lining tailings ponds with impermeable materials to prevent leaching. However, these measures are not always effective, and over time, there is a risk that the containment structures could fail. Environmental regulations around the world are gradually tightening to ensure better management of red mud. However, there remains a lack of comprehensive global standards for its disposal, which can lead to inconsistent practices.

RED MUD AND ITS UTILIZATION

A considerable research has been done on the utilization of red mud as a raw material for production of a range of products. It can be used as a construction/building material in bricks, blocks, light weight aggregates, in cement industry as cements and special cements and in concrete industry. Bauxite residues can be used for soil remediation, as geo-polymers and as a clay material. It can also be used as an additive to cements, mortars and concretes, construction of dykes and as ceramic or refractory product. In iron and steel industry it can be used after recovery of iron and Titania. In environmental field, it can be utilized in pollution control by acting as adsorbent for cleaning of industrial gases, as synthetic coagulants in waste water treatment and as a catalyst especially for coal hydrogenation. Red mud can as well be used in paints and pigments.

CASE STUDIES

Ajka Disaster (2010)

The most significant incidents involving red mud was the 2010 Ajka disaster in Hungary, where a dam containing red mud at an alumina plant collapsed. The resulting flood of red mud destroyed homes, polluted rivers, and caused several fatalities. This tragedy highlighted the severe risks associated with improper storage and disposal of red mud and spurred the industry to reevaluate its waste management practices.

Sustainable Practices in India

In India, several alumina refineries have adopted more sustainable approaches to red mud disposal, including the development of tailings ponds with higher containment standards and the use of red mud in the production of



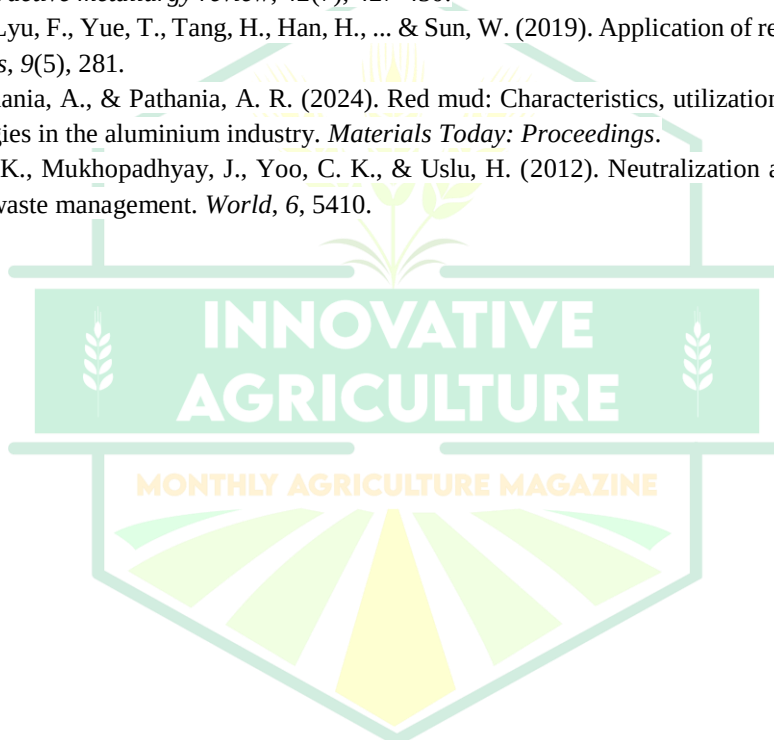
low-cost construction materials. These efforts have shown promise in minimizing environmental damage and reducing the overall volume of waste generated.

CONCLUSION

The red mud is highly complex material that differs due to the different bauxites used and the different process parameter. Red mud presents a significant environmental challenge, but with the right innovations, regulations, and sustainable practices, its impacts can be mitigated. The aluminum industry, alongside global efforts to address climate change and sustainability, must continue to focus on reducing waste, recycling, and finding new uses for red mud to ensure that this byproduct does not further harm our ecosystems. As we move towards more sustainable industrial practices, the future of red mud management looks more promising, but only through continued effort and collaboration can we truly tackle its long-term effects.

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RED GOLD ECONOMY



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Abstract

Saffron is widely known as the most expensive spice in the world, referred to as “red gold” because of its high market price and cultural importance. It is obtained from the delicate stigmas of the saffron flower and its production involves a highly labor-intensive process that significantly influences its economic value. This article examines the economic aspects of saffron, including its cultivation, cost structure, profitability and global trade. It also discusses the challenges faced by the industry, such as labor shortages, climate risks and market irregularities, while highlighting opportunities for growth through innovation and sustainable practices. The study aims to provide a comprehensive understanding of how saffron contributes to both local livelihoods and the global economy.

Introduction

Saffron has held a special place in human history for centuries due to its distinct color, aroma, and medicinal qualities. It is derived from the flower *Crocus sativus*, a plant that requires specific climatic conditions to grow successfully. Each flower produces only a few tiny strands of saffron, which must be carefully collected and processed by hand. This unique characteristic makes saffron production extremely time-consuming and labor-dependent.

Saffron (Crocus sativus L.), an autumnal herbaceous flowering plant belonging to the Iridaceae family. It is largely cultivated in Iran, India, Afghanistan, Greece, Morocco, Spain and Italy. Saffron global production is estimated at 418 t year on 121,338 ha. It is known as the most expensive spice in the world. It has three main bioactive compounds named crocin, picrocrocin and safranal which have health beneficial to the humans.

The economic importance of saffron goes far beyond its use as a culinary ingredient. It is deeply connected to the livelihoods of farmers in regions where it is cultivated. In countries such as Iran, India and Spain, saffron farming plays a vital role in supporting rural economies. In addition, the spice has found increasing applications in health, wellness and cosmetic industries, which has further boosted its global demand. As a result, saffron has become not just an agricultural product but also a valuable economic commodity.

Production and Supply Dynamics

Saffron cultivation is limited to certain parts of the world because it requires a specific combination of soil, temperature and seasonal conditions. Regions with dry summers and cold winters are generally more suitable for its growth. Iran is the leading producer, while India's Kashmir region is known for producing high-quality saffron with unique characteristics.

The supply of saffron is naturally restricted because of its biological limitations. A large number of flowers are needed to produce even a small quantity of the spice, which keeps overall production levels relatively low. In addition, factors such as weather conditions, soil fertility and farming practices can greatly influence the yield. This limited and uncertain supply plays a major role in determining the high price of saffron in International markets.

Cost Structure and Labor Dependence

One of the most defining features of saffron economics is its reliance on human labor. Saffron harvesting cannot be easily mechanized. The flowers must be picked by hand, usually during early morning hours, to maintain their quality. After harvesting, the delicate stigmas are carefully separated and dried, which requires both skill and precision.

A labor cost is one of the significant portions of the total cost of saffron production. In many cases, families or local communities participate in the harvesting process, making it a collective economic activity. Despite the high labor requirements, saffron cultivation does not demand heavy investment in machinery or advanced infrastructure. This makes it accessible to small-scale farmers who may not have large financial resources. The dependence on labor also creates certain challenges. Rising wages and migration of workers to urban areas can lead to labor shortages, which may affect production levels. As a result, maintaining a stable workforce is an important factor in the economic sustainability of saffron farming.

Profitability and Economic Significance

Saffron is one of the most profitable agricultural products due to its high market value. Even small quantities can generate substantial income, making it an attractive option for farmers with limited land. The returns from saffron cultivation often outweigh the costs, especially when the crop is managed efficiently and sold at good market prices.

Another advantage of saffron is its low bulk and high value, which reduces transportation and storage expenses. This makes it easier for farmers and traders to participate in International markets. In many rural areas, saffron cultivation has contributed to improved living standards by providing a steady source of income.

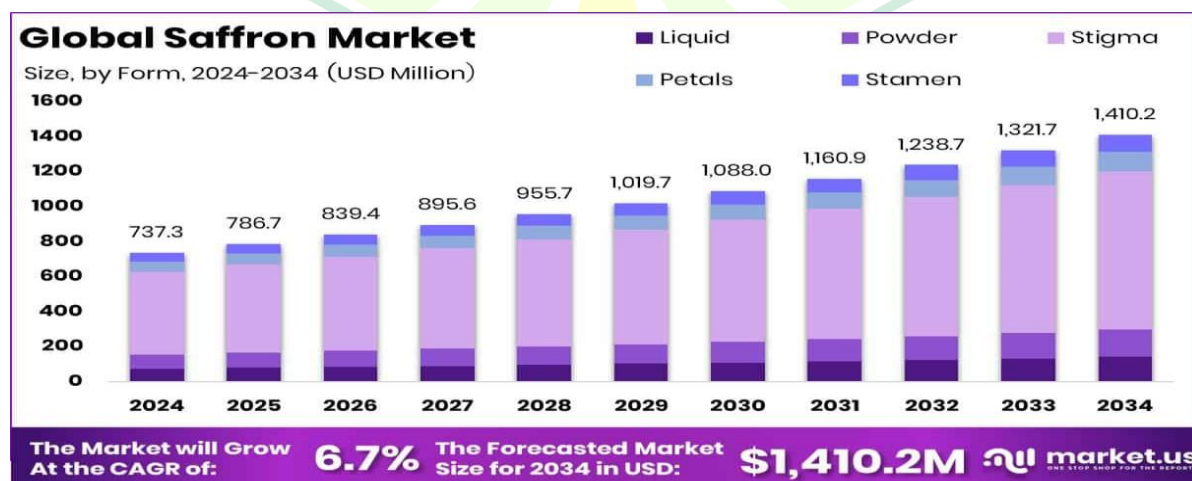
Profitability is influenced by several factors, including yield quality, market demand and price fluctuations. Farmers who have access to better cultivation techniques and market information are more likely to benefit from higher profits. Knowledge and resource availability play a crucial role in determining economic success in saffron farming.

Market Demand and Trade Patterns

The demand for saffron continues to grow due to its wide range of uses. In the food industry, it is valued for its ability to enhance flavor and color. Saffron is increasingly used in traditional and modern medicine because of its potential health benefits. The cosmetic industry also utilizes saffron extracts in skincare products, adding to its commercial value.

The global trade of saffron involves multiple stages, including production, processing, packaging and distribution. Prices can vary depending on factors such as quality, origin and branding. High-quality saffron with strong color and aroma tends to fetch higher prices in the market.

At the same time, the saffron market faces issues related to authenticity and quality control. Because of its high price, there is a risk of adulteration, where inferior substances are mixed with genuine saffron. This not only affects consumer trust but also creates unfair competition in the market. Strengthening quality standards and certification systems is essential for maintaining the integrity of saffron trade.



Value Addition and Resource Utilization

In recent years, there has been growing interest in maximizing the economic potential of saffron by utilizing all parts of the plant. While traditionally only the stigmas were used, researchers and producers are now exploring

the use of petals and other plant components. These by-products contain useful compounds that can be applied in food, medicine and cosmetic products.

Value addition through processing and branding has also become an important aspect of saffron economics. Packaging saffron in attractive and standardized forms can increase its appeal in International markets. By adopting such practices, producers can earn higher returns and reduce wastage.

This approach not only improves profitability but also supports sustainable resource management. By making full use of the plant, the overall efficiency of production increases, contributing to a more balanced economic system.

Challenges in Saffron Economics

The saffron industry faces several challenges that can affect its growth. One of the major concerns is climate variability, which can disrupt the growth cycle of the crop. Changes in temperature and rainfall patterns can reduce yield and affect quality.

Another challenge is the shortage of skilled labor, which is essential for harvesting and processing. As younger generations move away from agriculture, it becomes difficult to maintain traditional farming practices. Additionally, the lack of modern technology and infrastructure can limit productivity in some regions.

Market-related issues such as price instability and adulteration further complicate the situation. Without proper regulation and support, farmers may struggle to receive fair prices for their produce. Addressing these challenges is crucial for ensuring the long-term sustainability of saffron economics.

Future Prospects and Innovations

The future of saffron economics looks promising, especially with the introduction of new technologies and farming methods. Controlled environment agriculture, such as greenhouse cultivation, allows farmers to manage temperature and humidity more effectively, leading to better yields.

Advances in agricultural research are also helping improve planting material and disease resistance. While full mechanization of saffron harvesting remains difficult, partial automation and improved tools can reduce labor intensity.

In addition, digital platforms and online marketplaces are making it easier for farmers to connect directly with buyers, reducing the role of intermediaries. This can help farmers earn better prices and improve their economic position.

Conclusion

Saffron economics represents a unique blend of tradition, labor and high market value. It offers significant opportunities for income generation and rural development. At the same time, the industry faces challenges that require careful management and innovation.

By adopting modern techniques, improving quality standards and ensuring fair market practices, saffron can continue to play an important role in the global economy. Its combination of economic value and cultural significance makes it a truly remarkable agricultural product.

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ROLE OF E-COMMERCE PLATFORMS IN AGRICULTURAL MARKETING



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ABSTRACT

The rapid growth of digital technology has significantly transformed agricultural marketing, with e-commerce platforms emerging as a powerful tool for connecting farmers directly with consumers and markets. These platforms enable the online buying and selling of agricultural products, reducing the dependence on traditional intermediaries and improving price realization for farmers. By providing real-time market information, transparent pricing and wider market access, e-commerce systems enhance efficiency and competitiveness in the agricultural sector.

E-commerce platforms also facilitate better supply chain management through improved logistics, storage and distribution networks, thereby reducing post-harvest losses. They empower farmers, especially small and marginal producers by offering access to larger markets beyond local boundaries. Digital payment systems and mobile-based applications simplify transactions and promote financial inclusion in rural areas.

Challenges such as limited digital literacy, inadequate infrastructure, internet connectivity issues and trust concerns still hinder widespread adoption. Despite these constraints, the integration of e-commerce in agricultural marketing holds immense potential to modernize the sector, increase farmers' income and ensure sustainable agricultural development. Continued policy support, technological advancement and capacity building are essential to fully realize the benefits of e-commerce in agriculture.

INTRODUCTION

Agricultural marketing has traditionally relied on physical markets and intermediaries, often limiting farmers' profits and market access. The emergence of digital technologies has introduced e-commerce platforms as a modern solution to these challenges. These platforms enable farmers to connect directly with buyers, access wider markets and obtain fair prices. As digital adoption increases, e-commerce is becoming a key driver of transformation in agricultural marketing.

WHAT ARE E-COMMERCE PLATFORMS IN AGRICULTURE?

E-commerce platforms are online marketplaces where agricultural products and inputs are traded digitally. They connect farmers with consumers, traders, processors and retailers. Government initiatives like e-NAM and private platforms such as AgriBazaar and DeHaat provide integrated services including trading, logistics, advisory and financial support.

KEY ROLES OF E-COMMERCE IN AGRICULTURAL MARKETING

- 1. Direct Farmer-to-Consumer Linkage:** E-commerce reduces dependency on intermediaries, allowing farmers to sell directly to consumers or bulk buyers, increasing their share of profits.
- 2. Real-Time Market Information:** Farmers can access up-to-date price trends, demand patterns and market conditions, helping them make better marketing decisions.
- 3. Market Expansion:** Digital platforms remove geographical barriers, enabling farmers to sell beyond local mandis and access national and global markets.
- 4. Improved Supply Chain Efficiency:** E-commerce platforms streamline logistics, storage, and transportation, reducing delays and minimizing post-harvest losses.
- 5. Secure and Fast Payments:** Digital payment systems ensure transparency, quick transactions and reduced risk of fraud or delayed payments.

6. Access to Inputs and Advisory Services: Farmers can purchase inputs like seeds and fertilizers online and receive expert advice on crop management, weather forecasts and pest control.

Additional Roles of E-commerce Platforms

7. Promotion of Value Addition: Platforms encourage farmers to sell processed or graded products (e.g., cleaned grains, packaged fruits), which fetch higher prices.

8. Support for Small and Marginal Farmers: Small-scale farmers can collectively market their produce through digital platforms, improving their bargaining power.

9. Data-Driven Decision Making: E-commerce platforms collect data on prices, demand and supply, helping farmers plan production and marketing strategies effectively.

10. Reduction in Wastage: Better coordination between supply and demand reduces surplus production and spoilage of perishable goods.

ADVANTAGES OF E-COMMERCE PLATFORMS

- Higher income due to better price realization
- Transparency in transactions and pricing
- Time-saving and convenience
- Access to wider and competitive markets
- Improved efficiency in supply chain
- Encouragement of digital and financial inclusion

CHALLENGES AND LIMITATIONS

- Low digital literacy among farmers
- Inadequate rural internet connectivity
- Lack of cold storage and transport facilities
- Trust and reliability concerns in online trade
- Limited awareness and training opportunities

GOVERNMENT INITIATIVES SUPPORTING E-COMMERCE

The Government plays an important role in promoting digital agricultural marketing through initiatives such as:

- e-NAM for unified national markets
- Digital India programs to improve rural connectivity
- Farmer training and awareness programs
- Support for agritech startups

FUTURE PROSPECTS

The future of e-commerce in agriculture is promising with increasing digital penetration in rural areas. Technologies like artificial intelligence, big data and blockchain are expected to further enhance transparency and efficiency. Integration with mobile applications and farmer-producer organizations (FPOs) will strengthen adoption. With proper infrastructure and policy support, e-commerce can significantly improve agricultural marketing systems.

CONCLUSION

E-commerce platforms are reshaping agricultural marketing by bridging the gap between farmers and markets. They offer better pricing, transparency and efficiency while reducing dependence on traditional systems. Continuous technological advancement, government support and farmer education will ensure their successful adoption. E-commerce has the potential to make agriculture more profitable and sustainable.

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Climate-Smart Rice Farming: Understanding Greenhouse Gas Emissions and Sustainable Mitigation Approaches



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Abstract

Rice is one of the most important staple crops globally and occupies a significant proportion of agricultural land in South and South East Asia. However, conventional flooded rice cultivation is recognized as a major source of greenhouse gas (GHG) emissions, particularly methane (CH₄) and nitrous oxide (N₂O), which contribute substantially to global warming and climate change. Continuous inundation of paddy fields creates anaerobic conditions that favor methanogenesis, while nitrogen fertilization and soil microbial transformations lead to N₂O emissions. Andhra Pradesh, one of the major rice-producing states of India, follows intensive rice-rice cropping systems that often increase the environmental footprint of rice production. This review examines the mechanisms of GHG generation in rice ecosystems, factors influencing emissions, and scientifically validated mitigation strategies. Water management interventions such as alternate wetting and drying (AWD), improved nutrient management, biochar application, crop residue management, and climate-smart agricultural practices are discussed in detail. Adoption of these sustainable management approaches can significantly reduce GHG emissions while maintaining productivity, improving resource-use efficiency, and contributing to national carbon neutrality goals.

Keywords: Rice cultivation, Greenhouse gases, Alternate wetting and drying, Biochar, Climate-smart agriculture, Carbon footprint and Sustainable rice production

Introduction

Climate change has emerged as one of the most crucial global environmental challenges of the 21st century. The accumulation of greenhouse gases (GHGs) in the atmosphere has intensified the greenhouse effect, resulting in rising global temperatures, altered precipitation patterns and increased frequency of extreme weather events. Agriculture contributes substantially to anthropogenic GHG emissions, accounting for approximately 18% of global emissions, with rice cultivation being a major source of methane and nitrous oxide emissions.

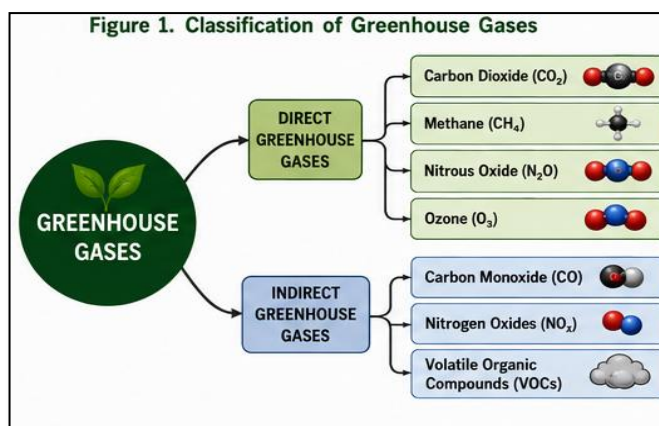
Rice covers about 25% of India's total gross cropped area, which approximately 51 to 52 million hectares. This makes rice the most extensively cultivated crop in the nation, positioning India as the leading rice producer globally. In India, traditional or conventional rice cultivation methods, which involve prolonged flooding, lead to anaerobic soil conditions that increase methane production. Simultaneously, nitrogen fertilizer applications contribute to nitrous oxide emissions through nitrification and denitrification processes. Therefore, sustainable rice production requires management interventions that minimize GHG emissions without compromising grain yield and profitability. The present review synthesizes current scientific understanding of greenhouse gas emissions from rice ecosystems and highlights practical mitigation strategies suitable for sustainable rice cultivation.

Greenhouse Gases and their Significance in Agricultural:

Greenhouse gases are atmospheric constituents capable of absorbing and re-emitting infrared radiation, thereby trapping heat within the Earth's atmosphere.

1. Classification of Greenhouse Gases:

- Direct Greenhouse Gases:** The gases like carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and ozone (O_3) are directly absorb thermal radiation and contribute to global warming.
- Indirect Greenhouse Gases:** The gases like carbon monoxide (CO), nitrogen oxides (N_2O) and Volatile organic compounds (VOCs) are influence atmospheric chemistry and facilitate the formation of greenhouse gases.



2. Global Warming Potential (GWP):

Methane (28-36) and nitrous oxide (265-298) possess significantly higher warming potentials than carbon dioxide (1), making their mitigation particularly important in agricultural systems.

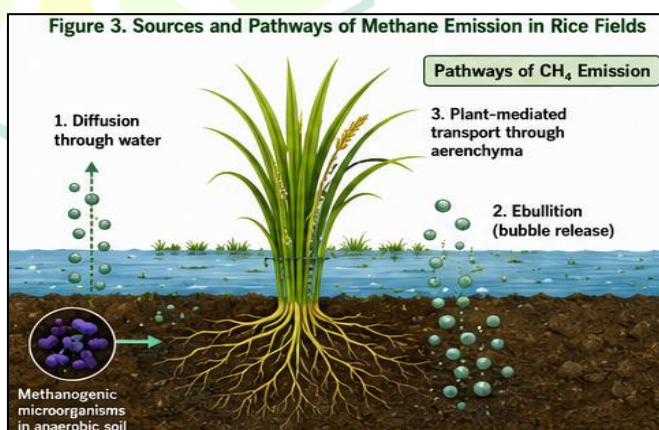
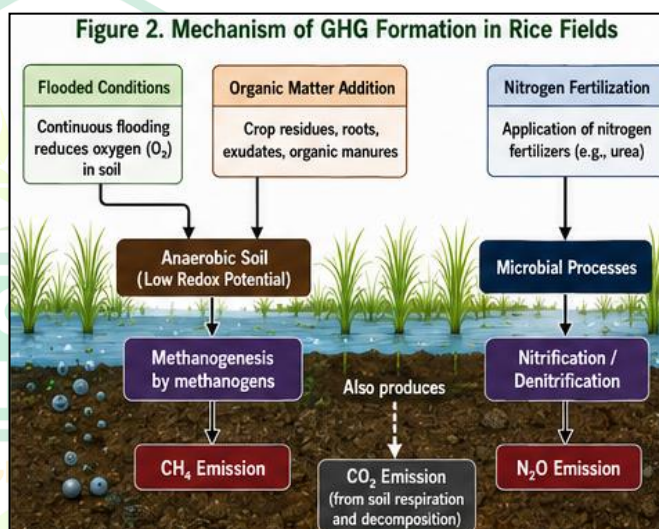
Greenhouse Gas Emissions from Rice Fields

Rice ecosystems contribute to atmospheric GHG concentrations through emissions of CO_2 , CH_4 , and N_2O . Among these gases, methane is the dominant contributor under flooded conditions.

Carbon Dioxide (CO_2) Emissions: Carbon dioxide emissions originate primarily from decomposition of soil organic matter, root respiration, microbial activity, crop residue decomposition and fertilizer-induced biological processes. Although rice fields emit CO_2 , flooded conditions generally suppress aerobic decomposition, resulting in lower CO_2 emissions compared with upland agricultural systems.

Methane (CH_4) Emissions: Methane is produced through methanogenesis under anaerobic conditions. When paddy soils remain submerged for prolonged periods, oxygen availability decreases, creating favorable conditions for methanogenic microorganisms. Methane reaches the atmosphere through diffusion through floodwater, ebullition (gas bubble release) and transport through rice plant aerenchyma tissues. Methane emissions are strongly influenced by water management, organic matter availability, soil redox potential, and rice cultivar characteristics.

Nitrous Oxide (N_2O) Emissions: Nitrous oxide is generated through nitrification, oxidation of ammonium (NH_4^+) under aerobic conditions, denitrification, reduction of nitrate (NO_3^-) under anaerobic conditions. N_2O emissions increase when nitrogen fertilizers are applied excessively or when wetting and drying cycles create alternating aerobic and anaerobic environments.



Factors Influencing Greenhouse Gas Emissions in Rice Ecosystems

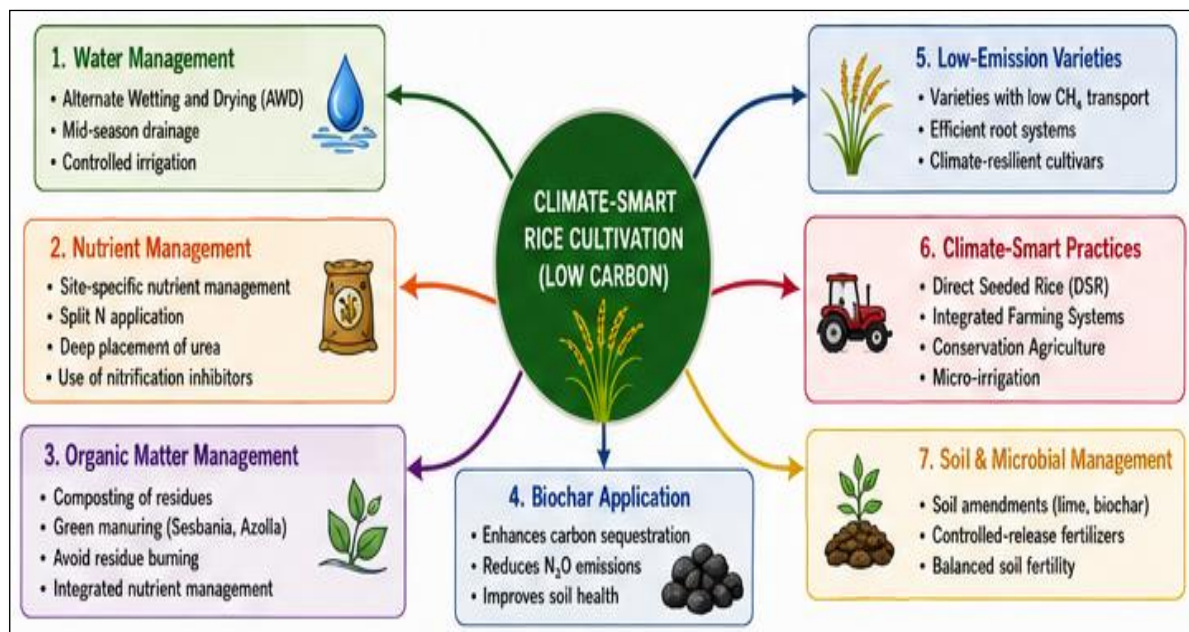
- a. Several biophysical and management factors influence GHG emissions:
- b. Water management practices
- c. Nitrogen fertilizer application rates
- d. Soil organic carbon content
- e. Crop residue incorporation
- f. Soil microbial activity
- g. Rice cultivar characteristics
- h. Soil texture and redox conditions
- i. Climatic variables

Understanding these factors is essential for designing effective mitigation strategies.

Mitigation Strategies for Reducing Greenhouse Gas Emissions

1. **Improved Water Management:** Water management is considered the most effective strategy for methane mitigation.
 - a. Alternate Wetting and Drying (AWD): AWD involves intermittent irrigation rather than continuous flooding. Benefits include reduction of methane emissions by up to 50%, water savings of 20–30%, maintenance of grain yield and improved root growth.
 - b. Mid-Season Drainage: Temporary drainage during crop growth introduces oxygen into the soil, suppressing methanogenic activity and reducing methane production.
 - c. Controlled Irrigation: Optimized irrigation scheduling reduces both water consumption and greenhouse gas emissions.
2. **Nutrient Management:** Effective fertilizer management plays a crucial role in reducing N_2O emissions. Key strategies involve tailoring nutrient management to specific sites, applying nitrogen in multiple stages, placing urea briquettes deeply, utilizing slow-release fertilizers, applying neem-coated urea, and incorporating nitrification inhibitors. These methods enhance the efficiency of nitrogen use and reduce the loss of nitrogen in gaseous form.
3. **Biochar Application:** Biochar, a material abundant in carbon, is generated by the pyrolysis of biomass. Its advantages encompass boosting soil carbon storage, lowering N_2O emissions, enhancing soil fertility, improving nutrient retention, and increasing water retention capacity. Additionally, biochar alters microbial activity in the soil and inhibits the nitrification-denitrification processes that lead to N_2O production.
4. **Organic Matter and Residue Management:** Effective management of organic amendments can help in lowering emissions. Recommended strategies include composting crop residues, employing sesbania and cowpea for green manuring, refraining from burning residues, and adopting integrated nutrient management (INM). The practice of burning residues should be avoided as it leads to increased greenhouse gas emissions and deteriorates soil health.
5. **Selection of Low-Emission Rice Cultivars:** Rice varieties differ in root exudation patterns, aerenchyma development and methane transport capacity. Cultivars with improved resource-use efficiency and lower methane transport potential should be promoted for climate-smart rice production.
6. **Soil Chemical and Microbial Management:** Amending soil to affect microbial activities can help reduce greenhouse gas emissions. This can be achieved through practices like applying lime, using biochar, employing controlled-release fertilizers, managing residues in an integrated manner, and selectively using herbicides. These strategies alter the microbial communities that play a role in producing methane and transforming nitrogen.
7. **Climate-Smart Agricultural Practices:** Several climate-resilient technologies contribute to emission reduction:
 - a. Direct Seeded Rice (DSR): Compared with transplanted rice reduces methane emissions by 16–54%, saves labor and water and facilitates mechanization.
 - b. Integrated Farming Systems: Combining the rice farming with other allied enterprises like fish farming, livestock and horticultural crops etc., enhances resource recycling and reduces net carbon footprint.

8. **Micro-Irrigation Technologies:** Use of precision irrigation systems can reduce emissions while improving water productivity.



Conclusion

Rice cultivation plays a dual role in global climate dynamics. While rice ecosystems contribute to food security and carbon sequestration, they are also important sources of methane and nitrous oxide emissions. Sustainable management interventions such as alternate wetting and drying, improved nutrient management, biochar application, residue recycling, direct-seeded rice, and integrated farming systems offer substantial opportunities for reducing greenhouse gas emissions without compromising productivity. Adoption of these climate-smart practices can contribute significantly toward sustainable agriculture, environmental protection, and national commitments to carbon neutrality.

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Paddy Straw Management in Crop Fields



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Abstract

Rice cultivation generates enormous quantities of paddy straw annually, creating a major challenge for sustainable agricultural management. Open-field burning of paddy straw, a common disposal practice, leads to significant environmental pollution, greenhouse gas emissions, nutrient loss, and deterioration of soil health. *In-situ* decomposition has emerged as an environmentally friendly and economically viable alternative for managing crop residues. This approach involves the decomposition of paddy straw directly in the field through the application of beneficial microbial consortia and appropriate agronomic practices. Specialized microorganisms produce lignocellulolytic enzymes that accelerate the breakdown of cellulose, hemicellulose, and lignin present in rice straw, converting the residues into valuable organic matter and plant-available nutrients. *In-situ* decomposition enhances soil organic carbon, improves nutrient cycling, increases microbial activity, and promotes better soil structure and water-holding capacity. Furthermore, it contributes to carbon sequestration and reduces air pollution by eliminating the need for residue burning. Recent advances in microbial technologies have improved the efficiency of straw degradation, making this approach a promising solution for sustainable residue management. Thus, *in-situ* decomposition transforms paddy straw from an agricultural waste into a valuable resource, supporting climate-smart agriculture and long-term soil health.

Keywords: Paddy straw, *In-situ* decomposition, Microbial consortium, Residue management, Soil health, Carbon sequestration, Sustainable agriculture

Introduction

India possesses one of the largest areas under agricultural cultivation in the world and is a major producer of rice. The continuous increase in rice production has led to a corresponding rise in rice straw generation, resulting in the accumulation of large quantities of crop residues every year much of which remains underutilized (Bhattacharya et al., 2021). Following harvest, farmers often face the challenge of managing these residues within a short interval before sowing the succeeding crop. Due to limited awareness and the lack of economically viable utilization options, open-field burning of rice straw and stubble has become a common practice because it is a rapid and inexpensive method of residue disposal. However, straw burning has emerged as a serious environmental and agricultural concern. It releases substantial quantities of greenhouse gases and particulate matter into the atmosphere, causing air pollution and contributing to climate change. In addition, open burning results in the loss of valuable plant nutrients, depletion of soil organic carbon, deterioration of soil health, and adverse effects on beneficial soil microorganisms (Zhan et al., 2018).

Therefore, sustainable residue management strategies are essential to mitigate these environmental impacts while maintaining agricultural productivity. Among the available residue management approaches, *in-situ* decomposition of rice straw has gained considerable attention as an environmentally friendly and economically

feasible alternative. Effective *in-situ* decomposition can convert crop residues into valuable organic matter, improve soil fertility, and provide long-term benefits to farmers. Nevertheless, rice straw is a recalcitrant lignocellulosic biomass composed primarily of lignin, cellulose, and hemicellulose, making its degradation relatively slow compared with other organic residues. Efficient decomposition therefore requires optimization of environmental conditions and the use of specialized lignocellulolytic microorganisms. Since microbes play a pivotal role in the decomposition process, the development of an effective microbial consortium capable of accelerating straw degradation within a short period is critical for successful field-level implementation.

What is *In-situ* Decomposition?

In-situ decomposition refers to the breakdown of paddy straw directly in the field where it is produced. Instead of burning or removing the residues, farmers incorporate or retain the straw in the field and facilitate its decomposition through microbial inoculants, moisture management, and suitable agronomic practices. Beneficial microorganisms produce enzymes such as cellulases, xylanases, and ligninases that degrade complex plant materials into simpler compounds. These compounds are eventually converted into soil organic matter and plant-available nutrients (Katyal et al., 2023). The process flow diagram of *in-situ* decomposition of paddy straw is given below (fig 1).

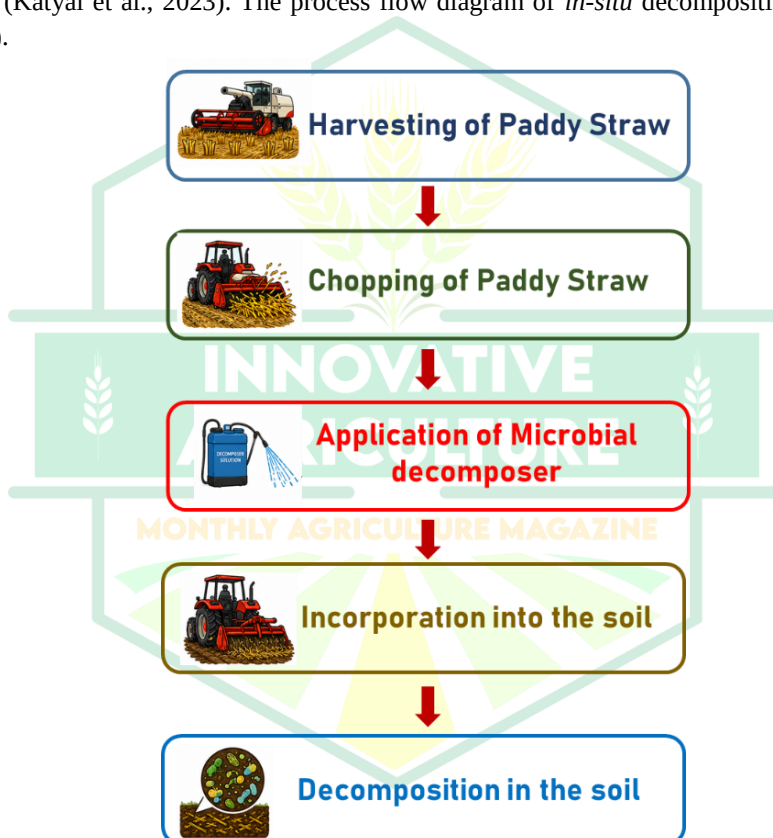


Figure 1: Process of *in-situ* decomposition of paddy straw

Role of Beneficial Microorganisms

Paddy straw contains high amounts of cellulose, hemicellulose, and lignin, making it resistant to natural degradation. Specialized microbial consortia comprising bacteria and fungi can accelerate the decomposition process. Researchers have reported that microbial consortia containing lignocellulose-degrading microorganisms significantly enhance straw degradation by increasing enzyme activity and reducing the carbon-to-nitrogen ratio of residues (Sharma et al., 2014). Field studies have further demonstrated that microbial inoculation increases microbial activity and accelerates residue breakdown under rice–wheat cropping systems (Kumar et al., 2019).

Benefits of *in-situ* decomposition of paddy straw

Soil Health

One of the major advantages of *in-situ* decomposition is the improvement of soil health. As the straw decomposes, it contributes organic carbon and releases nutrients such as nitrogen, phosphorus, potassium, and micronutrients

into the soil. Research has shown that microbial-assisted straw decomposition improves soil microbial populations, enzymatic activities, and nutrient cycling processes. Increased organic matter also enhances soil structure, water-holding capacity, and long-term fertility (Kumar et al., 2019; Katyal et al., 2023).

Contribution to Carbon Sequestration

Crop residues represent an important source of carbon. When straw is burned, much of this carbon is released into the atmosphere. In contrast, decomposition and incorporation of residues into soil help store carbon in the form of soil organic matter. Improved residue management contributes to carbon sequestration, thereby supporting climate-smart agriculture and reducing the environmental footprint of rice cultivation (Zhan et al., 2018).

Environmental Advantages

The environmental benefits of *in-situ* decomposition extend beyond soil health. Avoiding residue burning reduces emissions of carbon dioxide, methane, nitrous oxide, particulate matter, and other pollutants that negatively affect air quality and human health. Microbial-based residue management technologies offer an environmentally friendly alternative that supports sustainable agriculture while reducing pollution (Katyal et al., 2023). The overall benefits of *in-situ* decomposition of paddy straw is represented in fig 2.

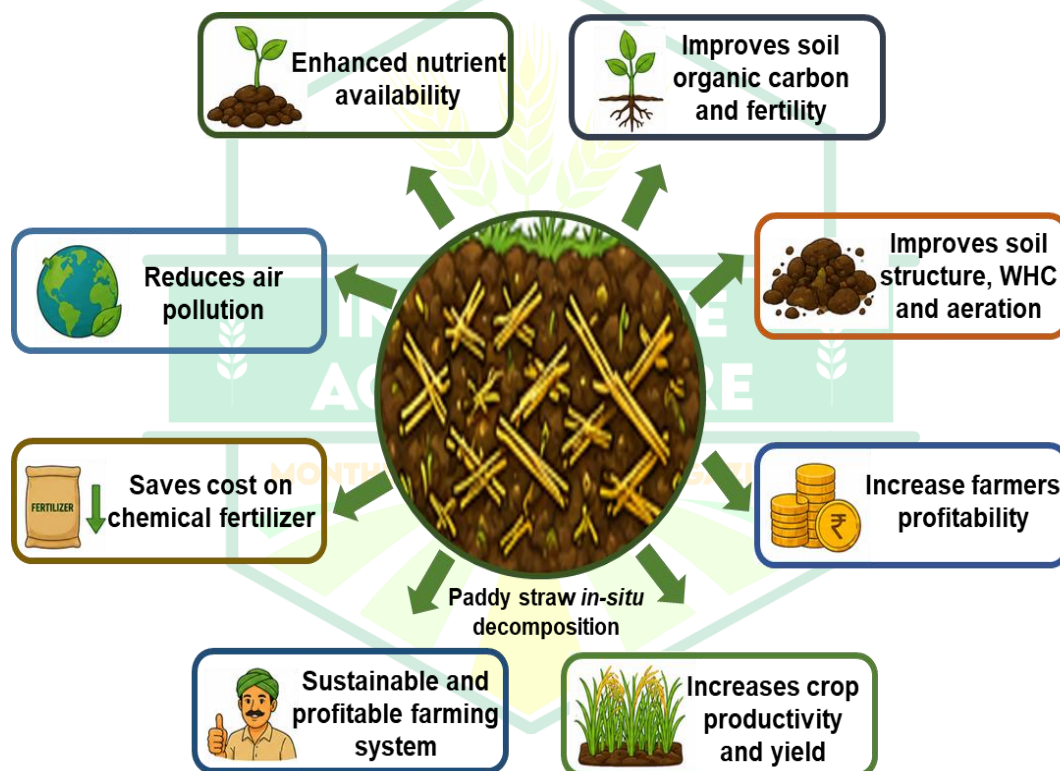


Figure 2: Benefits of *in-situ* decomposition of paddy straw

Future Prospects

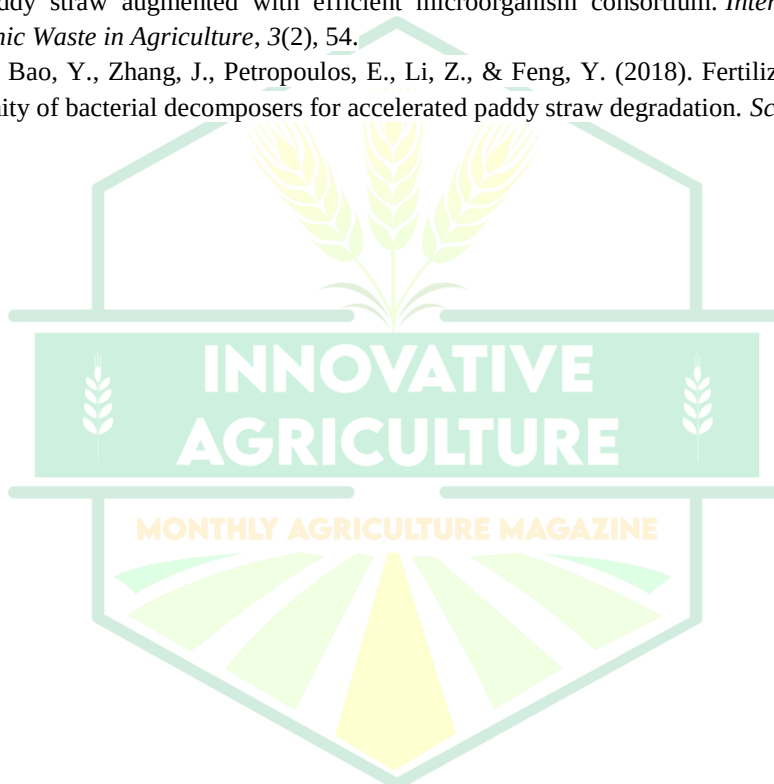
Advances in agricultural microbiology have led to the development of efficient microbial consortia capable of rapid decomposition of paddy straw. These technologies can help farmers recycle nutrients, reduce fertilizer costs, and improve soil quality. With increasing awareness of sustainable farming practices and governmental support for residue management, *in-situ* decomposition is emerging as a promising strategy for enhancing agricultural productivity while protecting the environment.

Conclusion

Paddy straw should be viewed not as waste, but as a valuable resource. *In-situ* decomposition converts crop residues into soil organic matter, improves nutrient recycling, enhances soil health, and contributes to environmental sustainability. Adoption of microbial-assisted residue decomposition can help achieve cleaner agriculture, healthier soils, and sustainable crop production for future generations.

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Ayurveda's Antibiotics: Five Herbs That Fight Lung Infections



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Abstract

This article looks at five plants long used in Ayurvedic medicine *Euphorbia hirta*, *Albizia lebbbeck*, *Cordia dichotoma*, *Cassia occidentalis*, and *Clerodendrum serratum* and how their traditional reputations for treating cough, bronchitis, and asthma hold up against modern laboratory testing. Drawing on published research, it explores the specific compounds behind each plant's effects, how they perform against key respiratory bacteria such as *Staphylococcus aureus*, *Streptococcus pyogenes*, and *Streptococcus pneumoniae*, and what this reveals about the shared chemistry connecting these otherwise unrelated species. Alongside the promising findings, the article highlights an important safety concern: raw *Cassia occidentalis* seeds have been linked to serious, sometimes fatal poisoning in children. Written for a general audience, the piece aims to make traditional plant medicine and its modern scientific validation approachable, while being clear that the current evidence remains preclinical and these herbs are not a substitute for professional medical care.

Keywords: Ayurveda; medicinal plants; respiratory infections; antimicrobial herbs; traditional medicine

Introduction

Walk along almost any roadside, riverbank, or patch of wasteland in rural India, and you'll likely pass at least a couple of the plants in this article without giving them a second glance. They're weeds, in the everyday sense of the word the kind of scrappy, fast-growing greenery that pushes up through cracked pavement and gets pulled out of gardens. But in Ayurveda, India's traditional medical system, these same overlooked plants have been prized for thousands of years as remedies for cough, bronchitis, and asthma. Classical Sanskrit texts even sorted plants by exactly this kind of job: herbs labeled *Kasahara* eased cough, *Shwasahara* calmed breathlessness, *Kaphahara* cleared mucus. Modern labs have started taking a second look at these old classifications, testing traditional plants directly against the bacteria known to cause respiratory infections. What they've found is a genuinely interesting mix of old wisdom holding up under new scrutiny here's a closer look at five of the most-studied.

Euphorbia hirta: The "Asthma Weed" That's Everywhere

If you've ever pulled weeds in the tropics, you've probably met *Euphorbia hirta* a small, hairy, ground-hugging herb that oozes a milky sap when snapped. It's earned the nickname "asthma weed" across several countries for a reason: traditional healers have reached for it for generations to treat coughs, bronchitis, and breathing trouble, alongside stomach complaints. Chemically, the plant is loaded with flavonoids, tannins, and other compounds known for their germ-fighting properties. When researchers tested extracts of the whole plant directly against the three bacteria most associated with respiratory infections *Staphylococcus aureus*, *Streptococcus pyogenes*, and *Streptococcus pneumoniae* the extracts showed real antibacterial activity, with *S. aureus* proving the most vulnerable of the three. Other studies have found the plant fights an even wider range of bacteria, suggesting its reputation as an all-purpose infection fighter isn't limited to the lungs. Traditionally, it's used as a decoction (a strong boiled tea) or fresh juice, though the raw milky sap itself can irritate skin and shouldn't be applied directly or ingested undiluted (Figure 1).

Albizia lebbbeck: The Tree Bark That Calms Angry Airways

The Siris tree is a common sight along Indian roads, its feathery leaves and seed pods (the source of the nickname "woman's tongue tree," for the way they rattle in the wind) instantly recognizable. Its bark has a long-standing reputation in Ayurveda specifically for asthma traditional practitioners brew it into a tea and recommend it to reduce how often and how severely asthma attacks strike. Part of the reason may be that bark compounds appear to calm down mast cells, the immune cells responsible for triggering allergic reactions in the first place. Lab testing backs up more than just the anti-allergy angle. Bark extracts tested against the same trio of respiratory

bacteria showed genuine antibacterial power, strongest in the alcohol-based extract. Digging deeper, researchers found that the bark's tannin-rich compounds were especially effective against *S. aureus*, while its alkaloid compounds stood out against *S. pneumoniae* giving a plausible chemical explanation for centuries of traditional use (Figure 1).

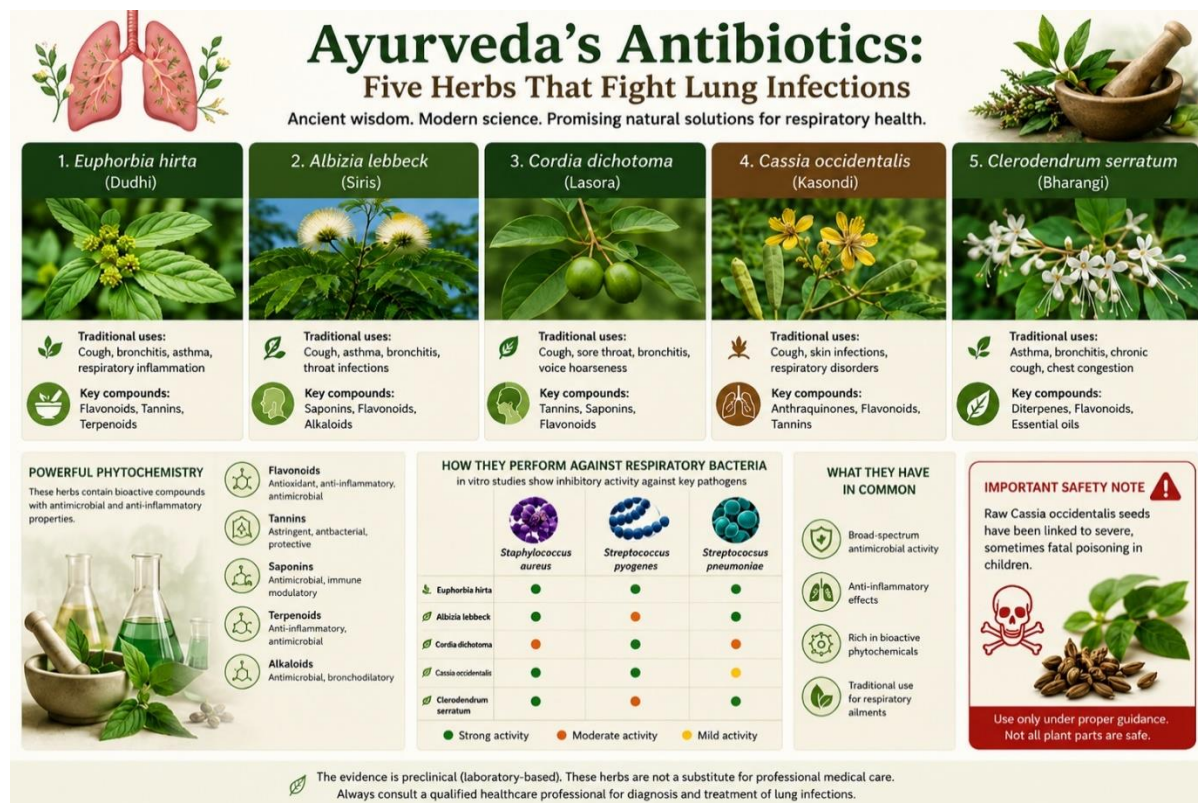


Figure 1. Traditional uses, major phytochemicals, and reported preclinical antimicrobial activity of five Ayurvedic medicinal plants (*Euphorbia hirta*, *Albizia lebeck*, *Cordia dichotoma*, *Cassia occidentalis*, and *Clerodendrum serratum*) against common respiratory bacterial pathogens. The figure also highlights the safety concern associated with raw *Cassia occidentalis* seeds and emphasizes that current evidence is laboratory-based.

***Cordia dichotoma*: The Soothing Bark of Bhokar**

Known as Bhokar in Hindi and Shleshmataka in Sanskrit a name that literally references its mucilaginous, soothing quality *Cordia dichotoma* is a fruit tree whose sticky-sweet berries are eaten across South and Southeast Asia, while its bark has a separate life in traditional medicine as a demulcent for cough and chest complaints. When researchers tested bark extracts against respiratory bacteria, the results were positive but came with an interesting wrinkle: the extracts actually inhibited a couple of unrelated gram-negative bacteria somewhat more strongly than they inhibited the classic respiratory culprits, *S. aureus* and *S. pyogenes*. That doesn't mean the plant has no effect on respiratory pathogens it clearly does just that its antibacterial strengths may lie a bit more broadly than the "cough remedy" reputation alone would suggest, a useful reminder that traditional use and laboratory potency don't always map onto each other perfectly (Figure 1).

***Cassia occidentalis*: The Herb Whose Name Means "Cough Destroyer"**

Few plants wear their reputation as plainly as this one: its Sanskrit name, *Kasamarda*, translates to roughly "cough destroyer." Classical Ayurvedic formulas mix its leaf juice with honey for cough relief and brew its flowers into a decoction for asthma. In the lab, seed extracts tested against *S. aureus*, *S. pneumoniae*, and *S. pyogenes* showed solid antibacterial activity, with tannin-rich fractions again standing out against the staph and strep bacteria, and alkaloid-rich fractions performing best against pneumococcus closely echoing the pattern seen in Siris bark. Here's the critical caveat, and it's a serious one: the raw seeds of this plant are genuinely dangerous, especially to children. In parts of northern India, recurring seasonal outbreaks of a severe illness in young children involving

liver damage, muscle damage, and brain swelling, with a distressingly high death rate have been directly linked to children eating the plant's raw seed pods, which they sometimes mistake for a curiosity to play with or chew during the autumn pod season. This isn't a mild "don't overdo it" caution like some of the other plants on this list; unprocessed *Cassia occidentalis* seeds are established as acutely toxic and should never be eaten raw by anyone, and children should be kept away from the plant's pods entirely. Traditional preparations rely on carefully processed leaf or flower material, not raw beans, and that distinction matters enormously (Figure 1).

5. *Clerodendrum serratum*: Bharangi, Ayurveda's Breathing Specialist

If any plant on this list has the deepest respiratory pedigree, it's this one. Bharangi shows up by name in the Sushruta Samhita, one of Ayurveda's foundational texts, specifically for cough, asthma, bronchitis, and lingering respiratory weakness. Its root the most valued part of the plant is classified as an expectorant and bronchodilator, meant to loosen mucus and ease labored breathing. Modern research has approached this plant a little differently than the others: rather than focusing purely on bacteria-killing power, much of the strongest evidence comes from an animal study of allergic asthma, where a root extract meaningfully calmed the inflammatory overreaction that drives asthma attacks reducing markers like IgE and several inflammatory signaling molecules while measurably improving lung function. On the antibacterial side, the essential oil from Bharangi's bark has shown real, dose-dependent activity against several bacteria, including drug-resistant staph strains, which is a genuinely encouraging finding given how hard those infections can be to treat. Compared to the other four herbs, less standardized head-to-head testing against the classic respiratory bacteria trio exists in the published literature, but the combination of calming inflammation and fighting infection gives Bharangi a well-rounded case for its ancient reputation.

The Common Thread

Look across all five plants, and a pattern starts to emerge. Whenever researchers compared different extraction methods, the alcohol-based (methanolic) extracts consistently outperformed water or oil-based ones likely because the compounds doing most of the antibacterial work, like tannins, flavonoids, and alkaloids, dissolve better in alcohol. And strikingly, the same two chemical classes kept showing up as MVPs against the same two bacteria: tannin-rich compounds repeatedly proved most effective against *Staphylococcus aureus*, while alkaloid-rich compounds repeatedly stood out against *Streptococcus pneumoniae*, across completely unrelated plant families. That's a reasonably strong hint that these compound classes are doing real, specific work not just a vague, generic "plants are healthy" effect.

A Necessary Caution

None of this evidence comes from human clinical trials it comes from extracts tested in lab dishes, and in one case, in an animal model of asthma. That's a meaningful gap between "shows promise against bacteria in a petri dish" and "ready to replace a prescribed antibiotic for an actual lung infection," and these plants shouldn't be treated as a substitute for proper medical care for anything beyond a mild, self-limiting cold. A few points are worth keeping close in mind: (i) Never eat raw *Cassia occidentalis* seeds or pods, and keep children away from the plant during its autumn seed season this is a documented, sometimes fatal poisoning risk, not a minor caution. (ii) Traditional preparations (decoctions, processed leaf or bark powders) are not the same as raw plant material, and the difference in safety can be enormous. (iii) *Euphorbia hirta*'s raw milky sap can irritate skin and shouldn't be ingested directly. (iv) Herbal supplement quality varies widely, and misidentified or contaminated plant material is a real risk when sourcing outside a reputable Ayurvedic supplier. (v) Pregnant or breastfeeding people, young children, and anyone on prescription medication should check with a doctor or qualified Ayurvedic practitioner before using any of these in concentrated or extract form.

The Takeaway

There's something quietly satisfying about watching modern microbiology circle back and confirm what generations of Ayurvedic physicians worked out through centuries of careful observation that a roadside weed like *Euphorbia hirta* really does have something to offer against the bacteria that cause chest infections, or that Bharangi's reputation as a breathing specialist rests on a genuine chemical foundation. These five herbs represent a real and growing area of scientific interest. But respect for tradition also means respecting its warnings, not just

its remedies and for now, that means treating them as a complement to good medical care, prepared correctly and used thoughtfully, rather than a replacement for it.

Conclusion

There's something quietly satisfying about watching modern microbiology circle back and confirm what generations of Ayurvedic physicians worked out through centuries of careful observation that a roadside weed like *Euphorbia hirta* really does have something to offer against the bacteria that cause chest infections, or that Bharangi's reputation as a breathing specialist rests on a genuine chemical foundation. These five herbs represent a real and growing area of scientific interest. But respect for tradition also means respecting its warnings, not just its remedies and for now, that means treating them as a complement to good medical care, prepared correctly and used thoughtfully, rather than a replacement for it

This article is for general educational purposes and isn't a substitute for professional medical advice. If you have a respiratory infection that's severe, persistent, or accompanied by high fever, difficulty breathing, or chest pain, seek medical care.



Defending Rice from Brown Planthopper: From Field Screening to Modern Genomics



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Abstract

The brown planthopper (*Nilaparvata lugens*) remains one of the most destructive pests in rice cultivation, causing direct feeding damage, "hopper burn," and transmission of viral diseases such as Rice Ragged Stunt Virus and Rice Grassy Stunt Virus. Decades of reliance on chemical insecticides have led to resistance evolution in pest populations and disruption of natural predator communities, prompting a shift toward host-plant resistance as a more sustainable management strategy. This article traces the pipeline from traditional phenotypic screening identifying resistant rice lines under controlled infestation to modern genomic approaches, including QTL mapping and genome-wide association studies (GWAS), which have enabled the identification of more than 35 brown planthopper resistance genes (e.g., *Bph1*, *Bph3*, *Bph14*, *Bph18*, *Bph32*). It further examines the molecular basis of resistance, encompassing structural defences, biochemical deterrents, and hormone-mediated signaling pathways, and highlights how marker-assisted selection, next-generation sequencing, multi-omics platforms, artificial intelligence, and CRISPR-Cas gene editing are accelerating breeding precision. Special attention is given to gene pyramiding as a strategy for achieving durable, broad-spectrum resistance. Taken together, these advances illustrate how integrating traditional breeding with modern genomics is shaping climate-resilient, pest-resistant rice varieties critical to global food security.

Keywords: Brown planthopper (*Nilaparvata lugens*); Host-plant resistance; QTL mapping/GWAS; Marker-assisted selection; Gene pyramiding

Introduction

Rice feeds more than half the world's population and underpins the livelihoods of billions of people, particularly across Asia. Every grain harvested represents months of labor by farmers who contend with unpredictable weather, shrinking natural resources, and a persistent, growing threat from insect pests. Among these pests, the brown planthopper (BPH), scientifically known as *Nilaparvata lugens*, stands out as one of the most destructive enemies of rice cultivation. Despite measuring only a few millimetres, this tiny insect has the power to devastate entire fields within weeks, leaving behind dried, scorched patches known as "hopper burn" and inflicting economic losses that can run into billions of dollars annually across rice-growing regions.

Unlike chewing insects that visibly shred leaves, brown planthoppers feed covertly. They pierce rice stems and leaf sheaths with needle-like mouthparts called stylets and draw nutrient-rich sap directly from the phloem the plant's internal transport system. This continuous, hidden feeding weakens the plant from within, disrupts water balance, reduces grain filling, and can kill the crop outright when populations build up. Compounding the damage, brown planthoppers act as carriers of destructive viral diseases, including Rice Ragged Stunt Virus and Rice Grassy Stunt Virus, which stunt growth and further cut yields. Climate change, shifts in agricultural practices such as excessive nitrogen fertilization, and the steady emergence of new insect "biotypes" capable of overcoming older resistance genes have made BPH outbreaks more frequent, more severe, and harder to predict making it one of the greatest recurring challenges to global rice production (Figure 1).

Why Chemical Control Is No Longer Enough

For decades, insecticides were the frontline weapon against brown planthopper infestations, and they worked well at first offering farmers fast, visible knockdown of pest populations. But repeated, heavy reliance on chemical sprays has produced a familiar and troubling pattern. Brown planthopper populations have evolved resistance to several widely used insecticide classes, so the same dose that once controlled an outbreak now barely dents it. Worse, indiscriminate spraying often wipes out the natural enemies of the planthopper spiders, mirid bugs, and other predators that would otherwise keep populations in check. Removing these beneficial insects can trigger what entomologists call "resurgence," where pest numbers rebound even larger than before the spray was applied.

The result is a costly, self-defeating cycle: rising input costs for farmers, mounting environmental pollution, and pest populations that keep adapting one step ahead of the next chemical. These mounting problems have pushed scientists and breeders toward a fundamentally different strategy one that works with the rice plant's own biology rather than against the insect with chemistry alone.

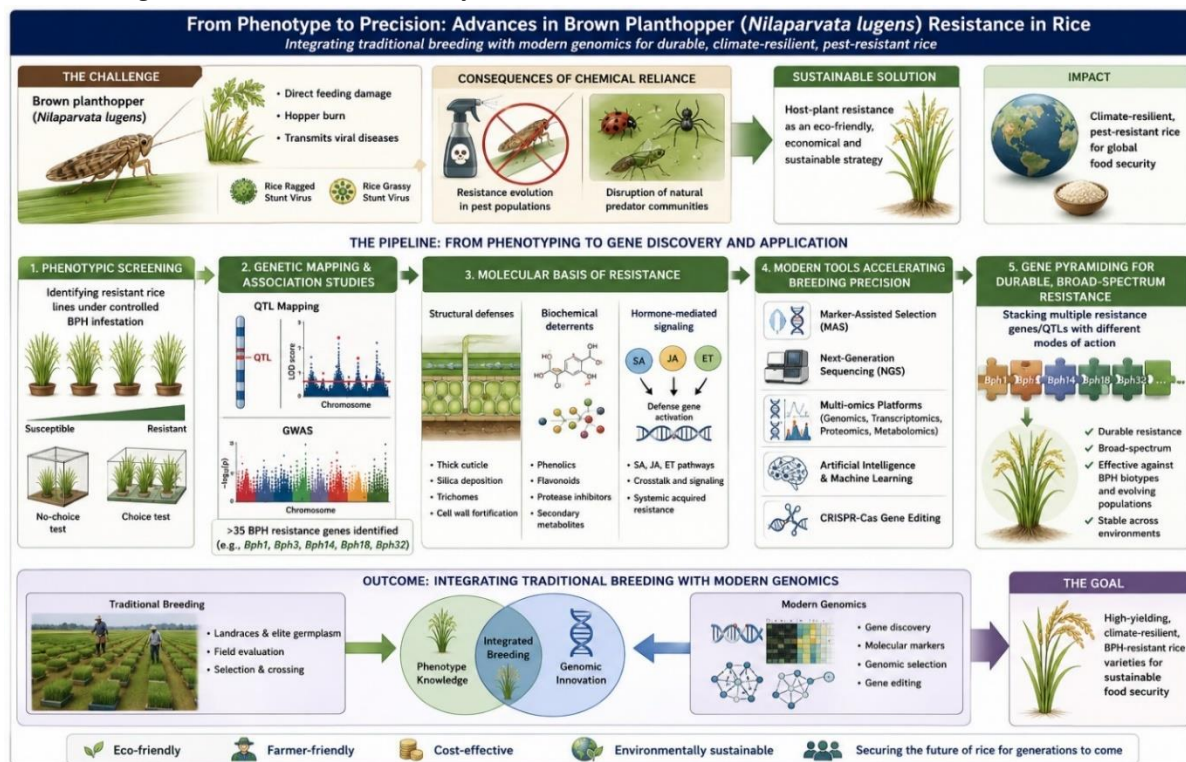


Figure 1. From Field to Genome: Advances in Brown Planthopper Resistance in Rice. Overview of the pipeline for developing brown planthopper-resistant rice, from phenotypic screening and QTL mapping to GWAS-based gene discovery. The figure highlights major resistance genes, the molecular mechanisms of resistance, and the integration of marker-assisted selection, gene pyramiding, multi-omics, artificial intelligence, and CRISPR-Cas genome editing to accelerate the development of durable, climate-resilient, pest-resistant rice varieties.

Searching for Nature's Defenders

Nature had already solved this problem in scattered pockets of rice diversity long before scientists began looking for it. Over thousands of years of natural selection, certain traditional rice varieties and their wild relatives evolved genuine resistance to brown planthopper attack. The task facing researchers is to find these resistant plants among enormous germplasm collections and move their protective traits into the high-yielding varieties that farmers actually grow. This search begins with phenotypic screening, a painstaking but essential process in which hundreds or thousands of rice lines are exposed to controlled brown planthopper infestations in greenhouses or specially built screening houses. Researchers track how each plant responds measuring leaf yellowing and wilting, overall plant survival, insect feeding damage, and how well the insect population grows and reproduces on that particular plant. Susceptible plants tell their own story quickly: leaves turn brown, growth stalls, and the plant may die within one to two weeks under heavy infestation. Resistant plants, by contrast, stay green and vigorous and go on to produce grain even as insects feed nearby. These survivors become the foundation stock for future breeding programs living proof that resistance is possible and a starting point for understanding why. Phenotypic screening can look deceptively simple count the healthy plants, discard the rest but it remains one of the most critical steps in the entire crop-improvement pipeline. No amount of downstream molecular sophistication can rescue a breeding program built on inaccurately identified resistant plants (Figure 1).

Looking Inside the Rice Genome

Identifying resistant plants answers one important question: *which plants survive?* Modern genomics answers a deeper and more useful one: *why do they survive?* Every rice plant carries thousands of genes distributed across

its twelve chromosomes. Among these, a select group plays outsized roles in recognizing insect attack, switching on defence signalling, reinforcing plant tissues, or manufacturing compounds that make sap less palatable or outright toxic to the feeding insect. Advances in DNA sequencing now let scientists scan the entire rice genome to pinpoint the genetic regions responsible for BPH resistance. Molecular markers such as simple sequence repeats (SSRs) and single nucleotide polymorphisms (SNPs) function like genomic landmarks or mile-markers, letting researchers narrow down a resistance trait from "somewhere in the genome" to a specific, well-defined stretch of DNA. Two tools in particular have transformed this search. Quantitative trait loci (QTL) mapping tracks how resistance is inherited across generations of a controlled cross, statistically linking specific chromosome regions to the resistant trait. Genome-wide association studies (GWAS) take a broader approach, scanning thousands of DNA markers across large, diverse rice populations collected from around the world to find regions that correlate with resistance, without needing a dedicated breeding cross first. Through decades of this work, researchers have cataloged more than 35 named brown planthopper resistance genes and loci, including well-characterized ones such as *Bph1*, *Bph3*, *Bph14*, *Bph17*, *Bph18*, *Bph26*, *Bph29*, and *Bph32*, many originally discovered in wild rice relatives or traditional landraces from India, Sri Lanka, and other parts of South and Southeast Asia. Each gene contributes a somewhat different defensive mechanism, and together they form a genetic toolbox that breeders can draw from to build more resilient rice (Figure 1).

Understanding How Rice Fights Back

Resistance to brown planthopper is rarely a single on/off switch it is a layered, multi-pronged defense system, and different genes contribute to it in different ways. Some resistant varieties develop physically tougher plant tissue, including denser silica deposits or thicker cell walls, that simply make it harder for the insect's stylet to reach the phloem. Others manufacture defensive biochemical compounds certain proteins, secondary metabolites, or altered sap chemistry that reduce the insect's survival, slow its growth, or impair its ability to reproduce once it does manage to feed. Still other resistance genes act more like an early-warning immune system: upon detecting insect saliva or feeding damage, they trigger rapid signalling cascades often involving plant hormones such as jasmonic acid and salicylic acid that switch on broader defensive responses within hours of attack. In the most robust resistant varieties, several of these mechanisms operate together, reinforcing one another. This dynamic mirrors a genuine evolutionary arms race. As brown planthopper populations are exposed to widely deployed resistance genes over large areas and many growing seasons, new insect biotypes gradually emerge that can overcome those defences which is precisely why the search for new resistance genes never really stops.

The Genomics Revolution in Rice Breeding

Modern rice breeding has entered an era where DNA information, not just field observation, guides decisions at nearly every stage of variety development. Rather than waiting for plants to mature and then testing them against live insects, breeders can now screen seedlings' DNA directly for the presence of known resistance genes. This approach, called marker-assisted selection, dramatically speeds up breeding programs by allowing breeders to advance only those young plants that already carry the desired genetic makeup saving years compared to traditional phenotype-only selection. Beyond gene-level markers, newer tools including next-generation sequencing, transcriptomics, proteomics, and metabolomics now offer a far more complete picture of what happens inside a rice plant under attack. Rather than studying one gene at a time, researchers can monitor thousands of genes simultaneously, track which ones switch on within minutes or hours of insect feeding, and map how different biological pathways interact to mount a coordinated defence.

Artificial intelligence and machine learning are increasingly layered on top of these datasets, helping breeders make sense of the sheer volume of genomic, phenotypic, and environmental information now being generated. These computational approaches can help predict which candidate breeding lines are most likely to carry durable, field-stable resistance narrowing the field before time-consuming physical trials even begin, and cutting both cost and development time. Meanwhile, genome-editing tools such as CRISPR-Cas are opening a more precise front altogether. Rather than transferring an entire resistance gene through conventional crossing which can drag along unwanted traits from the donor parent CRISPR allows scientists to fine-tune or introduce specific resistance-related DNA sequences directly, while leaving the rest of a high-yielding variety's genetic

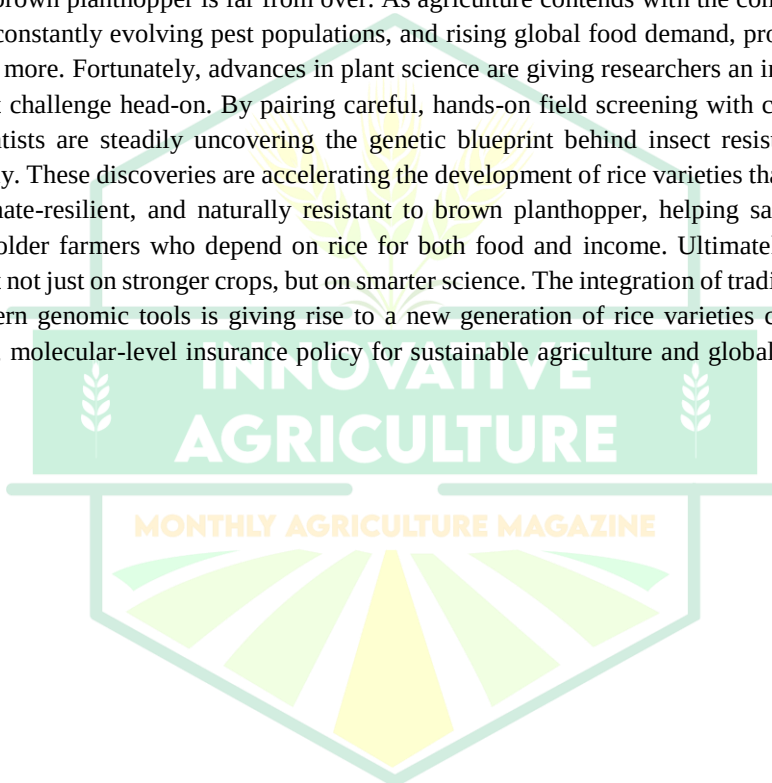
background untouched. This precision is helping researchers develop climate-resilient, pest-resistant rice without the years-long "backcrossing" traditionally needed to remove unwanted donor traits (Figure 1).

Building Rice for the Future

Among the most promising long-term strategies is gene pyramiding deliberately combining two, three, or more resistance genes into a single rice variety through successive breeding or, increasingly, gene-editing approaches. Because a brown planthopper population would need to simultaneously overcome several independent defence mechanisms at once not just one pyramided variety are expected to hold their resistance for far longer than varieties relying on a single gene, which pests can adapt to overcome in just a handful of growing seasons. When resistant varieties are combined with integrated pest management practices such as monitoring insect populations before spraying, conserving natural predator populations, and adjusting fertilizer use the payoff extends well beyond any single field. Farmers spend less on insecticides, production costs fall, biodiversity in and around rice paddies is better conserved, and the overall system becomes more environmentally sustainable.

A Sustainable Path Forward

The battle against brown planthopper is far from over. As agriculture contends with the combined pressures of a changing climate, constantly evolving pest populations, and rising global food demand, protecting the rice crop has never mattered more. Fortunately, advances in plant science are giving researchers an increasingly powerful toolkit to meet that challenge head-on. By pairing careful, hands-on field screening with cutting-edge genomic technologies, scientists are steadily uncovering the genetic blueprint behind insect resistance gene by gene, pathway by pathway. These discoveries are accelerating the development of rice varieties that are simultaneously high-yielding, climate-resilient, and naturally resistant to brown planthopper, helping safeguard harvests for millions of smallholder farmers who depend on rice for both food and income. Ultimately, the future of rice production will rest not just on stronger crops, but on smarter science. The integration of traditional plant breeding wisdom with modern genomic tools is giving rise to a new generation of rice varieties capable of defending themselves a quiet, molecular-level insurance policy for sustainable agriculture and global food security in the decades ahead.



CONSERVATION AGRICULTURE FOR SOIL HEALTH IMPROVEMENT



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Abstract

Soil degradation caused by intensive tillage, monocropping, and poor residue management has become a major challenge to sustainable agricultural production worldwide. Conservation agriculture (CA) has emerged as an effective and climate-resilient approach to restoring soil health while maintaining long-term productivity. This article examines the fundamental principles of conservation agriculture-minimal soil disturbance, permanent soil cover, and crop diversification-and their collective role in improving soil physical, chemical, and biological properties. Evidence from recent studies highlights that CA enhances soil organic carbon, microbial biomass, water infiltration, nutrient cycling, and aggregate stability while reducing erosion, greenhouse gas emissions, and production costs over time. The article also discusses the practical benefits experienced by farmers, including improved water-use efficiency, greater resilience to climate variability, and more stable crop yields after the transition period. Emerging technologies such as remote sensing, precision agriculture, and digital soil monitoring are explored for their contribution to wider adoption of conservation practices. Although challenges such as initial yield reductions, equipment costs, weed management, and competing uses of crop residues remain, these can be addressed through gradual implementation, extension support, and appropriate policy interventions. Overall, conservation agriculture offers a practical, scientifically validated pathway for restoring soil health, enhancing agricultural sustainability, and strengthening global food security under changing climatic conditions.

Introduction

Walk into a field that has been ploughed year after year, and the soil often tells its own story: hard, cracked in summer, quick to turn to mud in the rains, and increasingly poor at holding on to water or nutrients. Now walk into a neighbouring field that has not been tilled for a few seasons, is never left bare, and grows more than one crop in rotation. The difference is often visible within minutes darker, crumblier soil, earthworms near the surface, and water that soaks in rather than running off. This is the promise of conservation agriculture, a farming approach increasingly seen as one of the most practical routes back to healthy, productive soil.



Conservation agriculture, or CA, is not a single technique but a philosophy built on three interlinked principles: disturb the soil as little as possible, keep it covered at all times, and grow a diversity of crops rather than the same one repeatedly. According to a comprehensive 2025 review of the practice, these three pillars work together to restore soil structure, boost organic carbon, and strengthen the biological life of the soil far more effectively than any single practice on its own. Across climates and continents, farmers who have adopted this combined approach are quietly rebuilding soils that decades of intensive tillage had worn down.

What Exactly is Conservation Agriculture?

At its core, CA rests on three pillars that reinforce one another

Minimal soil disturbance: Instead of ploughing, farmers use no-till or reduced-till methods, sowing seeds directly into the residue of the previous crop. This protects the soil's natural structure and the fungal networks and channels built up by roots and earthworms.

Permanent soil cover: Crop residues, mulch, or living cover crops are left on the surface instead of being burned or removed. This blanket shields the soil from sun, wind, and heavy rain.

Crop diversification: Rotating cereals with legumes, or intercropping different species, breaks pest cycles, balances nutrient use, and feeds a wider range of soil organisms.

None of these ideas is new on its own farmers have practised versions of mulching or rotation for generations. What CA offers is a systematic way of combining all three, so that their benefits compound rather than working in isolation. This is why researchers increasingly describe it as the “cornerstone” of sustainable soil management rather than simply one option among many

Why the soil responds so well

Soil is not an inert growing medium; it is a living system, home to fungi, bacteria, earthworms, and countless microorganisms that cycle nutrients and build structure. Conventional tillage disrupts this community every time the plough passes through, breaking up fungal threads and exposing organic matter to rapid decomposition. Over years, this leads to compacted layers, declining organic carbon, and soils that erode easily and hold less water.

Long-term field studies comparing conservation and conventional systems have found meaningfully higher soil organic carbon and better soil aggregation under conservation practices, alongside lower carbon dioxide loss from the soil. Research on cover cropping in irrigated systems has similarly linked the practice to noticeably higher organic carbon storage and richer microbial activity within just a few growing seasons. Perhaps most striking, an eight-year field experiment on the North China Plain found that soils under conservation agriculture kept building organic carbon and microbial biomass even under sustained artificial warming, delivering a 21% average improvement in overall soil health and a 9.3% wheat-yield gain compared with conventionally managed soil under the same warming conditions clear evidence that healthier soil also buffers crops against a changing climate. “Healthy soil isn't just a growing medium it's a living infrastructure that determines how well a farm can withstand drought, flood, and heat.”

The Benefits Farmers Actually Notice

Better water management: Surface residue slows runoff and evaporation, letting more rain soak in a critical advantage during dry spells or erratic monsoons.

Lower input costs over time: Fewer tillage passes mean savings on fuel, labour, and machinery wear, while healthier soil structure can gradually reduce dependence on synthetic fertiliser.

Reduced erosion: A protected soil surface resists being washed or blown away, preserving the fertile topsoil that took centuries to form.

Higher, steadier yields over the long run: While the first one or two seasons after switching to no-till can see a dip as soil biology re-establishes itself, yields typically stabilise and often improve as organic matter builds and the soil's water-holding capacity increases.

Climate resilience: By storing more carbon and supporting diverse soil life, CA fields tend to cope better with heat stress, dry spells, and heavy rainfall events.

Wider ecosystem gains: Reviewers also point to biodiversity conservation, lower greenhouse gas emissions, and stronger food-system resilience as CA is adopted at larger scales.

IN THE FIELD

Getting Started with Conservation Agriculture

- Start small. Convert a portion of the farm first rather than the whole holding, and compare results before scaling up.
- Keep residue on the surface. Resist the urge to burn or remove crop stubble; it is the cheapest mulch available.
- Use a cover crop in the off-season. Legumes such as cowpea or clover add nitrogen and protect bare soil between main crops.
- Rotate, don't repeat. Alternate cereals with legumes or oilseeds to break pest and disease cycles naturally.

- Be patient with the transition. Soil biology takes one to three seasons to rebuild; early yield dips are common and usually temporary

A Global Shift, Still Gaining Ground

Conservation agriculture is now practised on a meaningful share of the world's arable land, with adoption spreading across large parts of the Americas, Australia, and increasingly Asia and Africa as extension agencies and farmer networks promote the approach. A recent systematic review linking soil health to the United Nations Sustainable Development Goals notes that improved soil management contributes directly to zero-hunger and climate-action targets by boosting nutrient cycling and carbon storage, while also supporting farmer incomes where adoption is backed by policy incentives.

Government and research bodies in several countries have woven conservation and regenerative practices into formal soil-health and climate-resilience programmes. In the United States, for example, the Natural Resources Conservation Service outlines core soil-health principles minimising disturbance, maximising cover, and building diversity as the foundation of its farmer-facing guidance, and in December 2025 it launched a new outcomes-based Regenerative Pilot Program aimed at strengthening soil health and water management on working farms. Similar extension pushes are underway elsewhere, often pairing training with subsidies for no-till equipment or support for cover-cropping and residue management.

Technology is Making Adoption Easier

New tools are lowering the barriers to adopting and sustaining conservation practices. Remote sensing and satellite imagery now help farmers track residue cover and soil moisture across large areas, while precision agriculture technologies are being used to fine-tune irrigation, cutting water use by as much as 12% in some documented cases while reducing crop water stress. Low-cost soil-testing kits and mobile apps let even smallholders monitor organic matter and plan rotations without expensive laboratory access. Reviewers describe this convergence of digital tools and conservation principles as key to scaling CA for higher productivity without sacrificing sustainability.

Researchers caution, however, that the carbon-building benefits of these practices are not indefinite: soils tend to reach a new, healthier equilibrium over a decade or two, after which the rate of further improvement slows. This is a reminder that conservation agriculture is a long-term strategy for soil stewardship, not a quick fix, and that gains should be measured in seasons and years rather than weeks

The Challenges Worth Knowing

Conservation agriculture is not without hurdles. Specialised no-till seed drills can be costly for smallholders, weed pressure can rise in the first seasons before residue cover suppresses it naturally, and competing uses for crop residue as fodder or fuel in many regions can make leaving it in the field a genuine trade-off. Climate volatility adds further complexity: rising temperatures and erratic rainfall are estimated to increase pest incidence and can reduce yields of major crops if left unmanaged, making the transition period itself more demanding for farmers already under pressure.

Extension experts generally advise a gradual, field-by-field transition, farmer-to-farmer learning, and access to shared equipment or government support schemes to ease the shift. Interdisciplinary collaboration between researchers, policymakers, and farming communities is repeatedly identified as essential for developing context-specific solutions rather than one-size-fits-all recommendations.

To Known

Will yields drop when I switch to conservation agriculture? Often, yes, briefly. Most farmers see a modest dip in the first one to two seasons as soil biology and structure re-establish themselves. Yields typically recover and frequently exceed previous levels once organic matter and water-holding capacity improve.

Do I need expensive machinery to begin? Not necessarily. While dedicated no-till seed drills help, many smallholders start with simple, low-cost steps retaining residue, adding a cover crop, and rotating with a legume before investing in specialised equipment.

Does conservation agriculture work in every climate? The underlying principles are considered universal, but the specific mix of practices, crop choices, and timing needs to be adapted to local soil type, rainfall pattern, and cropping system. Local extension advice is important before scaling up.

How long before I see a real difference in the soil? Visible improvements in structure and water infiltration can appear within two to three seasons, while measurable gains in organic carbon and microbial activity build over several years and continue for a decade or more before levelling off

Conclusion

Soil degradation is one of agriculture's quietest crises easy to overlook until yields begin to slip or a single hard rain washes away a season's topsoil. Conservation agriculture offers a practical, farmer-tested answer: disturb less, cover more, and diversify. The transition takes patience, but the destination is soil that drinks in water instead of shedding it, that feeds itself through living roots and residue, and that keeps working for the next season, and the one after that. In an era of erratic rainfall and rising heat, few investments a farmer can make matter more than the ground beneath their crop.



Harnessing the Gandak: Integrated Farming Strategies for the Diara Lands of Bihar



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Abstract

Bihar is a landlocked state with various constraints on seasonal cultivation. Although the agricultural lands are flood-prone, the Gandak Diara lands are fertile due to the repeated deposition of silt each year. The article highlights sustainable approaches to increase the productivity in the Diara area. It includes Integrated Farming System (IFS) by integrating crops, livestock, horticulture, fisheries, and riverbed farming. Such a diversified farming system reduces the risk as well as enhances the productivity and supports the farmers to increase their income in such an area. This article also discusses challenges faced by flooding, erosion, and other constraints, and considers some policies regarding them to uncover the potential of these dynamic areas.

Keywords: Gandak River, Diara, Integrated Farming System (IFS)

1. Introduction

Bihar's economy is mainly based on its agricultural sector. It engages 77% of the workforce and contribute 24.84% of the state's gross domestic product (GDP). The workforce in Bihar is much higher than the national average, indicating lower production per worker (Kumar, 2024). The main barrier to agricultural development in Bihar is its seasonal and geographical flooding and drought. Bihar constitutes 2.8% geographical area and 8% population of India, however the flood-affected cover around 17% area (73% of the state's geographical area) and 36% population of India (Ojha, 2018).

Gandak Diara lands in Bihar are dynamic riverine floodplains formed by annual deposition of nutrient-rich alluvial sediments. It shows some characteristics viz., seasonal land availability, high soil fertility, sandy to loamy texture, and moisture variability (Figure 1). After the monsoon, these Diara lands get exposed and remain in good condition to do cultivation for next 4-6 months. However, people who live in these areas face some challenges such as unpredictable floods and erosion, leading to unstable landforms and agricultural risk. It is mainly beneficial for rabi season because it remains wet for crop production. Since it is available for crop cultivation for a short time period, requires crop diversification, which includes maize, cucurbits, banana, sugarcane, and pulses. Thus, mixed cropping or intercropping systems increase farmers' resilience under unwanted conditions.

In the context, integrated farming system (IFS) became more important than crop diversification due to smaller land holdings. The integrated farming system, which includes crops, livestock, fisheries, and allied enterprises in Diara land, is very valuable for minimizing the risk of flooding and crop failure, providing year-round income opportunities despite seasonal land use, supporting a climate-resilient cropping system, and harnessing enriched soil and other resources in a highly efficient way.

2. Integrated farming strategies for Gandak Diara

There are several IFS strategies that can be considered for the Diara region, especially for the Gandak River (Figure 2) (Singh et al., 2024 and Kumar et al., 2018).

2.1. Crop diversification & sequential cropping

Crop diversification is preferred in flooded land, including short duration crops such as watermelon, muskmelon, and cucurbits. This approach minimizes the risk of crop loss and ensures harvest occur before drought or declines in soil moisture. In the post-monsoon conditions, the area can be used for cucurbits, followed by maize or pulses. Some flood-tolerant rice varieties can be grown for a short time period in kharif season.

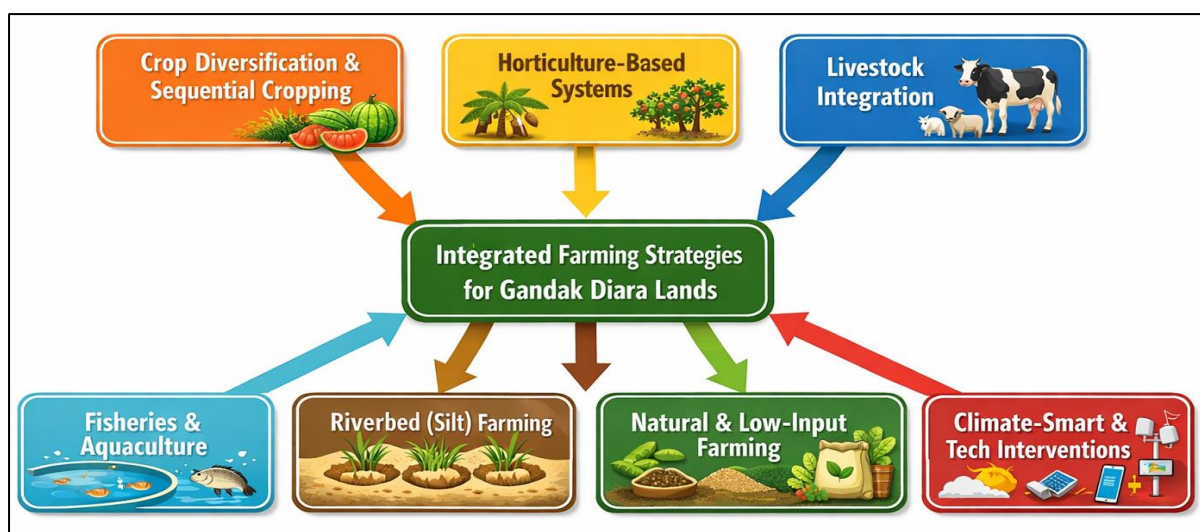


Figure 1. Integrated Farming Strategies

2.2. Horticulture-Based Systems

It is a farming system including long-term, high value crops such as fruits, vegetables and other plantation crops to stabilize and improve the productivity of Diara lands. The Gandak Diara condition mainly suitable for banana plantations and provide a reliable high income to farmers. Additionally, farmers can adopt an agroforestry model by growing trees viz., poplar and bamboo, alongside crops. These models help farmers to generate more income and act as natural barriers against wind and water erosion. In horticultural models, mango, guava, and litchi plantations are other options that help improve farmers' income and reduce the risk of flooding. Including perennial crops/plants ensures a continuous income source without frequent replanting. Therefore, these models help with income diversification, land stabilization, erosion control, and support for fragile and dynamic Diara ecosystem.

2.3. Livestock Integration

The inclusion of livestock with cropping system is an important component of IFS in the Diara region. It provides a continuous source of income during times of submergence of agricultural land. The goat rearing is an option, especially for landless and marginal farmers because it required low maintenance cost and survive well on locally available resources. They also serve as a flexible income source for farmers. Dairy farming is another component of livestock to support natural farming by providing agricultural inputs for nutrient management. It improves soil health, microbial activity, and creating a sustainable environment for agro-ecosystem. It utilizes crop residues during the flood season and serves as an income source throughout the year. Another important supporting enterprise that can be integrated with IFS is duck farming. Duckery thrives well in Diara conditions by utilizing underused water bodies. Thus, livestock serves as a buffer for farmers' overall income during crop failure and provides resilience in this fragile Diara ecosystem.

2.4. Fisheries and aquaculture

Fisheries and aquaculture are the most feasible component of the IFS by using the floodwater of the Gandak Diara. There are many areas where post-flood water remains trapped (waterlogged) for several months that provide suitable habitats for fish culture. There are various schemes in Bihar to support fisheries and aquaculture across different regions like Pathari Kshetr Talab Nirman Adharit Matsya Paalan ki Yojana, which enhance construction of ponds for controlled farming systems. Due to these, Bihar has witnessed significant growth in fish production. It can also be integrated with crop production, such as rice–fish systems. This type of farming system improves overall farm productivity and ensures a steady supply of nutrients and income to the farmers by harnessing the available resources in an optimal way.

2.5. Riverbed (Silt) farming innovations

Riverbed or silt farming is accepted by farmers to enhance the water holding capacity of soil. It is a innovative farming practice performed through pit technique after receding of flood. Mulching and organic manures are used

in this practice to enhance soil organic matter, soil structure, regulate soil temperature, and to suppress weed growth. Crops like watermelons, cucumbers, muskmelons, and other cucurbits are the important crops grown under this type of area. It converts the sandy zone into a profitable cultivation zone.

2.6. Natural & low-input farming

Diara regions required natural and low input farming system instead of heavily relying on chemical fertilizers and pesticides due to its dynamic and fragile soil condition. People who live in those areas mostly use animal-based products and other waste products (organic manure, green compost, and biofertilizer) in their farming and cut down the cost of cultivation by reducing external inputs. The government of Bihar has an organic belt to grow organic products and promoting natural farming in Diara region.

2.7. Climate-smart & technological interventions

Climate-smart agriculture is highly important in the Diara region. The technology, such as an early warning system for floods, is highly useful for alerting farmers, enabling early harvests, protecting livestock, and minimizing losses. The Government of Bihar also advises farmers on all aspects of agriculture and provides real-time information through mobile-based apps like the Bihar Krishi App. These technological interventions and traditional farming practices promote adaptability, risk reduction, and sustainable agriculture in the Diara region.

Challenges to Implementation

Although Diara regions have high potential for crop production, but it has several constraints. The major constraints are:

- ❖ Flooding and erosion, destroy crops and homes
- ❖ Lack of land tenure security
- ❖ Lack of good market access and infrastructure
- ❖ Fragmented landholding of the farmers and low capital investment.

Annual flooding continues to disrupt livelihoods across North Bihar.

Policy & Institutional Support Needed

To fully harness Gandak Diara lands, the following interventions are crucial:

- ❖ Development of Diara-specific farming models
- ❖ Strengthening Farmer-Producer Organisations (FPOs)
- ❖ Investment in storage, transport, and market linkages
- ❖ Promotion of integrated farming clusters
- ❖ Expansion of crop insurance and credit access

Conclusion

The Diara land of the Gandak basin is highly fertile, productive land, however these area faces some risk related to flooding and erosion, leading to unstable landforms and crop failures. The integrated farming system can significantly enhance livelihoods, ensure food security, and build climate resilience. By blending traditional systems with modern integrated strategies, Bihar may turn floodplain from zones of vulnerability into engines of agricultural prosperity.

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Prospects of smart agriculture: Transforming farming through IoT



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Abstract

Smart agriculture has emerged as a transformative approach to addressing the growing challenges of food security, climate change, resource scarcity, and declining agricultural productivity. The integration of the Internet of Things (IoT) with advanced digital technologies such as artificial intelligence, cloud computing, remote sensing, drones, and data analytics is revolutionizing conventional farming by enabling real-time monitoring, automated decision-making, and precision resource management. This review explores the concept of smart agriculture, highlighting the key components of IoT-based farming systems, including smart sensors, cloud computing, data analytics, and automated control systems. These technologies facilitate continuous monitoring of soil, crops, weather, and irrigation, enabling efficient use of water, fertilizers, and pesticides while enhancing productivity and environmental sustainability. The paper also discusses the future prospects of smart agriculture in improving farm profitability, climate resilience, and sustainable food production. Furthermore, it examines the major challenges limiting widespread adoption, including high implementation costs, inadequate digital infrastructure, limited technical expertise, and data security concerns. The review concludes that continued technological advancements, supportive government policies, affordable digital solutions, and capacity-building initiatives will be essential for accelerating the adoption of IoT-enabled smart agriculture. Embracing smart farming technologies can significantly contribute to sustainable agricultural development, efficient natural resource management, and global food security.

Keywords: Smart agriculture; Internet of Things (IoT); Precision agriculture; smart sensors; sustainable farming

Introduction

Agriculture is undergoing a profound transformation as digital technologies redefine conventional farming practices into intelligent, data-driven production systems. The increasing global population, projected to reach nearly 9.7 billion by 2050, is expected to raise food demand by approximately 70%, placing unprecedented pressure on agricultural systems to produce more with limited natural resources while minimizing environmental impacts (FAO, 2017). Simultaneously, climate change, declining soil fertility, water scarcity, labour shortages, and rising production costs pose significant challenges to sustainable agricultural development. These concerns necessitate the adoption of innovative technologies that improve resource-use efficiency, enhance productivity, and strengthen climate resilience.

Smart agriculture has emerged as a promising solution by integrating advanced digital technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), cloud computing, remote sensing, Geographic Information Systems (GIS), unmanned aerial vehicles (UAVs), and big data analytics into agricultural production. Among these, IoT has become the cornerstone of precision agriculture by enabling continuous monitoring of field conditions through interconnected sensors, automated data collection, real-time analysis, and intelligent decision-making. IoT-based systems provide farmers with timely information on soil moisture, weather conditions, crop health, irrigation requirements, nutrient status, and pest incidence, facilitating precise farm management while reducing input costs and environmental degradation (Wolfert et al., 2017).

The adoption of IoT-driven smart agriculture not only improves crop productivity and resource efficiency but also contributes to sustainable food production by optimizing water use, reducing greenhouse gas emissions, minimizing chemical inputs, and enhancing farm profitability (Zhang et al., 2017). As digital agriculture

continues to evolve, IoT is expected to play a pivotal role in transforming traditional farming into a more resilient, productive, and sustainable agricultural system capable of addressing future food security challenges.

What is Smart Agriculture?

Smart agriculture is an advanced farming approach that integrates modern digital technologies with agricultural production to enhance productivity, optimize resource utilization, and ensure environmental sustainability. It combines technologies such as the Internet of Things (IoT), artificial intelligence (AI), cloud computing, remote sensing, geographic information systems (GIS), global positioning systems (GPS), drones, robotics, and big data analytics to monitor and manage agricultural operations with greater precision and efficiency. Through interconnected sensors and automated systems, real-time information on soil moisture, weather conditions, crop health, nutrient status, irrigation requirements, and pest incidence is continuously collected and analyzed, enabling farmers to make timely, data-driven decisions. This technology-driven approach facilitates precision application

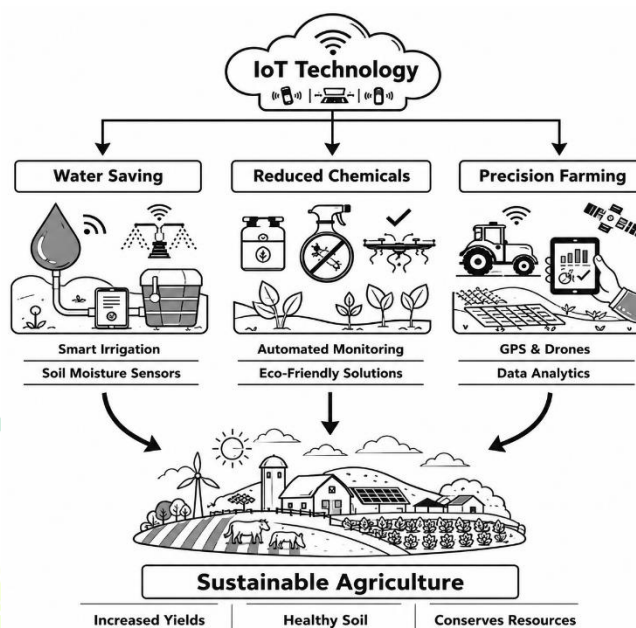


Figure 1. Smart agriculture ecosystem powered by IoT

of water, fertilizers, and plant protection measures, thereby reducing input costs, minimizing resource wastage, and lowering environmental pollution. Furthermore, smart agriculture enhances farm productivity, improves crop quality, strengthens resilience to climate variability, and supports sustainable natural resource management. By transforming traditional farming into an intelligent, automated, and information-based production system, smart agriculture enables efficient farm management while addressing the growing challenges of food security, labour shortages, resource scarcity, and climate change. As agriculture moves towards digital transformation, smart farming is emerging as a cornerstone of sustainable agricultural development, promoting higher profitability, improved resilience, and long-term environmental conservation.

Components based on IoT agriculture:

Sensors that are placed in the field to gather information on several environmental parameters, including temperature, humidity, soil moisture, and nutrient levels are the main components of IoT-based smart crop monitoring systems. These sensors are frequently networked, enabling real-time data transmission to a centralized cloud-based platform. To gain insights into crop health, growth rates, and yield potential, the data gathered from these sensors is then examined using machine learning and other data analytics techniques. Farmers can use this information to make choices on crop management including irrigation, pest control, and harvest. Implication of wireless sensor technologies can alert administrators and farmers regarding equipment fault and initiates trouble shooting. Moreover automated repairing tool could help in reducing energy consumption, escalating data processing, and enhancing actuation.

These sensors could aid in automated harvesting of crops, monitoring of environmental conditions, and measurement of crop yields. Sensors integrated with chips designated as smart sensors. Smart sensors can automatically record several environmental data and other related information in agricultural set ups with higher accuracy and store them in drives. These data are processed through microprocessors for interpretation and analysis. Smart sensors are the integral components of IoTs and data are transmitted using internet. It comprises wireless and actuator network system involving few to thousands of nodes connected to sensor hubs. Therefore a smart sensor is constituted of a sensor device, microprocessors, and wireless communication technology that

enable remote surveillance of several factors in agriculture. Smart sensors can be coupled with other components such as amplifiers, transducers, analog to digital converters and analog filters to enhance their performance.

Data collected through sensors gives information about different environmental condition to monitor the whole system properly. Monitoring the environmental conditions or crop productivity is not only the factor for the evaluation of crop but there are many other factors which effect the crops' productivity, e.g. field management, soil and crop monitoring, movement of an unwanted object, attacks of wild animals, and thefts.

Cloud computing:

Collaboration of IoT and cloud computing in agriculture provides pervasive access to shared resources. To meet various agricultural needs upon request over network and execute operations cloud computing plays vital role. Cloud based software architecture has been proposed which process and retrieve information and agricultural tasks in a more accurate way. In the field of IoT edge computing is considered as a solution to facilitate data processing at the source of data generation which are sensors, actuators and many other embedded devices. Edge computing or fog computing are measured as the backbone of cloud computing. This technology is deployed according to the features and requirements of smart farming. Cloud computing serves as the foundation for data storage, processing, and analysis in smart farming. Large amounts of data collected on the farm by sensors, drones, and other smart equipment are transferred to the cloud for centralized processing. Farmers may now get useful insights, make educated decisions, and reap the benefits of data driven precision agriculture.

The capabilities of fog computing are enhanced by bringing them nearer to the data-generating devices at the edge of the network, which improves cloud computing. The word "fog" refers to the computer infrastructure that exists between the cloud (centralized data centers) and end-user devices (or sensors). To reduce latency and boost efficiency are especially in applications that need real-time processing and decision-making , it aims to move computing power, storage, and networking closer to the data source. In smart farming, fog computing is utilized to install edge devices, including edge servers, actuators, and sensors. This decentralized strategy lowers latency, improves real-time data processing, and enables rapid reaction to changing environmental circumstances.

Data analytics:

Data analytics is a fundamental component of smart agriculture that transforms large volumes of agricultural data into meaningful information for informed decision-making. Data generated from sensors, weather stations, drones, satellites, and farm machinery are collected, processed, and analyzed to provide real-time insights into crop growth, soil health, weather conditions, irrigation requirements, and pest and disease incidence. The integration of remote sensing technologies with advanced data analytics enables continuous monitoring of agricultural fields through ground-based, aerial, and satellite observations. Modern analytical tools, including artificial intelligence (AI), machine learning (ML), image processing, and geospatial analysis, identify patterns, predict crop performance, detect crop stress at an early stage, and support site-specific farm management. Predictive analytics further assists farmers in forecasting weather events, estimating crop yields, optimizing irrigation schedules, and planning nutrient and pest management strategies. In addition, data analytics improves livestock management by monitoring animal health and behaviour, while enhancing supply chain efficiency through better production planning and market forecasting. By converting complex datasets into actionable recommendations, data analytics enables precision farming, improves resource-use efficiency, reduces production costs, minimizes environmental impacts, and enhances the overall productivity and sustainability of agricultural systems.

Automated control system:

Automated control systems are a vital component of IoT-based smart agriculture, enabling real-time monitoring and precision management of farming operations with minimal human intervention. These systems integrate a wide range of smart sensors to continuously monitor soil moisture, nutrient availability, pH, electrical conductivity, organic matter content, and irrigation water quality. The information collected is transmitted to automated irrigation and fertigation systems, ensuring that water and nutrients are applied only when and where they are needed. This precision-based approach minimizes resource wastage, reduces production costs, improves input-use efficiency, and enhances soil health. In addition, wireless sensor networks (WSNs) facilitate seamless communication between field devices and cloud platforms, enabling remote monitoring and control of agricultural

operations. Such automation supports timely decision-making, improves water-use efficiency, and contributes to sustainable crop production under varying environmental conditions.

Advances in automated control systems have been further strengthened through the integration of drones, remote sensing, artificial intelligence (AI), and machine learning (ML). Unmanned Aerial Vehicles (UAVs) equipped with multispectral and thermal sensors provide high-resolution images for monitoring crop growth, nutrient deficiencies, pest infestations, and disease outbreaks at an early stage. AI-powered image analysis and predictive algorithms convert these observations into actionable recommendations, allowing farmers to implement timely interventions and optimize crop management practices. Intelligent pest monitoring systems, autonomous irrigation controllers, and low-power IoT devices further enhance farm automation by reducing labour requirements while improving the accuracy of field operations. Together, these technologies create an intelligent decision-support system that enhances crop productivity, conserves natural resources, strengthens climate resilience, and promotes sustainable agricultural development.

Prospects of smart agriculture

Smart agriculture holds immense potential to transform the future of farming by improving productivity, profitability, and sustainability through the integration of digital technologies. The adoption of IoT, artificial intelligence, cloud computing, drones, robotics, and data analytics enables farmers to make precise, data-driven decisions that optimize the use of water, fertilizers, pesticides, and other agricultural inputs. This technology-driven approach not only enhances crop yield and quality but also reduces production costs, minimizes environmental impacts, and improves resource-use efficiency. Smart agriculture plays a crucial role in addressing major challenges such as climate change, water scarcity, labour shortages, and declining soil fertility by supporting climate-resilient and precision farming practices. Real-time monitoring and automated farm management systems facilitate early detection of pests, diseases, and nutrient deficiencies, enabling timely interventions and reducing crop losses.

Furthermore, digital platforms improve market access, supply chain management, and farm advisory services, empowering farmers with timely information for better decision-making. As governments, research institutions, and private organizations continue to invest in digital agriculture, smart farming technologies are becoming increasingly accessible to farmers of all scales. In the coming years, the integration of next-generation technologies such as 5G communication, blockchain, autonomous machinery, digital twins, and advanced artificial intelligence is expected to further revolutionize agricultural production, contributing significantly to global food security, environmental conservation, and sustainable rural development. Smart agriculture therefore represents a transformative pathway towards building a resilient, efficient, and future-ready agricultural sector.

Challenges and future outlook

Despite its immense potential, the widespread adoption of smart agriculture faces several challenges, including high initial investment costs, inadequate digital infrastructure, limited internet connectivity in rural areas, lack of technical knowledge among farmers, and concerns related to data security and privacy. Small and marginal farmers often encounter difficulties in accessing advanced technologies due to financial and infrastructural constraints. Addressing these challenges requires supportive government policies, affordable digital solutions, capacity-building programmes, and stronger collaboration among research institutions, technology providers, and farming communities. Looking ahead, rapid advancements in artificial intelligence, robotics, blockchain, 5G connectivity, and autonomous farm machinery are expected to make smart agriculture more accessible, efficient, and scalable. With sustained investments in innovation and digital literacy, smart agriculture has the potential to transform farming into a resilient, productive, and sustainable sector capable of meeting future food security and environmental challenges.

Conclusion

Smart agriculture, driven by the Internet of Things (IoT), is transforming conventional farming into a more intelligent, efficient, and sustainable production system. By integrating smart sensors, data analytics, cloud computing, artificial intelligence, and automated control systems, farmers can make informed decisions, optimize resource utilization, and improve crop productivity while minimizing environmental impacts. Although challenges such as high investment costs, digital infrastructure, and technology adoption remain, continued

technological advancements and supportive policies are expected to accelerate the adoption of smart farming. Embracing IoT-enabled smart agriculture will not only enhance farm profitability and resilience but also contribute significantly to sustainable food production, natural resource conservation, and global food security in the years to come.

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Metalaxyl Resistance in Phytophthora: A Growing Challenge for Sustainable Crop Protection



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Abstract

Metalaxyl has been one of the most effective systemic fungicides for controlling diseases caused by *Phytophthora* species. Its extensive use in crops such as potato, pepper, soybean, vegetables and fruit crops has greatly reduced disease losses. However, repeated and unplanned applications have resulted in the rapid development of resistant pathogen populations, reducing the effectiveness of this fungicide. A review of published studies from 1983 to 2024 indicates that resistance has now been reported from many agricultural regions worldwide and in several important *Phytophthora* species. Intensive cropping, continuous fungicide use, lack of fungicide rotation and monoculture farming have accelerated resistance development. This review summarizes the global status of metalaxyl resistance, explains the major factors responsible for its emergence, discusses resistance mechanisms and highlights practical strategies for sustainable disease management.

Keywords: Metalaxyl, *Phytophthora*, fungicide resistance, intensive agriculture, disease management, phenylamide

Introduction

Phytophthora species are among the most destructive oomycete pathogens, causing diseases such as late blight, root rot, foot rot, crown rot and damping-off in numerous agricultural and horticultural crops. These diseases frequently result in severe yield and quality losses, particularly under warm and humid conditions (Savary *et al.*, 2019). Metalaxyl, a systemic phenylamide fungicide introduced in the late 1970s, has long been regarded as an effective tool for managing oomycete diseases because of its excellent systemic movement and curative action (FRAC, 2023). However, its continuous and intensive use has led to the emergence of resistant *Phytophthora* populations, reducing its long-term effectiveness. This review highlights the global occurrence of metalaxyl resistance, the factors responsible for its development and sustainable strategies to preserve its efficacy.

Global Distribution of Resistance

Resistance to metalaxyl has been reported in several economically important *Phytophthora* species. Resistant populations are now widespread with the highest incidence occurring in regions practicing intensive cultivation of high-value crops. Long-term surveys indicate a steady increase in resistance, particularly in monoculture production systems where repeated fungicide applications are common (Bittner & Fry, 2021).

1.	North and South America	<i>P. infestans</i> , <i>P. capsici</i> , <i>P. sojae</i>
2.	Europe	<i>P. infestans</i> in potato and tomato production
3.	South Asia	<i>P. parasitica</i> , <i>P. palmivora</i> , <i>P. colocasiae</i>
4.	East and Southeast Asia	High resistance prevalence in pepper and cucurbit systems
5.	Africa	Emerging reports in cacao and taro systems

Factors Contributing to Resistance

Frequent application of metalaxyl without rotation with fungicides having different modes of action remains the primary factor driving resistance development. Continuous exposure favours the survival and multiplication of resistant isolates, eventually leading to field control failures. Monocropping further accelerates this process by providing a continuous host for pathogen survival. In addition, the movement of infected planting materials, contaminated irrigation water, soil and farm equipment facilitates the spread of resistant populations. Climate

change, especially increased temperature and prolonged periods of high humidity, has further intensified disease pressure and increased dependence on fungicides.

Mechanisms of Resistance

Metalaxyl suppresses pathogen growth by interfering with ribosomal RNA synthesis. Resistance develops through genetic alterations that reduce fungicide sensitivity, along with physiological adaptations such as reduced fungicide uptake and enhanced detoxification mechanisms (Kamoun *et al.*, 2022). Many resistant isolates retain high pathogenicity and competitive fitness, allowing them to survive and persist even in the absence of fungicide selection pressure. Consequently, resistant populations may remain established in agricultural fields for several cropping seasons.

Impact on Disease Management

The widespread occurrence of resistant populations has significantly reduced the effectiveness of metalaxyl in disease management programmes. While susceptible isolates are effectively controlled, resistant populations survive recommended doses, resulting in greater disease severity, yield reduction and increased production costs (Torres *et al.*, 2019). In several production regions, metalaxyl has become unreliable within only a few years of intensive use, compelling growers to rely on alternative fungicides and integrated disease management practices.

Detection and Sustainable Management

Early detection of resistant populations is essential for preventing large-scale field failures. Conventional laboratory bioassays, together with molecular diagnostic techniques such as PCR and DNA sequencing, provide reliable methods for monitoring fungicide sensitivity (Grunwald *et al.*, 2021). Sustainable management should focus on rotating fungicides with different FRAC groups, using fungicide mixtures, adopting resistant cultivars, practicing crop rotation, improving irrigation and soil health and integrating biological control agents such as *Trichoderma* and *Pseudomonas* (Wang *et al.*, 2019). Disease forecasting systems should also be used to optimize fungicide applications and reduce unnecessary chemical use (Yang *et al.*, 2025).

Conclusion

Metalaxyl continues to play an important role in managing *Phytophthora* diseases, but its long-term sustainability is threatened by the rapid spread of resistant pathogen populations. Intensive farming practices, repeated fungicide applications and inadequate resistance management have accelerated this problem worldwide. Preserving the effectiveness of metalaxyl will require integrated disease management, responsible fungicide stewardship, continuous resistance monitoring and the adoption of improved crop production practices.

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AI-Powered Smart Farming: Transforming the Future of Indian Agriculture



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Abstract

Artificial Intelligence (AI) is rapidly transforming Indian agriculture by enabling data-driven and precision-based farming practices. Through the integration of drones, satellite imagery, sensors, machine learning, and mobile applications, AI assists farmers in crop monitoring, disease diagnosis, weather forecasting, irrigation management, and market decision-making. These technologies improve productivity, reduce input costs, enhance resource-use efficiency, and promote sustainable agricultural development. Despite challenges such as limited digital literacy, inadequate rural infrastructure, and high initial investment, government initiatives and the expanding agri-tech ecosystem are accelerating the adoption of AI across the agricultural sector. As India moves towards digital agriculture, AI has the potential to strengthen climate resilience, improve farmers' incomes, and contribute significantly to national food security. This article highlights the emerging role, opportunities, and future prospects of AI-powered smart farming in transforming Indian agriculture.

Introduction

Agriculture has always been the backbone of the Indian economy, supporting millions of livelihoods and ensuring national food security. However, today's farmers face unprecedented challenges, including climate change, erratic rainfall, labour shortages, rising production costs, and declining natural resources. In this rapidly changing environment, Artificial Intelligence (AI) is emerging as a powerful tool that is revolutionizing farming practices and paving the way for a more productive, profitable, and sustainable agricultural sector.

AI is no longer limited to laboratories or large industries. It has entered the agricultural landscape through smartphones, drones, sensors, satellite imagery, and intelligent software. These technologies help farmers make timely decisions based on real-time information rather than guesswork.

One of the most significant contributions of AI is in precision farming. Using satellite images, drones, GPS technology, and field sensors, AI continuously monitors crop growth, soil moisture, nutrient status, and pest incidence. Instead of applying fertilizers or pesticides uniformly across the field, farmers can treat only the affected areas. This targeted approach not only reduces production costs but also minimizes environmental pollution while improving crop productivity.

Crop diseases and insect pests are responsible for substantial yield losses every year. AI-powered mobile applications now enable farmers to diagnose diseases simply by taking photographs of infected leaves. Within seconds, these applications identify the likely disease and recommend suitable management practices. Early detection helps farmers control outbreaks before they spread, reducing dependence on excessive pesticide use and promoting environmentally friendly crop protection.

Weather uncertainty remains one of the greatest risks in agriculture. AI-based weather forecasting systems analyze historical climate records along with real-time meteorological data to provide accurate forecasts of rainfall, temperature, humidity, and extreme weather events. Farmers receive timely advisories regarding irrigation scheduling, fertilizer application, sowing, and harvesting, allowing them to minimize weather-related losses and improve resource management.

Water scarcity has become a major concern in many parts of India. AI-driven smart irrigation systems monitor soil moisture continuously and irrigate crops only when required. This intelligent irrigation not only

conserves precious water resources but also reduces electricity consumption and improves water-use efficiency, making farming more sustainable.

Marketing is another area where AI is making a significant impact. Digital agricultural platforms analyze market trends, demand, and price fluctuations across different markets. Farmers can use these insights to determine the most profitable time and location to sell their produce. Better market information strengthens farmers' bargaining power and reduces post-harvest losses.



The integration of AI with drones and robotics is further transforming Indian agriculture. Drones are increasingly used for crop monitoring, precision spraying, nutrient application, and field mapping. These technologies reduce labour requirements, improve application efficiency, and lower operational costs. AI-enabled robots are also being developed for tasks such as weed detection, fruit harvesting, and crop monitoring, offering promising solutions to the growing problem of agricultural labour shortages.

Recognizing the importance of digital agriculture, the Government of India has launched several initiatives, including the Digital Agriculture Mission, AgriStack, and programs promoting agricultural drones and precision farming. Numerous agri-tech startups are also developing affordable AI-based advisory services, smart irrigation systems, digital soil testing, and farm management platforms specifically designed for Indian farmers.

Despite these remarkable advancements, several challenges remain. Limited digital literacy, poor internet connectivity in rural areas, high initial investment, and concerns regarding data privacy continue to restrict the widespread adoption of AI technologies. Addressing these barriers through farmer training, improved rural digital infrastructure, and affordable technologies will be essential for realizing the full potential of AI in Indian agriculture.

The future of agriculture will depend on integrating traditional farming wisdom with modern digital technologies. Artificial Intelligence is not intended to replace farmers; rather, it serves as an intelligent decision-support system that empowers them to make informed choices, increase productivity, optimize resource use, and improve farm profitability. As India moves towards a digitally empowered agricultural economy, AI will undoubtedly play a pivotal role in building resilient, climate-smart, and sustainable farming systems.

The journey towards smart agriculture has already begun. Farmers, researchers, policymakers, and agri-tech innovators must work together to ensure that AI reaches every farm, regardless of its size. By embracing digital innovation today, Indian agriculture can secure a more prosperous and sustainable tomorrow.

Conclusion

Artificial Intelligence is redefining the future of Indian agriculture by making farming more precise, efficient, and sustainable. AI-based technologies are helping farmers optimize resource use, minimize production risks, improve crop productivity, and make informed decisions throughout the crop cycle. Although challenges related to affordability, digital infrastructure, and awareness remain, continued government support, technological innovation, and capacity-building initiatives are expected to accelerate adoption among farmers. The successful integration of AI with traditional agricultural knowledge can enhance farm profitability while ensuring

environmental sustainability. Embracing AI-driven smart farming will not only improve the livelihoods of farmers but also strengthen India's agricultural resilience and food security in the years to come.

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Small-Scale Fisheries vs. Diesel Subsidies in India: Equity, Sustainability, and Policy Reforms



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1. Introduction

India is the third largest producer of fish in the world, with fisheries being responsible for 1.07% of the GDP of the country and generating employment for more than 28 million people (DAHD, 2023). The SSF segment comprises about 80% of the active fishers in India but suffers from structural disadvantages owing to discriminatory policies regarding fuel subsidies. The subsidies on diesel meant to cut down the cost of fishing tend to favour industrial trawlers causing overfishing, ecological destruction, and economic inequalities. This chapter will discuss:

- ❖ Diesel subsidies in Indian fisheries.
- ❖ Their disparate effects on SSF and industrial fisheries.

2. Diesel Subsidies in Indian Fisheries

2.1 Current Subsidy Mechanism: The Indian government is well aware of the challenges of increasing fuel prices for fishermen who are just about to start fishing thereby favouring diesel subsidy as part of its two initiatives. Diesel subsidy is given an importance of a primary thing in these schemes instead of treating it the way most policies treat wage subsidy, i.e. as a secondary issue.



Fig 1: Traditional Fishers Vs Diesel Subsidies

Fishery Mechanization Scheme introduces an innovative idea of sustainability into fishing through modernization by getting rid of all old boats and methods of fishing and replacing them with new fishes and technological means of fishing. Subsidizing diesel fuel gives rise to favourable conditions for achieving success in this endeavour by enabling fishermen to easily obtain modern vessels.

Kisan Credit Card for fisheries is another brilliant option of this project since it incorporates subsidized diesel into the fishermen's capital. The interesting part is that real loans are granted to the fishermen, which makes it so much easier for him to deal with the high prices of fuel. These benefits indirectly contributed towards the overexploitation of fisheries resources.

2.2 Unequal Gains to Industrial Sector:

Mechanized fishing vessels constitute only 10% of the total fishing fleet but consume 70% of the subsidized diesel fuel (CMFRI, 2022). A report also indicates that artisanal fishermen are disadvantaged because they do not have proper documentation.

3.1 Financial and Socioeconomic Disparities

Market exploitation: Industrial fishery companies have monopolized the cargo transport system, thus leading to the impoverishment of small-scale fishers (Bavinck et al., 2022). According to a case studies conducted in Kerala- with the advent of LPG reform, the income of small fishers has dropped by 30%, while that of trawl fishermen has risen (ICSF, 2021).

4. Policy Challenges & Global Concerns

4.1 WTO & Overfishing Subsidies

There are criticisms regarding India's lack of compliance with the WTO Agreement on Fisheries Subsidies. There are also the international efforts to stop subsidies for illegal fishing (which is consistent with U.N. Sustainable Development Goal 14.6).

4.2 Leakage & Corruption

It is estimated that about 40% illegal diversion of subsidized diesel is towards the non-fishing sectors (CAG, 2020).

5. Recommendations for Reform

- Move to Direct Benefit Transfers (DBT): Use cash transfers and vouchers rather than fuel subsidies for small-scale fishermen.
- Limit Industrial Subsidies: Use quotas for mechanized boats.
- Promote Sustainability Solutions: Solar boats and energy-efficient engines.
- Enhance Monitoring: Use Aadhaar-based monitoring to reduce leakages.

6. Conclusion

The diesel subsidy system in India aims to support those in need but actually damages small fishers and the marine ecosystem around the country. Fairness, environmental quality, and clear methods of allocation should be the guiding principles behind this reform to secure people's and fish resources' future.

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Supply Chain Resilience



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Abstract

In today's globalized world, supply chains are exposed to various uncertainties such as natural disasters, pandemics, political conflicts, transportation failures and cyberattacks. These disruptions can delay production, increase costs, and reduce customer satisfaction. Supply chain resilience refers to the ability of a supply chain to prepare for unexpected events, respond effectively, recover quickly and continue operating with minimal losses. A resilient supply chain not only survives disruptions but also learns from them and becomes stronger. This article discusses the concept of supply chain resilience, its importance, key strategies for improving resilience, challenges faced by organizations and future directions. Strengthening resilience has become essential for businesses to remain competitive and ensure long-term sustainability.

Introduction

Modern businesses depend on complex supply chains that connect suppliers, manufacturers, distributors, retailers and customers across different regions of the world. While globalization has improved efficiency and reduced production costs, it has also increased the vulnerability of supply chains. A disruption occurring in one location can quickly affect production and distribution across many countries. Recent events such as the COVID-19 pandemic, earthquakes, floods and geopolitical conflicts have demonstrated how fragile supply chains can be. Many industries experienced shortages of raw materials, transportation delays, and increased operating costs. These challenges have emphasized the need for organizations to build resilient supply chains that can withstand unexpected disruptions and recover quickly. Supply chain resilience is therefore no longer an option but a strategic necessity for organizations aiming to achieve sustainable growth and customer satisfaction.

Importance of Supply Chain Resilience

A resilient supply chain enables organizations to continue operations even during periods of uncertainty. Companies with resilient supply chains experience fewer production interruptions, faster recovery from disruptions and greater customer trust. Resilience also reduces financial losses and helps organizations maintain their market position. Another important advantage is improved adaptability. Businesses that continuously learn from disruptions are better prepared for future challenges. This learning process enhances innovation, operational flexibility, and long-term competitiveness.

Key Strategies to Improve Supply Chain Resilience

Several strategies can strengthen supply chain resilience. The most widely accepted approaches include:

1. Flexibility

Flexibility enables organizations to modify production schedules, sourcing strategies, transportation methods and workforce allocation according to changing conditions. Flexible operations allow businesses to respond quickly to disruptions while minimizing delays and costs.

2. Redundancy

Redundancy involves maintaining backup suppliers, additional inventory, or extra production capacity. Although redundancy increases operational costs, it provides a safety buffer during emergencies and prevents complete interruption of business activities.

3. Collaboration

Strong collaboration among suppliers, manufacturers, distributors and customers improves information sharing and coordinated decision-making. Open communication allows supply chain partners to identify risks early and work together to reduce their impact.

4. Supply Chain Agility

Agility refers to the ability to respond rapidly to changing customer demands and unexpected disruptions. Organizations achieve agility through real-time information systems, effective monitoring, quick decision-making, and efficient logistics management.

5. Digital Technologies

Modern technologies such as Artificial Intelligence (AI), Internet of Things (IoT), Big Data Analytics, Cloud Computing and Blockchain improve supply chain visibility and enable early detection of potential risks. These technologies support faster and more informed decision-making.

Challenges in Building Supply Chain Resilience

Despite its importance, building resilience presents several challenges. Maintaining additional inventory and backup suppliers requires significant financial investment. Small and medium-sized enterprises often struggle due to limited financial resources. Global supply chains are also becoming increasingly complex, involving multiple suppliers and transportation networks. This complexity makes risk identification and coordination more difficult. In addition, organizations may face challenges related to data sharing, lack of transparency, cybersecurity threats and rapidly changing market conditions. Balancing operational efficiency with resilience is another major challenge. While lean supply chain practices reduce costs, they may also reduce the ability to respond effectively during disruptions.

Future Perspectives

Future supply chains are expected to become more digital, sustainable, and resilient. Organizations will increasingly use predictive analytics, artificial intelligence and machine learning to identify risks before they occur. Climate change, environmental sustainability, and responsible sourcing will also become important considerations in supply chain management. Businesses should invest in continuous learning, employee training, supplier relationship management and technological innovation. Governments and industries must work together to strengthen infrastructure and develop policies that support resilient supply chains.

Conclusion

Supply chain resilience has become one of the most important aspects of modern business management. It enables organizations to prepare for disruptions, respond effectively, recover quickly, and continue delivering products and services with minimal interruption. Strategies such as flexibility, redundancy, collaboration, agility and digital technology significantly improve resilience. Although developing resilient supply chains requires investment and careful planning, the long-term benefits include improved competitiveness, customer satisfaction and sustainable business performance. As global uncertainties continue to increase, organizations that prioritize supply chain resilience will be better positioned to achieve long-term success.

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DeHaat of India: Revolutionizing Indian Agriculture Through Digital Innovation



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Abstract

DeHaat is one of India's leading agri-tech companies, founded in 2012 with the mission of transforming agriculture through technology-driven, end-to-end solutions for farmers. Operating across more than 12 agrarian states, DeHaat connects millions of farmers with a comprehensive range of services, including quality agricultural inputs, AI-based personalized crop advisory, soil testing, weather-based advisory, financial services and market linkages. By integrating digital technology with an extensive network of local service centers and Farmer Producer Organizations (FPOs), the company enables farmers to make informed decisions throughout the crop cycle. DeHaat's platform helps improve farm productivity, optimize input usage, reduce production risks and increase farmers' income through better access to markets and modern agricultural practices. Its technology-enabled ecosystem has positioned DeHaat as a key contributor to the modernization and sustainable development of Indian agriculture, empowering smallholder farmers with data-driven solutions and efficient supply chain services.

Introduction

Agriculture is the backbone of the Indian economy, supporting the livelihoods of more than half of the country's population. Despite significant advancements in agricultural technologies, millions of small and marginal farmers continue to face challenges such as limited access to quality inputs, lack of timely advisory services, inadequate market linkages and fluctuating crop prices. These challenges often reduce farm productivity and profitability. In recent years, agritech startups have emerged as powerful drivers of change by integrating technology with traditional farming practices. Among these, DeHaat has become one of India's leading digital agriculture platforms, transforming the way farmer access agricultural services. Founded in 2012, DeHaat has developed a comprehensive digital ecosystem that connects farmers with agricultural experts, quality farm inputs, financial services and reliable markets through a single platform. The company's mission is to improve farmers' incomes by making modern agricultural services affordable, accessible and sustainable. Today, DeHaat serves millions of farmers across multiple states and has become a model for digital agricultural transformation in India.

History and Foundation of DeHaat

DeHaat was established in 2012 by four young entrepreneur, Shashank Kumar, Manish Kumar, Shyam Sundar and Pramod Kumar, who recognized the challenges faced by Indian farmers. The founders observed that smallholder farmers lacked access to reliable agricultural information, quality seeds and fertilizers, affordable credit and organized markets. They envisioned a technology-driven platform capable of addressing these problems through an integrated approach.

The company begun its the state of Bihar by working closely with rural farmers. Over time, DeHaat expanded its services to several Indian states including Uttar Pradesh, Jharkhand, Odisha, West Bengal and Maharashtra. Today, it has become one of the fastest-growing agritech companies in the country, helping farmers improve productivity while promoting sustainable agricultural practices.

Vision and Mission

The vision of DeHaat is to create prosperous agricultural ecosystem where every farmer has access to modern technology, scientific knowledge, quality agricultural inputs, and fair market opportunities.

Its mission of DeHaat includes the following objective:

- To increasing farmers' income through better productivity.

- To providing end-to-end agricultural solutions.
- To promoting sustainable farming practices.
- To bridging the gap between farmers and markets.
- To digitizing rural agriculture through technology.

Business Model

DeHaat follows an integrated business model by connecting all stakeholders within the agricultural value chain. The company works with:

- Farmers
- Input manufacturers
- Agricultural scientists
- Financial institutions
- Food processing companies
- Retailers
- Exporters
- Revenue is generated through:
- Sale of agricultural inputs
- Market linkage services
- Advisory services
- Supply chain management
- Value-added agricultural services

This integrated approach benefits both farmers and agribusiness companies.

Services Offered by DeHaat

DeHaat provides an integrated "one-stop solution" for farmers throughout the entire crop production cycle from input procurement to post harvest marketing.

1. Quality Agricultural Inputs

DeHaat supplies high-quality agricultural inputs through its network of DeHaat Centers and digital platform. The company partners with leading agri-input brands to ensure farmers receive genuine products at competitive prices.

- Certified and hybrid seeds
- Fertilizers and specialty nutrients
- Crop protection products (insecticides, fungicides, herbicides)
- Bio-fertilizers and bio-pesticides
- Plant growth promoters and micronutrients
- Farm equipment and accessories

2. Personalized Crop Advisory

DeHaat offers crop-specific and farm-specific advisory services through experienced agronomists and AI-enabled technology. Recommendations are customized according to the farmer's crop, growth stage, soil condition and local farming practices.

- Crop planning and variety selection
- Sowing recommendations
- Nutrient management
- Irrigation scheduling
- Pest and disease identification
- Fertilizer and pesticide dosage recommendations
- Harvesting and post-harvest guidance

3. Soil Testing Services

DeHaat provides scientific soil testing to help farmers understand the fertility and nutrient status of their fields.

- Collection of soil samples
- Laboratory analysis

- Soil Health Card generation
- Measurement of pH, organic carbon, nitrogen (N), phosphorus (P), potassium (K) and other nutrients
- Fertilizer recommendations based on test results
- Crop suitability recommendations
- Personalized nutrient management plans

4. Weather-Based Advisory

DeHaat provides weather-informed advisories to help farmers minimize climate-related risks and plan field operations efficiently.

- Sowing and transplanting schedules
- Irrigation timing
- Fertilizer application planning
- Pest and disease risk alerts
- Heavy rainfall and extreme weather warnings
- Harvest timing recommendations
- Preventive measures before adverse weather events

5. Crop Disease Diagnosis

Using digital technology and artificial intelligence, farmers can upload crop photographs to identify diseases and pest infestations. Agricultural experts provide suitable recommendations for disease management, minimizing yield losses.

6. Market Linkages

One of the major challenges faced by farmers is selling their produce at fair prices. DeHaat connects farmers directly with institutional buyers, wholesalers, food processing industries and retailers. This reduces the role of middlemen and enables farmers to receive better prices.

7. Financial Services

The company also facilitates access to:

- Crop loans
- Insurance
- Credit facilities
- Digital payment systems

These services improve farmers' financial inclusion and reduce dependence on informal lenders.

Technology Behind DeHaat

Technology forms the backbone of DeHaat's operations.

The platform utilizes:

- Artificial Intelligence (AI)
- Machine Learning
- Data Analytics
- Geographic Information Systems (GIS)
- Mobile Applications
- Cloud Computing

The mobile application allows farmers to:

- Order agricultural inputs
- Consult experts
- Receive weather alerts
- Book soil testing
- Sell produce
- Track crop management activities

The platform generates location-specific recommendations based on local climate, soil characteristics and crop conditions.

Impact on Indian Agriculture

DeHaat has significantly contributed to improve agricultural productivity and farmer welfare

Its major contributions include:

- Increased crop productivity through scientific practices.
- Improve access to certified agricultural inputs.
- Reduction in fake seed and pesticide usage.
- Improved market prices for farm produce.
- Timely advisory services.
- Adoption of climate-smart agricultural practices.
- Enhanced digital literacy among farmers.
- Improved income for small and marginal farmers.

Millions of farmers now use DeHaat's services to make data-driven farming decisions.

Advantages of DeHaat

The major advantages include:

- End-to-end agricultural solutions under one platform.
- Easy access through smart phones and local service centers.
- Scientific and personalized crop advisory.
- Reliable supply of quality agricultural inputs.
- Direct connection to agricultural markets.
- Weather-based farming recommendations.
- Reduced dependence on middlemen.
- Better income generation opportunities.
- Promotion of sustainable agriculture.
- Improved efficiency across the agricultural supply chain.

Challenges Faced by DeHaat

- Despite its success, DeHaat faces several challenges:
- Limited internet connectivity in remote villages.
- Low digital literacy among some farmers.
- Climate change affecting agricultural production.
- Competition from other agritech companies.
- High logistics and distribution costs.
- Farmer resistance to adopting new technologies.
- Regional differences in farming practices.

Continuous innovation and farmer education remain essential for overcoming these challenges.

Conclusion

DeHaat has emerged as one of India's most successful agritech companies by creating a comprehensive digital ecosystem for farmers. Through technology-driven advisory services, quality agricultural inputs, market access, financial inclusion and sustainable farming solutions, the company has significantly improved the lives of millions of Indian farmers. Its integrated approach addresses major challenges across the agricultural value chain while promoting modern, data-driven farming practices. As India continues its transition toward digital agriculture, DeHaat represents an inspiring example of how innovation can empower rural communities, increase farm productivity, strengthen food security and contribute to national economic growth. With continued expansion and technological advancement, DeHaat is well-positioned to play a vital role in shaping the future of Indian agriculture.

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Gender Pay Gaps in Economics



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Abstract

The gender pay gap remains one of the most persistent issues in labor economics, reflecting inequalities in wages between men and women across industries and countries. This paper examines the causes, economic theories and consequences of the gender pay gap. It explores factors such as human capital differences, labor market discrimination, occupational segregation and institutional influences. Empirical evidence from studies conducted across the add indicates that although the gender pay gap has narrower over time it continues to exit due to both measurable and unobservable factor. The findings suggest that closing the gender pay gap is not only a matter of social justice but also an economic necessity, as it can improve productivity, economic growth, and overall welfare.

Introduction

The persistence of gender wage disparities over time has been well documented by Claudia Goldin (1990) and Francine D. Blau and Lawrence M. Kahn (2017), with academia continuing to reflect these inequalities. Furthermore, the participation of women in high-paying academic disciplines like economics, science, and engineering has shown little growth since 2000. Recent research has increasingly focused on gender inequalities within the field of economics, identifying barriers and suggesting measures to promote women's career progression. Despite women constituting a significant proportion of the labor force, wage inequality continues to persist. Men and women are often not paid equally for performing the same work, reflecting ongoing wage discrimination.

Overall, women tend to earn low wages, receive lower salaries and face less favorable working conditions than to men. These pay differences not only limit women's opportunities in the labor market but also reduce their influence and decision-making power within households. Moreover, the effects of wage inequality extend into later life. Lower earnings result in reduced social security level retirement benefits, income thereby reinforcing economic inequality even retirement.

Human capital theory

Gender differences in qualifications have been widely analysed using the human capital theory. Human capital refers to whose basic premise is that every. Women may be discouraged from accepting positions that require extensive firm-specific skill development because the benefits of acquiring such skills are realized only through long-term employment with the same organization. Similarly, employers may be unwilling to place women in these roles, as they invest resources in firm-specific training and may worry that they will not recover the costs if female employees leave the organization before the investment yields adequate returns.

Labour market discrimination

The wage difference that remains after accounting for variations in education, experience, skills and other productivity-related factors is often considered a result of labour market discrimination. Researchers have proposed several theories to understand and evaluate discrimination in the workplace. In economic terms, discrimination does not refer to wage differences that arise because of differences in occupations or skill levels, where higher-skilled workers are expected to earn more than less-skilled workers. rather, economic discrimination exists when workers with comparable qualifications and abilities receive unequal pay or unequal opportunities for recruitment, promotion, or career advancement solely because they belong to different groups, such as men and women

The monopsony theory says that where the employer is in a monopoly position, the lack of competition leads to a low price for labour. One way in which a firm gains monopsony power is when it is large buyer of labour relative to the size of a particular market. A controversial approach to the pay gap question Warren Farrell set out in his new book. Based on his research, he came to the conclusion that women pay an economic price for seeking more flexible, less risky and more fulfilling careers.

Data and Descriptive Statistics

To examine the gender, pay gap among academic economists a dataset was developed consisting of faculty members from departments of economics and applied economics. The study focuses on universities that are highly ranked in agricultural and applied economics according to the National Research Council (NRC). Information on individual faculty salaries was obtained from publicly available online sources, including data released by media outlets, state governments and universities on annual salaries of state employees. Using these sources, a unique dataset was compiled covering faculty members from 11 major public universities included in the NRC rankings, spanning the years 2010 to 2018.

However, one limitation is that the definition of “Annual salary” is not consistent across institutions. Some universities report only base salary, while others include total earnings such as summer teaching pay, performance incentives and retirement contributions. To account for these differences, the analysis incorporates university fixed effects, meaning that salary comparisons are made within the same institution rather than across different universities. Nevertheless, some inconsistencies in reporting practices may still remain. Since salary datasets typically lack detailed personal information about faculty members, additional data were obtained by linking the salary information with the Academic Analytics Database.

Conceptual Framework

Definition and Measurement of gender pay gap

The gender pay gap is measured in two primary ways:

- **Unadjusted pay gap:** The raw difference in average wages between men and women. Without control job related categories.
- **Adjusted pay gap:** The difference after accounting for factors such as education, experience, occupation and working hours.

While the adjusted gap is smaller, it does not disappear entirely, suggesting that other factors such as discrimination play a role.

Causes of the Gender Pay Gap

1. Human Capital Differences

Human capital is the economic value of a person's acquired skills, knowledge, and experience. The "difference" often refers to its contrast with physical capital (e.g., machinery vs. workforce skills) or its distinction from operational human resources.

2. Occupational Segregation

Occupational segregation is a major contributor to the gender pay gap. It occurs in two forms:

- **Horizontal segregation:** Women and men work in different sectors.
- **Vertical segregation:** Men are more likely to occupy higher-level positions within the same sector.

Discrimination

Despite legal protections in many countries, discrimination persists in hiring, promotion, and pay decisions. Women may be offered lower starting salaries or fewer advancement opportunities compared to equally qualified men.

Overt Pay Discrimination: In many regions, particularly in informal or unregulated sectors, women receive lower starting wages or are denied bonuses and increments despite identical qualifications.

Occupational Segregation: Societal norms and discriminatory hiring practices often steer women into historically female-dominated professions. Because these roles (such as caregiving, nursing, and teaching) are persistently undervalued by the market, they naturally yield lower average salaries.

The Motherhood Penalty: Traditional gender roles disproportionately burden women with unpaid domestic and care work. When women take career breaks or work part-time to fulfill these responsibilities, they often face penalized career progression, fewer promotions and reduced long-term earning potential.

Motherhood Penalty

The "motherhood penalty" refers to the negative impact of having children on women's earnings. Employers may perceive mothers as less committed to their careers, leading to fewer promotions and lower wages. The motherhood penalty is the primary driver of the gender pay gap, causing women's earnings to drop by an average of 4% to 5% per child. It stems from career interruptions, unequal unpaid domestic labor, and workplace biases that view mothers as less committed, while fathers often receive a "fatherhood bonus."

The "Mommy Track" Mothers are more likely to seek out part-time roles, flexible hours, or take extended time off to manage childcare. These transitions often result in lower hourly wages, reduced seniority, and lost opportunities for career advancement.

Unpaid Labour Discrepancies: Working mothers continue to take on the vast majority of unpaid care and domestic work. This "double shift" constrains their economic mobility and limits the time and energy they can dedicate to high-pressure "greedy jobs".

The Fatherhood Premium: Conversely, the wage gap is exacerbated by the fact that fatherhood is frequently rewarded by employers. Men often see an increase in income after having children, as parenthood is viewed as a signal of stability and dedication to work.

Work-Life Balance and Flexibility

Women are more likely to seek flexible working arrangements, which are often associated with lower pay and fewer career advancement opportunities. This contributes to the overall wage gap.

The Unpaid Work Penalty: Globally, women perform the majority of caregiving and domestic labor. Because inflexible workplace systems cannot accommodate these heavy caregiving responsibilities, women are more likely to seek out part-time positions or take career breaks.

European Institute for Gender Equality +3

The Flexibility Stigma: Even when flexible or remote work is offered, it can unintentionally penalize women. Workers who utilize flexible arrangements are often passed over for promotions or key projects if employers equate physical presence with dedication, thereby worsening long-term pay inequality.

Loss of Career Capital: The "work-experience pay gap" accounts for a large portion of the overall wage difference. Women average fewer years of continuous, full-time labor compared to men, heavily affecting their salary progression and pension savings.

Causes of the Gender Pay Gap

Differences in Work Experience

Career interruptions due to care giving responsibilities reduce women's work experience and earnings.

Education and Skills

Although women now often attain higher levels of education than men, differences in fields of study still contribute to wage disparities.

Social Norms and Cultural Factors

Cultural expectations regarding gender roles influence occupational choices and labor force participation.

Negotiation and Behavioural Factors

Research suggests that women may negotiate salaries differently than men, contributing to wage differences.

Economic Consequences

1. Impact on Economic Growth

Reducing the gender pay gap can increase labor productivity and GDP. When women are paid fairly, their participation in the workforce increases.

2. Income Inequality and Poverty

The gender pay gap contributes to overall income inequality and increases the risk of poverty among women, especially single mothers.

3. Efficiency Losses

From an economic perspective, discrimination leads to inefficient allocation of resources, as talent is not rewarded equally.

Policy Responses

1. Equal Pay Legislation

Governments have implemented laws requiring equal pay for equal work. However, enforcement remains a challenge.

2. Pay Transparency

Policies promoting wage transparency have been shown to reduce the gender pay gap by limiting discriminatory practices.

3. Family-Friendly Policies

Policies such as parental leave, childcare support, and flexible work arrangements help reduce career interruptions for women.

4. Education and Awareness

Encouraging women to enter high-paying fields such as STEM can help reduce occupational segregation

Conclusion

The gender pay gap is a complex issue influenced by economic, social, and institutional factors. While progress has been made in reducing the gap, it persists due to both measurable differences and discrimination. Economic theories such as human capital, discrimination and labor market segmentation provide valuable insights into its causes.

Addressing the gender pay gap requires a combination of policy interventions, cultural change and organizational reforms. Closing the gap is not only a matter of fairness but also essential for improving economic efficiency and growth. Future research should continue to explore innovative methods for measuring and reducing wage disparities.

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Cultivating a Greener Tomorrow: Innovations and Technologies for Sustainable Agriculture in India



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Abstract

India's agricultural sector is undergoing a rapid transition from input-intensive, linear production systems toward technology-enabled, climate-smart models that prioritize resource efficiency, resilience, and farmer prosperity. This paper examines how five major innovation domains—circular bioeconomy, Agriculture 4.0, CRISPR-based climate-smart crops, regenerative agriculture, and a supportive digital policy ecosystem can jointly cultivate a greener agricultural future for India. It highlights the potential of converting more than 500 million tonnes of crop residues into biogas, bio-fertilizer, and rural employment, while reducing air pollution and greenhouse gas emissions. Parallel advances in CRISPR-enabled rice and mustard varieties, zero-tillage and carbon farming practices, and smart irrigation and nutrient-delivery techniques are discussed as pathways to enhance productivity, soil health, and carbon sequestration.

Key words: Circular Bioeconomy, CRISPR Crops, Precision Agriculture 4.0

Agriculture remains the cornerstone of India's economy, sustaining nearly 42.3% of the nation's workforce, and its share in GVA surged from 24.38% in FY15 to 30.23% in FY23, highlighting its rising strength in India's economy (PIB, 2025). However, this sector faces a complex blend of structural and environmental challenges. Crop yields in India continue to lag by 20–60% behind global averages, 52% of farming is rainfall-dependent, and 89.4% of farmers are smallholders with less than 2 hectares of land. In addition to these challenges, the sector faces growing threats of climate variability, groundwater depletion, and significant post-harvest losses, necessitating a shift from traditional linear "take-make-dispose" models toward sustainable intensification.

To secure a sustainable agricultural future, India is progressively aligning its farming strategies with the United Nations Sustainable Development Goals (SDGs). A broad spectrum of emerging innovations, ranging from circular bio-economy models and precision farming practices to CRISPR-based crop enhancement and blockchain-driven governance, is reshaping the sector. These transformative approaches aim not only to boost productivity and farmer income but also to build a resilient, resource-efficient, and carbon-sequestering agricultural ecosystem capable of meeting the demands of a changing climate and a growing population.

Circular Bioeconomy: Transforming Waste into Wealth

India's transition toward a circular bioeconomy holds remarkable promise, with the potential to generate over \$2 trillion in market value and create nearly 10 million jobs by 2050 (PIB, 2025). Each year, the country produces approximately 500–550 million tonnes of crop residue, much of which is burned in fields, particularly in the northern states, contributing to 18–25% of PM_{2.5} emissions during the harvest season. This widespread practice not only aggravates air pollution but also wastes significant quantities of biomass that could otherwise serve as valuable energy and soil nutrient sources.

Adopting a circular economy framework enables agricultural by-products to be converted into clean and renewable energy, directly advancing Sustainable Development Goals (SDG) 7 and 13. Among the available technologies, anaerobic digestion offers the most practical and scalable option for rural India, efficiently converting manure and wet crop residues into biogas. Presently, more than five million small-scale biogas plants are helping to reduce dependence on conventional, polluting fuels such as firewood.

Table 1: State-wise Total Biomass Available from crops (thousand tonnes) in India

States	Wheat	Rice	Maize	Bajra	Sugarcane	Groundnut	Rapeseed Mustard	Arhar/Tur	Total Crops
Uttar Pradesh	65194.1	23005.1	3571.3	4656.6	8561.7	210.9	1751.9	903.6	124692.8
Madhya Pradesh	31555.6	5131.5	5316.4	1319.4	187.8	756.5	1168.6	1298.8	70233.1
Rajasthan	20609.2	636.7	3315.4	9767.5	25.5	2656.3	6359.4	36.2	59504.1
Punjab	30925.8	18921.5	1013.1	0	366.2	5.6	81.4	12.1	53003.9
Maharashtra	3048.1	4456.0	6231.7	1579.7	3433.8	843.1	6.0	0	52540.1

(Source: MNRE,2025)

The by-product of biogas production, known as bio-slurry or digestate, plays a vital role in improving soil fertility and agricultural productivity. According to research by the Indian Council of Agricultural Research (ICAR), the application of digestate can increase soil organic carbon (SOC) by 15–25% and enhance crop yields by 8–12%, contributing directly to Sustainable Development Goal (SDG) 12 and SDG 15. This nutrient-rich organic fertilizer not only recycles essential elements back into the soil but also reduces dependence on chemical fertilizers, which weaken long-term soil health. By 2030, the bioenergy sector is expected to employ more than 1.2 million people, with nearly 70% of these jobs located in rural areas, strengthening both soil ecosystems and local economies through sustainable, circular bioresource utilization.

Table 2: Integrated Data of Circular Economy, Employment and Biogas Benefits in Rural India

Implementation Level	Biogas Plants	Waste Processed (million tonnes/year)	Bio-fertilizer Produced (million tonnes/year)	Direct Employment (thousands)	Indirect Employment (thousands)	Annual Economic Value (₹ crore)	GHG Reduction (million tonnes CO ₂ e/year)	Agricultural Productivity Increase (%)
Current (2023)	52,70,000	7.9	3.9	195	342	8,200	14.8	2.3
Basic Expansion	80,00,000	14.6	7.3	310	542	14,500	24.6	4.1
Full Potential (2030)	2,50,00,000	68.0	34.0	920	1,610	78,500	92.4	16.8

(Source: European Economic Letters (EEL),2025)

Agriculture 4.0: Digital Transformation and Precision Tools

The advent of the Fourth Industrial Revolution (4IR) is revolutionizing the Indian agricultural landscape, marking the beginning of Agriculture 4.0, where data, technology, and innovation converge to bring unprecedented efficiency and sustainability to farm management. At the heart of this transformation lies Precision Agriculture (PA), a data-driven approach that enables farmers to apply essential inputs, such as water, fertilizers, and pesticides, precisely where and when they are needed. This transition not only improves resource efficiency but also supports long-term sustainability and profitability across India's diverse agroecosystems.

Among the technologies powering this transformation, Unmanned Aerial Vehicles (UAVs) or drones play a particularly significant role. Equipped with high-resolution (less than 10 cm) multispectral and hyperspectral cameras, these drones can detect subtle variations in crop health, enabling the early identification of stress, nutrient deficiencies, pest infestations, and weed presence. By integrating multispectral sensing technologies, drones can differentiate between crop species and weed types, allowing for precise herbicide application, which can reduce overall chemical usage by nearly 20%, thereby minimizing environmental contamination and input costs. This innovation directly aligns with SDG 2 and SDG 9, promoting food security and sustainable industrial growth.

A key pillar of modern agriculture is the development of Precision Agriculture Information Systems (PAIS), which are digital platforms that integrate drone imagery, satellite data such as Sentinel-2, and IoT-based field sensors to generate real-time, actionable insights. These systems enable farmers to fine-tune irrigation, nutrient application, pest management, and harvest scheduling while also supplying verified data for crop insurance and financial inclusion.

Genetic Resilience: CRISPR-Cas9 and Climate-Smart Crops

As climate change threatens to reduce India's crop yields by nearly 30% by 2050, the country is increasingly turning to cutting-edge biotechnology to safeguard its agricultural productivity. The CRISPR-Cas9 gene-editing system has emerged as a powerful tool, allowing precise, targeted modifications to plant genomes without the

introduction of foreign DNA. This distinction helps genome-edited (GE) crops avoid many of the regulatory complexities faced by traditional Genetically Modified Organisms (GMOs). Using CRISPR-Cas9, scientists have edited the genes responsible for drought and salinity tolerance in the *MTU-1010* rice variety and modified ten glucosinolate transporter genes in mustard to improve nutrient efficiency and resistance to stress. The CRISPR-Cas12a technique has been applied to edit the cytokinin oxidase 2 (Gn1a) gene in *Samba Mahsuri* rice, increasing cytokinin levels and thereby boosting both spikelet formation and grain yields.

Notable breakthrough varieties in India include *Pusa Rice DST1*, a drought- and salt-tolerant line engineered by adjusting the genes that regulate stomatal density to optimize water use. Another remarkable innovation is *DRR Dhan 100 (Kamala)*, a high-yielding variety that matures 15–20 days earlier than conventional types and achieves a 19–20% yield increase, leading to potential water savings of nearly 7,500 million cubic meters. Additionally, CRISPR has been successfully applied to produce bacterial leaf blight-resistant rice and canker-resistant citrus by knocking out target susceptibility (S) genes responsible for disease vulnerability. India's progress in traditional genetically modified (GM) crops stalled after the approval of Bt cotton in 2006, but genome-edited (GE) crops are advancing swiftly. In 2023 and 2024, two GE rice lines—enhanced versions of *Samba Mahsuri* and *MTU-1010*—were approved for multi-location field trials in India. The results have been encouraging: the improved *Samba Mahsuri* variant recorded a 19% increase in yield, whereas the GE *MTU-1010* line showed remarkable tolerance to saline and alkaline soils. A third GE crop, a canola-quality mustard variety resistant to major fungal diseases and insect pests, is currently in its second year of national trials at 16 locations.

In addition to its precision, CRISPR technology offers exceptional speed and efficiency. Whereas conventional breeding for climate-resistant or nutrient-efficient traits typically takes 8–10 years, CRISPR enables direct heritable genetic edits within just 2–3 years.

Regenerative Agriculture: Soil as a Carbon Sink

Conservation Agriculture (CA) represents a paradigm shift in sustainable farming, focusing on restoring and enhancing soil health through three fundamental principles: minimum soil disturbance (primarily through zero tillage), permanent soil cover (achieved via mulching and cover crops), and crop rotation/diversification. Far from being mere techniques, these practices work synergistically to rebuild soil organic matter, improve water retention, enhance biodiversity, and transform agricultural land from a source of greenhouse gas emissions into a powerful carbon sink.

Zero Tillage (ZT) eliminates the energy-intensive and soil-degrading practice of traditional plowing, delivering multiple benefits simultaneously. A single hectare of ZT saves farmers approximately 60 liters of diesel fuel while reducing CO₂ emissions by 156 kg per hectare annually. In India's fertile Indo-Gangetic Plains, where rice-wheat systems dominate, ZT adoption has consistently delivered 10–17% higher yields for both crops while sequestering up to 3,667 kg CO₂ per hectare annually at peak capacity.

Carbon farming takes this sustainability model to the next level by creating economic incentives for the environmental stewardship. India's 170 million hectares of arable land has the extraordinary potential to sequester 3–8 billion tonnes of CO₂ equivalent annually. This massive capacity represents a \$63 billion economic opportunity for rural communities through participation in global carbon markets, creating a powerful financial mechanism to drive the widespread adoption of regenerative practices.

Resource Efficiency: Smart Irrigation and SMART Fertilizers

The staggering 70% share of global freshwater withdrawals by agriculture underscores the urgent need for precision resource management, particularly in water-stressed regions such as India. IoT-based smart irrigation systems are revolutionizing water use by providing farmers with unprecedented control and precision in water management. Using affordable microcontrollers, such as the ESP32, integrated with cloud platforms, such as ThingsBoard, these systems continuously monitor soil moisture, temperature, humidity, and weather forecasts to automate irrigation pumps. Complementing water efficiency, SMART (Specific, Measurable, Achievable, Relevant, and Time-bound) fertilizers utilize nanotechnology and controlled-release mechanisms to synchronize nutrient delivery with plant growth phases. This prevents nutrient runoff, which is a primary cause of eutrophication in water bodies.

Governance and Tradition: Blockchain and the Khadi Model

India's sustainable transformation blends cutting-edge digital governance with time-tested traditional practices, creating a uniquely holistic approach to rural development. Blockchain technology introduces unprecedented transparency and trust into agricultural supply chains through an immutable digital ledger. In India, blockchain applications range from ensuring accurate subsidy distribution and fair pricing through automated smart contracts to creating complete "farm-to-fork" traceability.

Equally remarkable is the Khadi model, India's indigenous, low-carbon, and decentralized textile industry that embodies sustainability rooted in tradition. Hand-spun and handwoven using zero electricity, Khadi production completely avoids the microplastic pollution generated by synthetic textiles while requiring minimal water and chemicals to produce. Modern innovations, such as solar-powered charkhas (spinning wheels), further reduce drudgery and emissions while preserving Khadi's artisanal character and cultural significance.

Integrated Policy Framework and Institutional Support

India's ambitious sustainable agriculture transformation rests on a comprehensive policy ecosystem and a robust institutional architecture designed for nationwide implementation. The Digital Agriculture Mission (2024) channels a ₹2,817 crore investment to seamlessly integrate AI, IoT, blockchain, drones, and remote sensing technologies across diverse farming systems, thereby creating a unified digital backbone for modern agriculture. The AgriStack Project is building digital identities for over 11 crore farmers, linking them to Aadhaar authentication, geo-referenced village maps, and real-time crop monitoring data to enable precision decision-making and service delivery.

Parallel initiatives, such as the Sub-Mission on Agricultural Mechanization (SMAM), provide comprehensive financial support for precision equipment and farm Machinery Banks, ensuring that smallholders can access advanced tools without prohibitive upfront costs. The Soil Health Card Scheme has distributed 24.74 crore cards equipped with GIS mapping and mobile app integration, delivering customized fertilizer and crop recommendations directly to farmers. Meanwhile, Namo Drone Didi (2023) allocated ₹1,261 crore to empower 15,000 Women Self-Help Groups with drone technology by 2026, fostering gender-inclusive technological adoption.

This expansive policy framework draws strength from India's expansive agricultural policy framework is powered by a robust research and extension network that includes 113 ICAR institutes, 74 Agricultural Universities, 731 Krishi Vigyan Kendras, 8,875 Farmer Producer Organizations, and over 1,01,000 Primary Agricultural Cooperative Societies. This interconnected system advances several sustainable development goals (SDGs): SDG 17 by fostering collaboration among government, academia, private enterprises, and farmer collectives; SDG 4 by promoting quality education through extension services and digital platforms; and SDG 9 by driving technology transfer and agripreneurship.

Conclusion: The Path to India@2047

India's agricultural revolution seamlessly integrates cutting-edge technologies from digital twins and precision drones to CRISPR gene editing and circular waste management, creating a resilient, tech-powered food system that converts agricultural waste into clean energy wealth, optimizes water and nutrients through the Internet of Things, and engineers crops with enhanced genetic resilience to honor planetary boundaries while uplifting rural prosperity. As the nation charts its course toward Amrit Kaal 2047, sustained investment in rural digital infrastructure, multilingual capacity building, and empowered farmer cooperatives will scale these innovations nationwide, transcending mere productivity gains to form the bedrock of a greener, more inclusive, and Atmanirbhar future that not only secures food systems but also positions India as a global leader in harmonizing human progress with ecological stewardship, fully aligned with the 2030 Sustainable Development Goals.

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Breeding Climate-Resilient Crops: Genomics as a Shield for Global Food Security



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Abstract

Climate change is reshaping agriculture faster than farmers can adapt through traditional means alone. Rising temperatures, erratic rainfall, and more frequent droughts and floods are eroding yields of staple cereals precisely when a growing global population needs more food, not less. This article examines how genomics-assisted breeding and precision gene-editing tools such as CRISPR-Cas9 are accelerating the development of crop varieties that can withstand heat, drought, flooding, and salinity while retaining yield and nutritional quality. Drawing on recent advances in rice, wheat, and maize improvement programmes, the article discusses the science behind stress-tolerance breeding, highlights successful field examples, and considers the regulatory, economic, and social barriers that still stand between the laboratory and the farmer's field. It concludes that genomics alone cannot solve the climate challenge, but combined with sound policy, seed-delivery systems, and farmer training, it offers one of agriculture's most promising paths to durable food security.

Introduction

Agriculture has always been a wager against the weather, but the odds are shifting. The Intergovernmental Panel on Climate Change has repeatedly warned that warming of even 1.5 to 2 degrees Celsius will significantly reduce yields of wheat, maize, and rice in many tropical and sub-tropical regions unless adaptation measures are scaled up quickly. At the same time, the world's population is projected to approach nearly ten billion by 2050, meaning food production must rise even as the climate becomes less predictable.

For most of agricultural history, farmers and breeders responded to environmental stress through slow, incremental selection: saving seed from plants that survived a bad season and replanting them the following year. This approach built the resilient landraces that still underpin many farming systems today, but it is too slow to keep pace with the rate of climate change now being observed. A new generation of tools rooted in genomics and molecular breeding is compressing breeding cycles from decades to just a few years, allowing scientists to identify, transfer, and stack stress-tolerance traits with a precision that was unimaginable a generation ago.

Why Climate Resilience Has Become Urgent

Cereal crops are particularly vulnerable at specific growth stages. Wheat and rice both suffer sharp yield penalties when high temperatures coincide with flowering, while maize is highly sensitive to moisture stress during silking. Flooding, once a rare event in many rice-growing deltas, has become a recurring hazard, submerging fields for days at a time and destroying entire harvests. Soil salinity, worsened by both flooding and reduced freshwater flow, is steadily degrading productive land along many coastal and delta regions.

These stresses rarely occur in isolation. A single growing season may bring a delayed monsoon followed by intense flooding, or a heat wave layered on top of drought. Breeding for one stress at a time, the traditional approach, is no longer sufficient. Climate-resilient breeding programmes now aim to stack multiple tolerance traits into a single high-yielding variety, a task that depends heavily on understanding the genetic basis of stress response.

From Conventional Breeding to Genomic Precision

Genomics-assisted breeding uses DNA markers linked to traits of interest, allowing breeders to screen seedlings for stress tolerance in a laboratory rather than waiting for a full growing season to observe how plants perform in

the field. Marker-assisted selection and, more recently, genomic selection, which uses whole-genome data to predict a plant's performance before it is even grown, have shortened breeding cycles considerably. Where a conventional breeding programme might take twelve to fifteen years to release a new variety, genomics-assisted approaches can cut this to six or seven years.

One of the most widely cited successes is submergence-tolerant rice carrying the SUB1 gene, which allows plants to survive complete submersion for over two weeks by conserving energy rather than trying to outgrow the floodwater. Varieties built on this trait have been adopted across flood-prone areas of South and Southeast Asia, protecting yields that would otherwise be lost entirely in a flood year.

CRISPR and Gene Editing: Editing, Not Inserting

Where genomic selection identifies useful traits already present in a crop's genetic diversity, CRISPR-Cas9 and related gene-editing tools go a step further by allowing scientists to make precise, targeted edits to a plant's own genome. Unlike older transgenic approaches, which typically introduced genes from unrelated species, most gene-editing applications in crop improvement work by switching a gene off, fine-tuning its expression, or correcting it, changes that closely resemble the kind of mutations that occur naturally but happen far faster and with much greater precision.

Editing programmes are now targeting genes that control water-use efficiency, root architecture, and heat-shock response in rice, wheat, and maize. Because this precision reduces the years once needed to screen thousands of random mutants for a useful trait, it has meaningfully shortened the path from discovery to a field-ready variety. Regulatory treatment of gene-edited crops still varies considerably between countries, which shapes how quickly these varieties can reach farmers in different regions.

Beyond the Lab: What It Takes to Reach the Farmer

A resilient variety sitting in a research station's seed bank does nothing for food security until it reaches a farmer's field. Seed multiplication and distribution systems, extension services that can explain a new variety's requirements, and affordability all determine whether adoption follows innovation. In many smallholder systems, the larger constraint is not the availability of a resilient variety but the lack of a reliable channel to deliver certified seed at the right time and price.

There are also open questions around genetic diversity. Repeatedly deploying the same few stress-tolerance genes across large areas risks a narrowing of the crop's genetic base, potentially leaving future harvests vulnerable to a pest or disease that overcomes the current defences. Breeding programmes are increasingly turning to crop wild relatives and traditional landraces, which harbour genetic diversity accumulated over centuries of natural selection, as a reservoir of traits for the next generation of resilient varieties.

The Road Ahead

Artificial intelligence is beginning to complement genomics by helping breeders sift through vast datasets of genetic markers, weather records, and field trial results to predict which crosses are most likely to succeed, further compressing the breeding timeline. International gene banks, which conserve hundreds of thousands of crop varieties and their wild relatives, are being digitised and characterised at the genomic level, making it easier to locate rare stress-tolerance traits before they are lost to habitat change or genetic erosion.

None of this replaces the fundamentals of good agronomy, soil health, and water management. Climate-resilient varieties perform best as one component of an integrated strategy that also includes conservation agriculture, efficient irrigation, and crop diversification. Genomics offers speed and precision, but resilience in the field is ultimately built from the combination of a good seed, a well-managed soil, and a farmer equipped with the knowledge to use both.

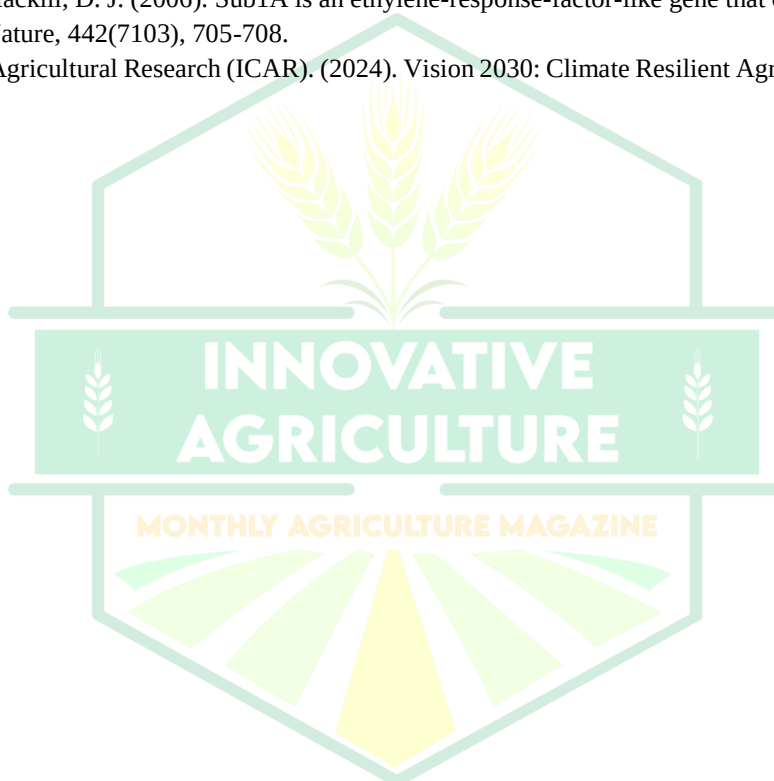
Conclusion

Climate change has removed the luxury of slow adaptation from modern agriculture. Genomics-assisted breeding and gene editing have given plant scientists tools that can identify and deploy stress-tolerance traits at a pace that at least partially matches the pace of a changing climate. The successes already visible in submergence-tolerant rice, heat-tolerant wheat lines, and drought-adapted maize hybrids demonstrate that the science works. The remaining challenge is largely one of delivery: strengthening seed systems, ensuring fair regulatory pathways for gene-edited crops, safeguarding genetic diversity, and reaching millions of smallholder farmers with both the seed

and the knowledge to use it well. Investment in these delivery systems, alongside continued scientific advancement, will determine how much of this promise reaches the field in time.

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DNA Barcoding: A Revolutionary Tool for Insect Identification



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Introduction

Correct identification of insects is the foundation of effective pest management, biodiversity conservation, ecological studies, quarantine measures, and biological control programmes. Traditionally, insects have been identified based on their external morphological characteristics such as body shape, colour, wing venation, antennae, and genital structures. Although morphology-based identification has been the backbone of insect taxonomy for centuries, it often becomes challenging when dealing with immature stages, cryptic species, damaged specimens, or insects with very similar physical characteristics (Hebert et al., 2003a; Triplehorn and Johnson, 2005).

Recent advances in molecular biology have transformed insect identification through the development of DNA barcoding, a rapid, reliable, and standardized technique that uses a short segment of DNA as a unique "barcode" for each species. In animals, including insects, the mitochondrial cytochrome c oxidase subunit I (COI) gene has emerged as the universal barcode because it shows sufficient variation among species while remaining relatively conserved within a species (Hebert et al., 2003a; Hebert et al., 2003b).

DNA barcoding has revolutionized insect taxonomy by enabling accurate identification regardless of the insect's life stage or physical condition. It has become an indispensable tool in agriculture for identifying invasive pests, monitoring quarantine species, detecting stored-product insects, authenticating beneficial insects such as pollinators and natural enemies, and supporting integrated pest management (IPM) programmes. Beyond agriculture, DNA barcoding also contributes significantly to biodiversity assessment, conservation biology, ecological monitoring, and forensic entomology (Ratnasingham and Hebert, 2007; Kress et al., 2015).

With the increasing accessibility of DNA sequencing technologies and global barcode databases, DNA barcoding is bridging the gap between classical taxonomy and modern molecular science. This revolutionary approach not only accelerates species identification but also enhances our understanding of insect diversity, ultimately contributing to sustainable agriculture, environmental conservation, and biosecurity.

What is DNA Barcoding?

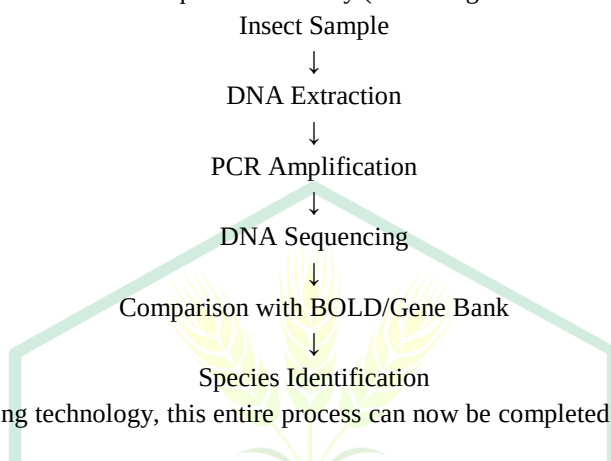
DNA barcoding is a molecular technique that identifies organisms using a short, standardized DNA sequence, much like a supermarket barcode uniquely identifies a product. In insects, a small region of the mitochondrial cytochrome c oxidase subunit I (COI) gene is commonly used because it varies sufficiently between species while remaining relatively constant within the same species (Hebert et al., 2003a).

Every species possesses a unique DNA barcode. By comparing the DNA sequence of an unknown insect with sequences stored in international databases, scientists can accurately determine its identity within a short period.

How Does DNA Barcoding Work?

The DNA barcoding process involves only a few simple steps:

1. Collection of an insect specimen.
2. Extraction of DNA from a small tissue sample.
3. Amplification of the COI gene using Polymerase Chain Reaction (PCR).
4. DNA sequencing of the amplified fragment.
5. Comparison of the obtained sequence with reference databases such as the Barcode of Life Data System (BOLD) or Gene Bank.
6. Identification of the insect based on sequence similarity (Ratnasingham and Hebert, 2007).



With advances in sequencing technology, this entire process can now be completed much faster than traditional taxonomic methods.



Why is DNA Barcoding Important?

DNA barcoding has transformed insect identification because it overcomes many limitations of traditional methods. It can identify insects regardless of their life stage, whether egg, larva, pupa, or adult. Even damaged specimens, body fragments, or processed insect materials can often be identified accurately. The technique is also useful for distinguishing cryptic species that appear morphologically identical but are genetically distinct (Kress et al., 2015). The usefulness of DNA barcoding has been demonstrated in several insect groups, including mosquitoes, where it has enabled accurate species identification even among closely related species (Kumar et al., 2007).

Applications of DNA Barcoding in Agriculture

1. Identification of Crop Pests

Many insect pests closely resemble harmless or beneficial species. DNA barcoding helps distinguish these species quickly, enabling farmers and researchers to adopt appropriate management practices. It has been widely used to identify pests such as fruit flies, stem borers, whiteflies, aphids, thrips, and armyworms.

2. Detection of Invasive Species

Invasive insects spread rapidly across countries and continents through international trade and travel. DNA barcoding enables early detection of invasive pests before they become widespread, helping quarantine authorities prevent their establishment (Armstrong and Ball, 2005).

3. Biological Control Programmes

Successful biological control depends on accurate identification of predators, parasitoid, and target pests. DNA barcoding ensures that the correct natural enemy is selected for pest management programmes, improving their effectiveness.

4. Biodiversity Conservation

Scientists use DNA barcoding to document insect diversity in forests, wetlands, agricultural fields, and protected areas. This information helps monitor ecosystem health and supports conservation planning.

5. Pollinator Identification

Many pollinator species resemble one another and are difficult to distinguish based on appearance alone. DNA barcoding facilitates accurate identification of bees, butterflies, and other pollinators, contributing to pollinator conservation and sustainable agriculture.

6. Stored Product Protection

DNA barcoding is useful for identifying insect fragments found in stored grains, flour, spices, and processed food products. Accurate identification helps determine the source of infestation and improve storage management.

7. DNA Barcoding in Forensic Entomology

DNA barcoding is increasingly used in forensic investigations to identify insects associated with decomposing bodies. Accurate identification helps estimate the post-mortem interval and provides valuable evidence in criminal investigations.

Advantages of DNA Barcoding

DNA barcoding offers several important advantages:

- ❖ Fast and accurate species identification.
- ❖ Applicable to all developmental stages.
- ❖ Useful for damaged or incomplete specimens.
- ❖ Detects cryptic and closely related species.
- ❖ Supports quarantine and biosecurity programmes.
- ❖ Assists biodiversity monitoring.
- ❖ Creates standardized global reference databases.
- ❖ Reduces dependence on highly specialized taxonomic expertise.

Traditional Identification vs DNA Barcoding

Traditional Identification	DNA Barcoding
Based on external features	Based on DNA sequence
Requires taxonomic expertise	Can be performed using molecular techniques
Difficult for immature insects	Identifies all life stages
Time-consuming	Faster and highly accurate
Damaged specimens difficult to identify	Even damaged specimens can be identified

Limitations

Despite its advantages, DNA barcoding is not without limitations. The technique requires specialized laboratory facilities, DNA sequencing instruments, and trained personnel. Accurate identification depends on the availability of reliable reference sequences in barcode databases. Closely related species may sometimes possess highly similar DNA sequences, making identification difficult. Therefore, DNA barcoding is most effective when used

together with traditional morphological identification rather than replacing it completely (Collins and Cruickshank, 2013).

Future Prospects

Rapid advances in molecular biology and next-generation sequencing are making DNA barcoding faster, cheaper, and more accessible. Portable DNA sequencing devices may soon enable field-based insect identification within a few hours. Environmental DNA (eDNA) analysis and artificial intelligence integrated with DNA databases are expected to further improve biodiversity monitoring, pest surveillance, and precision agriculture.

As barcode databases continue to expand, DNA barcoding will become an increasingly valuable tool for farmers, researchers, quarantine agencies, and conservationists worldwide.

Conclusion

DNA barcoding has revolutionized insect identification by providing a rapid, reliable, and standardized method for recognizing species. It complements traditional taxonomy and has become an indispensable tool in agriculture, pest management, biodiversity conservation, and biosecurity. As molecular technologies become more affordable and accessible, DNA barcoding will play an even greater role in protecting crops, conserving beneficial insects, and ensuring sustainable agricultural development. Integrating DNA barcoding with conventional taxonomic methods will strengthen our ability to understand and manage insect diversity for future generations.

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Koster's Curse (*Clidemia hirta*): The Silent Invader Threatening Tropical Forests



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Distribution

Koster's Curse is native to Central and South America and the Caribbean, where it grows as one shrub among thousands in a hyper-diverse Neotropical flora, kept in balance by co-evolved herbivores, pathogens, and competitors. It belongs to the family Melastomataceae, a large tropical plant family known for showy flowers and richly veined leaves, and its closest botanical relatives include other ornamental melastomes grown in gardens around the world.

Koster's Curse did not travel the world as a stowaway in cargo holds or contaminated soil alone, in some regions, deliberately cultivated as an ornamental plant for its attractive foliage and dainty flowers. From botanical gardens and private collections, it escaped into the wild, first in Pacific islands such as Fiji and Hawaii in the early twentieth century, and from there it has marched steadily across the tropics. Today it is recorded as invasive across American Samoa, Australia, Bhutan, Brunei, Cambodia, the Federated States of Micronesia, Fiji, Guam, India, Indonesia, Japan, Malaysia, Palau, Papua New Guinea, Samoa, Singapore, the Solomon Islands, Thailand, Vietnam, and the Wallis and Futuna Islands.

A single plant can produce more than 500 berries in a year, and each berry contains over 100 seeds that can lie dormant in the soil for up to four years. This high fecundity combined with a long-lived seed bank explains a great deal about why the species is so hard to eradicate once it gains a foothold. Cut it down today, and it can reappear from the soil years later, the moment conditions become favorable again. A single plant can produce more than 500 berries in a year, and each berry contains over 100 seeds that can lie dormant in the soil for up to four years.

Description

Koster's Curse is a perennial, densely branching shrub, typically growing one to two meters tall, though it can become taller and more straggling where conditions favor it. Its branchlets are rounded and covered with conspicuous, reddish, bristly hairs, a feature reflected in its scientific epithet 'hirta', Latin for 'hairy'. The leaves are arranged opposite each other along the stem, ovate to oblong-ovate in shape, five to sixteen centimeters long and three to eight centimeters wide, with a pointed or short tail-like tip and a rounded to slightly heart-shaped base.

One of the most distinctive features of the leaf is its venation: each leaf carries five prominent longitudinal nerves running from base to tip, giving the foliage a strongly ribbed, almost corrugated appearance. The upper leaf surface is sparsely rough to the touch, while the underside is finely bristly, and the leaf margins are fringed with short hairs. The petioles, or leaf stalks, are short, generally half a centimeter to three centimeters long.

The flowers are small and white, borne in clusters at the tips of branches or in the leaf axils, each only four to five millimeters across, with a glandular, bristly receptacle surrounded by a distinctive ring of small, comb-like scales are diagnostic features that botanists use to confirm identification. After flowering, the plant produces berries six to nine millimeters across that ripen from green to dark blue, purplish, or nearly black. Each berry is packed with light brown seeds, less than a millimeter long, themselves covered in stiff hairs when young.

Why This Biology Matters

None of these features are, by themselves, dramatic. There is no toxin, no special weapon, no parasitic trick. What makes Koster's Curse dangerous is the sheer reproductive arithmetic: rapid growth, early and prolific flowering, hundreds of berries per plant per year, seeds dispersed widely by birds, civets, and feral pigs that eat the sweet berries, and a seed bank that can simply wait out unfavorable years. It is the botanical equivalent of compound

interest, individually small advantages that, multiplied across thousands of plants and several years, produce an overwhelming ecological force.

Distribution in Kerala

Koster's Curse is, above all, a plant of disturbed ground. It readily colonises pastures, riversides, roadsides, logging trails, and forest margins and anywhere that the closed canopy of mature forest has been opened up, letting in light. Kerala's forest fringes, plantation boundaries, and disturbed patches in districts such as Pathanamthitta provide exactly this kind of opportunity: a humid, warm climate, frequent small-scale disturbance from logging, grazing, or path-making, and dappled light at the forest edge.

Crucially, however, Koster's Curse is not restricted to disturbed habitats alone. Unlike many invasive plants that need continuous light and cannot survive under a forest canopy, this species has the unusual ability to also establish itself inside relatively undisturbed, shaded forest understorey, albeit at lower densities and with slower growth. This dual strategy of explosive growth in gaps, patient persistence in the shade means that there is almost no part of a humid tropical forest where the plant cannot eventually appear.

Impact of Koster's Curse

The danger of Koster's Curse lies not in any single dramatic event but in a slow, cumulative transformation of habitat structure. Once established, it grows and spreads with remarkable speed, rapidly producing seedlings that out-compete native ground flora and tree seedlings for light, moisture, and nutrients. Over time, dense thickets of Koster's Curse can become so continuous and impenetrable that they form what ecologists call monotypic stands, where the rich multi-species undergrowth of a natural tropical forest is replaced by a uniform green wall of one invasive shrub.

This has several knock-on consequences. First, it disrupts natural forest regeneration: tree seedlings that would normally re-establish in canopy gaps after a tree falls or after logging are smothered before they can grow, slowing or halting the forest's natural recovery. Second, it physically obstructs the movement of animals and people, with its dense thickets creating real barriers across grazing land, trails, and access routes. Third, populations of feral pigs, which relish the berries, often help spread the species further into new areas, creating a feedback loop between an invasive animal and an invasive plant that compounds the damage to native ecosystems. Even in places where Koster's Curse cannot dominate completely for instance, deep inside intact, undisturbed forest, its mere presence at low density still represents a long-term risk, since any future disturbance (a fallen tree, a forest fire, a new road) can trigger explosive growth from the existing seed bank or surviving plants.

Koster's Curse in Kerala's Forest Landscapes

In Kerala, and more broadly across the southern Western Ghats, Koster's Curse has become an increasingly familiar and increasingly troublesome presence in plantation understoreys and along the margins of moist deciduous and evergreen forests. The combination of high rainfall, warm temperatures, and widespread small-scale disturbance from plantation management, road construction, and forest-edge agriculture creates near-ideal conditions for the species to establish and spread.

This regional spread has, in turn, attracted growing scientific attention. Researchers are examining not only the ecological behaviour of the species how it regenerates after disturbance such as cutting or fire, and how it competes with native vegetation through allelopathy, the release of chemical compounds that suppress the germination and growth of neighboring plants, but also whether the very qualities that make Koster's Curse a successful invader might be turned to some practical use.

Two lines of applied research are particularly interesting in this context. The first explores whether extracts from the plant possess bioactive or antimicrobial properties of value against agriculturally important plant pathogens, turning a forest pest into a potential source of crop-protection compounds. The second examines the plant's biomass for pelletisation, that is, compressing the harvested shrub into dense fuel pellets for energy use, evaluated against recognised pellet quality standards such as ISO 17225-2, the European ENplus certification scheme, and India's own IS 17084:2018 standard for solid biofuel pellets, often using natural plant compounds like lignin as a binding agent. If viable, such approaches would convert the cost of controlling an invasive weed into a productive bioeconomy opportunity, clearing infested land while generating a useful biomass product.

Management

Koster's Curse combines fast growth with a persistent seed bank, no single method of control is likely to succeed on its own; effective management typically blends mechanical, chemical, and biological approaches, chosen according to the scale and location of the infestation.

Manual and Mechanical Control

For small, newly established populations, manual weeding remains an effective and low-cost first line of defence, particularly when carried out before plants reach reproductive maturity and begin producing berries. Repeated follow-up is essential, however, since the seed bank in the soil will continue to produce new seedlings for several years after the visible plants have been removed.

Chemical Control

For larger infestations, cutting plants at the base followed immediately by treating the freshly cut stump with a water-based herbicide such as triclopyr has proven effective, since the cut surface allows rapid absorption of the herbicide into the root system before the wound can seal over.

Biological Control

Because Koster's Curse has so successfully escaped the natural enemies that keep it in check in its native range, classical biological control, deliberately introducing some of those natural enemies into invaded regions has been an active area of research for decades. A thrips species, *Liothrips urichi*, has shown good results as a biocontrol agent in open, sunlit areas, feeding on young shoots and flower buds, although it is markedly less effective in the shaded understorey of closed forest. A beetle, *Lius poseidon*, and several moth species including *Antiblemma acclinalis*, *Carposina bullata*, and *Mompha trithalama* are under active evaluation as additional biocontrol agents, each targeting different parts of the plant's life cycle. Perhaps most promising from a research standpoint is the fungal pathogen *Colletotrichum gloeosporioides*, isolated from naturally diseased Koster's Curse leaves in Panama, which has demonstrated strong, aggressive pathogenicity against the species and is being studied as a potential biological control or even a bio-herbicide.

Uses of Koster's Curse

It is worth remembering that Koster's Curse was, and in places still is, valued for one simple reason: people find it attractive. Its neat, ribbed foliage and dainty white flowers have made it a popular ornamental shrub in gardens across the tropics, the very trait that triggered its escape into the wild in the first place. Beyond ornamental use, emerging research into its antimicrobial compounds and its potential as a pelletised biomass fuel hints that, managed carefully, the same biomass that makes it such a disruptive forest invader could be converted into something of economic value, turning control efforts into a source of raw material rather than pure cost.

Conclusion

Koster's Curse is, in many ways, an object lesson in how a plant does not need spectacular biology to become one of the world's most damaging invasive species. It needs only to be slightly better than its competitors at a few simple things including growing fast, flowering early, producing abundant seed, persisting patiently in the soil, and tolerating a wide range of light conditions and then to be carried, by birds, by pigs, by gardeners, far beyond the natural enemies and ecological checks that kept it in balance at home. The result, replicated across forest after forest in Asia and the Pacific, is the slow replacement of diverse native undergrowth with dense, species-poor thickets of a single hairy shrub.

The story of Koster's curse is, however, not simply one of loss. It is also a story of how careful, sustained science, studying a weed's regeneration ecology, testing biological control agents, identifying chemical compounds in its tissues, and exploring uses for its harvested biomass can begin to turn the tables. Manual weeding, targeted herbicide application, classical biocontrol with insects and fungal pathogens, and policy measures restricting further ornamental trade together offer a realistic, if labour-intensive, path toward containing this species. And the growing interest in its biomass for fuel pellets and its extracts for antimicrobial activity suggests that, with continued research of the kind being carried out in Kerala and elsewhere along the Western Ghats, a problem species might yet be made to pay, in some small way, for the damage it has done.

For forest managers, ecologists, and students of invasion biology, Koster's Curse remains a compelling case study precisely because it sits at the intersection of so many themes that define the modern invasive species crisis:

the unintended ecological consequences of the ornamental plant trade, the outsized impact of small reproductive advantages compounded over time, the challenge of controlling a species with a long-lived seed bank, and the tantalising possibility that ecological problems can sometimes be converted, through careful applied research, into modest economic opportunities. In that sense, this unassuming, bristly-stemmed shrub from the forests of Central and South America has much to teach us, not only about itself, but about the broader, ongoing struggle to keep the world's tropical forests intact in an age of constant human disturbance and global movement of species.



The Rise of Digital Banking



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Abstract

The rapid advancement of digital technologies has significantly transformed the global banking landscape. Digital banking has emerged as a dominant force, reshaping how financial services are delivered and consumed. This article examines the rise of digital banking by analyzing its drivers, benefits, challenges and implications for financial institutions. It highlights how innovations such as mobile banking, fintech integration and digital payment systems are enhancing customer experience, improving operational efficiency and promoting financial inclusion. However, the transformation also introduces risks related to cybersecurity, regulatory compliance and financial stability. The study concludes that while digital banking is redefining the future of finance, its sustainable growth depends on effective regulation, technological resilience and continuous innovation.

Introduction

The banking industry has undergone a profound transformation due to the digital revolution. Traditionally, banking services relied heavily on physical branches, paperwork and face-to-face interactions. However, the emergence of digital technologies such as mobile applications, internet banking and Financial Technology (FINTECH) solutions has shifted the industry toward a more customer-centric and technology-driven model.

Digital banking refers to the digitization of all traditional banking activities and services, allowing customers to perform transactions electronically without visiting a physical branch. This transformation is driven by increasing customer demand for convenience, speed, and seamless financial transactions. Additionally, the rapid growth of smartphones and internet penetration has further accelerated the adoption of digital banking services worldwide.

In recent years, digital banking has gained momentum due to the integration of advanced technologies such as Artificial Intelligence (AI), big data analytics, cloud computing, and blockchain. These technologies enable banks to provide innovative services, enhance operational efficiency and improve decision-making processes. At the same time, Non-Banking entities such as fintech companies are entering the financial sector, intensifying competition and driving continuous innovation.

Evolution of Banking Systems

Banking has evolved significantly over time, moving from traditional banking to modern digital banking. Initially, banking operations were manual and paper-based, requiring customers to visit bank branches for every transaction. The introduction of Automated Teller Machines (ATMs) marked the first step toward automation, allowing customers to withdraw cash and perform basic transactions outside banking hours.

The next phase involved the adoption of internet banking, which enabled customers to access their accounts online. This was followed by mobile banking, which brought banking services directly to customers' smartphones. Today, digital banking encompasses a wide range of services, including online payments, digital wallets, and real-time fund transfers.

The rise of digital money and electronic payment systems has further transformed the financial ecosystem. Digital currencies, e-money and Central Bank Digital Currencies (CBDCs) are redefining the concept of money and challenging traditional banking models. These innovations have introduced new opportunities as well as risks in the financial system.

Drivers of Digital Banking Growth

Several factors have contributed to the rapid growth of digital banking:

Technological Advancements

Technological innovations such as AI, machine learning, and blockchain have enabled banks to automate processes, enhance security, and provide personalized services. Cloud computing has reduced infrastructure costs and improved scalability.

Changing Consumer Behavior

Modern consumers prefer fast, convenient, and user-friendly banking services. The demand for 24/7 access to financial services has encouraged banks to adopt digital solutions.

Fintech Innovation

Fintech companies have introduced innovative products and services, such as peer-to-peer payments, mobile wallets and digital lending platforms. These innovations have disrupted traditional banking models and forced banks to adapt.

Government Initiatives

Governments and central banks have promoted digital payments and financial inclusion through policies and regulatory frameworks. Initiatives such as cashless economies and digital identity systems have supported digital banking growth.

Benefits of Digital Banking

Digital banking offers numerous benefits to both customers and financial institutions:

Convenience and Accessibility- Customers can access banking services anytime and anywhere, eliminating the need for physical visits to bank branches.

Cost Efficiency- Digital banking reduces operational costs by minimizing the need for physical infrastructure and manual processes.

Improved Customer Experience- Personalized services, faster transactions, and user-friendly interfaces enhance customer satisfaction.

Financial Inclusion- Digital banking enables access to financial services for underserved populations, particularly in rural and remote areas.

Enhanced Efficiency- Automation and digital processes improve operational efficiency and reduce errors in banking operations

24/7 Banking Services – Customers can access banking services anytime and anywhere using the internet.

Convenience – Transactions such as fund transfers, bill payments, and account management can be completed without visiting a bank branch.

Faster Transactions – Digital banking enables instant or quick transfers, online payments, and faster processing of banking services.

Cost Savings – It reduces operational costs for banks and saves customers time and travel expenses.

Easy Account Management – Customers can check account balances, download statements, and monitor transactions in real time.

Secure Transactions – Features such as encryption, multi-factor authentication, and biometric verification improve the security of online banking.

Paperless Banking – Digital banking reduces the use of paper by providing electronic statements, receipts, and online applications.

Online Bill Payments – Customers can conveniently pay utility bills, taxes, and other payments from their devices.

Better Customer Experience – Mobile apps, chatbots and personalized financial services make banking more efficient and user-friendly.

Financial Inclusion – Digital banking provides banking services to people in remote and underserved areas through mobile and internet access.

Challenges and Risks

Cybersecurity Threats

Despite its advantages, digital banking presents several challenges:

Increased digitalization exposes banks to cyberattacks, data breaches, and fraud.

Regulatory Compliance- Banks must comply with complex and evolving regulatory requirements, which can be challenging.

Technological Risks- System failures, software bugs, and technical issues can disrupt banking services.

Financial Stability Concerns- The rise of digital money and fintech may impact traditional banking models and financial stability.

Digital Divide- Limited access to technology and internet connectivity can hinder the adoption of digital banking

Data Privacy Concerns – Protecting customers' personal and financial information is a major challenge due to increasing cyber threats.

Fraud and Identity Theft – Criminals may use stolen identities, fake websites, or unauthorized transactions to commit financial fraud.

Technical Failures – System crashes, server downtime, or software bugs can interrupt banking services and inconvenience customers.

Internet Dependency – Digital banking requires a stable internet connection, making access difficult in areas with poor connectivity.

Digital Literacy Issues – Some customers, especially elderly users or those unfamiliar with technology, may find digital banking difficult to use.

Regulatory Compliance – Banks must comply with changing financial regulations and data protection laws, which can be complex and costly.

Third-Party Risks – Banks often rely on external technology providers, creating risks if those providers experience failures or security breaches.

High Technology Costs – Developing, maintaining, and upgrading secure digital banking systems requires significant investment.

Customer Trust – Security incidents or service outages can reduce customer confidence in digital banking services.

Impact of Digital Banking on the Banking Sector

Digital banking has significantly impacted the banking sector by transforming business models and operations. Traditional banks are shifting toward digital-first strategies to remain competitive. The role of physical branches is declining, while digital channels are becoming the primary means of service delivery.

Fintech companies are playing a crucial role in driving innovation and competition in the banking industry. Collaboration between banks and fintech firms is becoming increasingly common, leading to the development of new products and services.

Digital banking has also improved bank performance by increasing efficiency, reducing costs, and expanding customer reach. However, the transition to digital banking requires significant investment in technology and infrastructure.

Improved Customer Convenience – Customers can access banking services anytime and anywhere through mobile apps and online platforms.

Reduced Operating Costs – Digital banking decreases the need for physical branches and paperwork, helping banks lower operational expenses.

Faster Transactions – Online fund transfers, bill payments, and account services are completed quickly, improving efficiency.

Enhanced Customer Experience – Personalized services, AI-powered chatbots, and instant support increase customer satisfaction.

Greater Financial Inclusion – Digital banking extends banking services to people in rural and underserved areas through internet and mobile access.

Increased Competition – Traditional banks face competition from digital banks and fintech companies, encouraging innovation and better services.

Improved Security – Banks use advanced technologies such as encryption, biometric authentication, and multi-factor authentication to protect customer accounts.

Data-Driven Decision Making – Banks use customer data and analytics to understand customer needs, improve services, and manage risks.

Growth of Cashless Payments – Digital banking promotes online payments, digital wallets, and contactless transactions, reducing the use of cash.

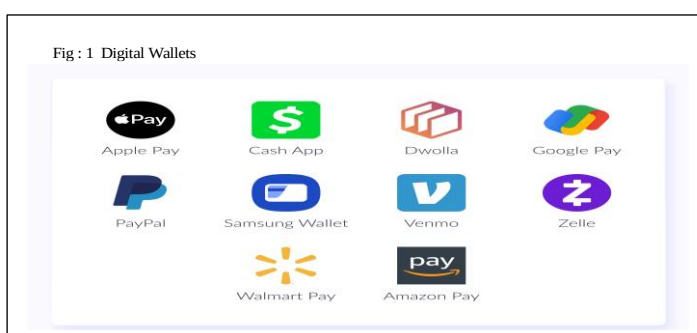
Job Role Transformation – While automation reduces some manual tasks, it creates demand for professionals with digital, cybersecurity, and data analytics skills.

Current trends in digital banking

Mobile Banking – Customers increasingly use mobile apps to transfer money, pay bills, check balances, and manage accounts anytime.

Artificial Intelligence (AI) and Chatbots – Banks use AI-powered chatbots to provide 24/7 customer support, answer queries, and detect fraud.

Digital Wallets and Contactless Payments – Services like Apple Pay, Google Pay, and other digital wallets enable fast and secure cashless transactions.



Biometric Authentication – Fingerprint, facial recognition and voice authentication improve security and simplify login processes.

Open Banking – Banks share customer-approved financial data with third-party providers through secure APIs to offer innovative financial services.

Blockchain Technology – Banks are exploring blockchain to improve payment security, transparency, and the speed of cross-border transactions.

Cloud Computing – Financial institutions are moving to cloud-based systems to reduce costs, improve scalability, and enhance service reliability.

Personalized Banking – AI and data analytics help banks provide customized financial products, spending insights, and investment recommendations.

Cybersecurity Enhancements – Banks are investing in advanced security technologies, such as multi-factor authentication and real-time fraud detection, to protect customer data.

Digital Lending – Online loan applications with automated approval processes allow customers to receive loans more quickly and conveniently

Future Trends in Digital Banking

The future of digital banking is shaped by emerging technologies and evolving customer expectations:

Artificial intelligence and machine learning will enhance decision-making and customer service. Blockchain technology will improve security and transparency in financial transactions. Central bank digital currencies (CBDCs) will transform the monetary system. Open banking will promote data sharing and innovation in financial services. Biometric authentication will enhance security and user experience.

Conclusion

The rise of digital banking represents a fundamental shift in the financial services industry. Driven by technological innovation and changing consumer expectations, digital banking has improved accessibility, efficiency, and customer experience. However, it also introduces new risks and challenges that must be carefully managed. For digital banking to achieve sustainable growth, financial institutions must invest in secure technologies, adopt customer-centric strategies, and comply with regulatory requirements. Governments and

regulators also play a crucial role in ensuring financial stability and fostering innovation. Ultimately, digital banking will continue to shape the future of the global financial system.

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Cold Plasma Technology in Food Processing: A New Era of Safe and Sustainable Foods



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Abstract

Cold plasma (CP) technology has emerged as a promising non-thermal processing method that is rapidly transforming food safety and preservation. Generated by applying electrical energy to gases, CP produces reactive oxygen and nitrogen species, ultraviolet photons, and charged particles that collectively inactivate pathogens, degrade mycotoxins, remove pesticide residues, and extend shelf life without the use of heat or chemical additives. Unlike conventional thermal methods that often compromise nutritional integrity and sensory attributes, CP operates at near-ambient temperatures, making it suitable for heat-sensitive food products. This article reviews the fundamental principles, generation methods, and applications of CP across various food categories, while highlighting its potential to advance sustainable food processing. The safety profile, environmental benefits, and future prospects of CP are also discussed.

1. Introduction

The global food industry faces mounting pressure to deliver products that are not only microbiologically safe but also nutritionally rich, sensorially acceptable, and produced through environmentally responsible methods (Varilla et al., 2020). Conventional thermal processing techniques such as pasteurization and sterilization have long served as the backbone of food safety; however, these methods are associated with nutrient degradation, sensory deterioration, and the potential formation of harmful by-products (Zhang et al., 2022). In response to growing consumer demand for minimally processed, chemical-free food products, researchers and food technologists have directed considerable attention toward non-thermal technologies as viable alternatives (Harikrishna et al., 2023).

Among the emerging non-thermal technologies, cold plasma (CP) has attracted the most significant scientific interest due to its unique ability to simultaneously address microbial safety, chemical decontamination, and functional quality enhancement in a single treatment (Sharma et al., 2025). CP is defined as a partially ionized gas maintained at temperatures close to ambient conditions, generated when a sufficient electrical field is applied to a gas such as air, nitrogen, helium, or argon (Varilla et al., 2020). The resulting ionized medium contains a complex mixture of reactive oxygen species (ROS), reactive nitrogen species (RNS), ultraviolet photons, ions, electrons, and free radicals, all of which interact with food surfaces and microbial cells to bring about decontamination (Harikrishna et al., 2023). This unique physicochemical composition distinguishes CP from other non-thermal methods such as high-pressure processing, pulsed electric fields, or ultrasonication, since CP can simultaneously target biological and chemical contaminants without leaving toxic residues (Zhang et al., 2022).

The growing body of research on CP spanning fruits, vegetables, cereals, meat, dairy, and packaged foods demonstrates that this technology holds considerable promise for both industrial-scale implementation and laboratory-level application (Rao et al., 2023). Furthermore, the low energy consumption, absence of chemical reagents, and adaptability to different food matrices position CP as one of the most sustainable food processing technologies currently under development (Sharma et al., 2025).

2. Principles and Generation of Cold Plasma

Understanding why CP is effective requires first appreciating how it is physically generated. CP is produced when an electrical energy source is applied to a gas, causing ionization of the gas molecules and the release of electrons, ions, radicals, and photons (Varilla et al., 2020). This process does not require elevated temperatures because the energy input preferentially excites electrons rather than heating the gas as a whole, resulting in a thermodynamically non-equilibrium state where the gas remains cool while the electron temperature is extremely high (Harikrishna et al., 2023). It is this non-equilibrium condition that makes CP uniquely suitable for food

processing, since food products can be exposed to the reactive plasma environment without undergoing thermal damage (Zhang et al., 2022).

Several technical configurations have been developed to generate CP for food applications. The most widely studied systems include dielectric barrier discharge (DBD), atmospheric-pressure plasma jets (APPJ), corona discharge, glow discharge, radio frequency discharge, and microwave-induced plasma (Sharma et al., 2025). Among these, DBD is especially popular for food applications because it can generate plasma uniformly over large surface areas within sealed food packages, enabling in-package decontamination without opening the packaging barrier (Varilla et al., 2020). In a DBD system, an insulating dielectric material is placed between two electrodes, which disperses the current flow and prevents localized arcing while producing a diffuse plasma discharge that generates ROS and RNS directly within the treatment zone (Varilla et al., 2020). Plasma jets, on the other hand, produce a directed stream of plasma effluent that can be applied to food surfaces in a targeted manner, making them suitable for treating irregularly shaped products (Sharma et al., 2025).

The choice of working gas also significantly influences the composition and reactivity of the plasma. Air plasmas are regarded as particularly rich sources of both ROS and RNS, since atmospheric nitrogen and oxygen participate in discharge reactions to yield species such as ozone (O₃), atomic oxygen (O), singlet oxygen (1O₂), nitric oxide (NO), and nitrogen dioxide (NO₂) (Sharma et al., 2025). When inert gases such as helium or argon are used, the plasma tends to produce fewer RNS but can generate metastable species with distinct reactive properties (Harikrishna et al., 2023). Additional parameters such as applied voltage, frequency, electrode geometry, treatment time, and gas flow rate also modulate the density and composition of reactive species, allowing researchers to tailor CP treatment conditions to specific food safety objectives (Rao et al., 2023).

An important derivative of CP technology that has gained increasing attention is plasma-activated water (PAW). PAW is produced when CP is applied to water or an aqueous liquid, transferring reactive species into the water phase to create an acidic, oxidative solution that retains antimicrobial activity even after the plasma discharge has ceased (Sharma et al., 2025). PAW has been explored as a sanitizing agent for washing fresh produce, treating food contact surfaces, and serving as a component in food processing operations where direct plasma application is not feasible (Sharma et al., 2025).

3. Mechanisms of Microbial Inactivation

The antimicrobial action of CP is multifaceted and operates through several simultaneous mechanisms, making it particularly effective against a broad spectrum of foodborne pathogens (Varilla et al., 2020). The first and most chemically significant mechanism involves the interaction of ROS and RNS with the outer surfaces of microbial cells. These highly reactive species attack the lipid bilayer of the microbial cell membrane, causing lipid peroxidation and a consequent loss of membrane integrity, which eventually leads to leakage of intracellular contents and cell death (Harikrishna et al., 2023). A second mechanism involves the penetration of ROS and RNS into the cell interior, where they target nucleic acids, particularly DNA, causing strand breaks, base modifications, and disruption of replication, thereby preventing microbial reproduction (Zhang et al., 2022). The third mechanism is the direct photochemical action of ultraviolet photons generated during plasma discharge, which are capable of inducing DNA damage in surface-exposed microorganisms without the need for thermal energy (Varilla et al., 2020).

Research has confirmed that CP is effective against a wide range of pathogenic bacteria, including *Listeria monocytogenes*, *Salmonella Typhimurium*, *Escherichia coli* O157:H7, *Campylobacter jejuni*, and *Staphylococcus aureus*, which are among the most commonly implicated organisms in foodborne illness outbreaks worldwide (Varilla et al., 2020). Notably, CP has demonstrated efficacy not only against vegetative bacterial cells but also against bacterial spores and biofilms, which are typically more resistant to conventional decontamination treatments (Harikrishna et al., 2023). Fungal pathogens and yeast are also susceptible to CP treatment, as the reactive species disrupt fungal cell walls and membrane structures in a manner broadly similar to the mechanisms observed in bacteria (Rao et al., 2023).

The extent of microbial inactivation achieved by CP depends on several treatment parameters. Treatment duration is one of the most influential variables, with longer exposure times generally producing greater log reductions in microbial load (Zhang et al., 2022). Applied voltage, the type of working gas, electrode

configuration, and the nature of the food matrix also substantially influence efficacy (Rao et al., 2023). For example, the presence of moisture, fat, protein, or surface roughness in a food matrix can shield microorganisms from reactive species, reducing the effective antimicrobial impact of CP treatment (Harikrishna et al., 2023). These matrix effects underscore the importance of optimizing CP parameters for each specific food application rather than applying a universal treatment protocol.

4. Mycotoxin Degradation and Chemical Decontamination

Beyond microbial inactivation, one of the most scientifically compelling applications of CP in food safety is its ability to degrade chemical contaminants, particularly mycotoxins, which are toxic secondary metabolites produced by mold species such as *Aspergillus*, *Fusarium*, and *Penicillium* (Rao et al., 2023). Mycotoxins including aflatoxin B1 (AFB1), deoxynivalenol (DON), zearalenone (ZEN), ochratoxin A (OTA), fumonisins, and T-2 toxin pose serious threats to both human and animal health, with documented effects including hepatotoxicity, nephrotoxicity, carcinogenicity, and immunosuppression (Rao et al., 2023). Because mycotoxins are chemically stable compounds that survive most conventional thermal processing conditions, the development of effective, non-thermal decontamination strategies is of high public health importance (Zhang et al., 2022).

CP degrades mycotoxins primarily through the oxidative action of ROS and RNS, which attack the chemical bonds responsible for mycotoxin toxicity. In the case of AFB1, reactive species generated by CP have been shown to disrupt the coumarin lactone ring and the furan double bond, which are the structural features primarily responsible for the compound's mutagenic and carcinogenic properties (Rao et al., 2023). Similarly, DON degradation by CP involves oxidative cleavage of the epoxide group and modification of the ketone moiety, leading to structural transformation of the toxin into less toxic degradation products (Rao et al., 2023). These degradation pathways suggest that CP does not merely suppress mycotoxin-producing fungi but directly transforms the toxin molecules into chemically distinct, less harmful species.

Low-moisture foods such as grains, spices, nuts, and seeds are particularly susceptible to mycotoxin contamination, and conventional decontamination approaches are often limited in their effectiveness for these matrices (Rao et al., 2023). CP has demonstrated notable success in reducing mycotoxin loads in these products. Studies reviewed by Rao et al. (2023) showed that CP treatment significantly reduced AFB1 in contaminated peanuts, maize, and wheat under optimized treatment conditions while maintaining acceptable physicochemical quality. In addition to mycotoxins, CP has shown efficacy in the degradation of pesticide residues on fresh produce, offering an environmentally friendly approach to reduce agrochemical contamination in fruits and vegetables (Varilla et al., 2020). The reactive species generated by CP interact with pesticide molecules on food surfaces, breaking down organophosphate, pyrethroid, and carbamate compounds through oxidative pathways (Varilla et al., 2020).

5. Effects on Nutritional and Sensory Quality

A fundamental concern with any food processing technology is whether it preserves or degrades the nutritional and sensory attributes that consumers value. In this regard, CP has consistently demonstrated a more favorable profile compared to conventional thermal methods (Zhang et al., 2022). Because CP operates at near-ambient temperatures, the degradation of heat-sensitive nutrients such as vitamin C, vitamin B-group vitamins, and bioactive phenolic compounds is significantly minimized relative to pasteurization or sterilization (Harikrishna et al., 2023). Several studies have reported that CP treatment either preserved or even enhanced the antioxidant capacity of treated fruits and vegetables by promoting the release of bound phenolics from cell wall matrices through oxidative modification of plant tissue (Zhang et al., 2022).

Regarding protein functionality, CP has been shown to modify the structure of food proteins through oxidation of specific amino acid residues, leading to changes in solubility, water-holding capacity, emulsification, and foaming properties (Zhang et al., 2022). While moderate protein oxidation can improve functional properties and enhance the digestibility of plant-based proteins, excessive oxidation at high treatment intensities may cause aggregation and reduced nutritional value (Harikrishna et al., 2023). Therefore, careful optimization of CP treatment parameters is necessary to achieve beneficial functional modifications without compromising nutritional quality.

Starch and lipid components in food are also affected by CP treatment. In cereal grains, CP treatment has been shown to modify starch granule surfaces, alter crystallinity, and reduce cooking time, effects attributed to surface etching and partial depolymerization of starch chains by reactive species (Rao et al., 2023). In terms of lipid quality, short-duration CP treatments at moderate intensities generally do not significantly increase lipid oxidation markers, particularly when treatment conditions are well controlled (Sharma et al., 2025). However, prolonged exposure or high-voltage treatment can initiate lipid oxidation, which represents a potential challenge for fatty food products such as nuts, seeds, and meat that are rich in unsaturated fatty acids (Rao et al., 2023).

Sensory quality parameters including color, aroma, texture, and flavor are also important determinants of consumer acceptance. Research reviewed by Zhang et al. (2022) demonstrated that CP treatment at appropriate conditions did not cause significant changes in the color of treated foods. In fresh produce, CP has been found to reduce enzymatic browning by partially inhibiting polyphenol oxidase (PPO) and peroxidase (POD) activities, enzymes responsible for the undesirable browning of cut surfaces (Zhang et al., 2022). Careful control of treatment intensity is needed to prevent the development of off-flavors, particularly in dairy and meat products (Harikrishna et al., 2023).

6. Applications Across Food Categories

The versatility of CP is evidenced by the breadth of food categories to which it has been successfully applied. In fresh fruits and vegetables, CP has been used to reduce surface contamination by bacteria, molds, and yeasts while simultaneously inhibiting enzymatic browning and extending shelf life (Varilla et al., 2020). CP treatment of romaine lettuce has been shown to be effective against Tulane virus, while treatment of fresh produce has demonstrated significant reductions in *E. coli* O157:H7 and *Salmonella* spp. without causing visible damage to the product surface (Varilla et al., 2020). For meat and meat products, CP treatment has been applied to reduce surface contamination by *L. monocytogenes* and *Salmonella* spp. while preserving color stability and maintaining acceptable sensory characteristics (Harikrishna et al., 2023). CP has also been evaluated for the treatment of eggs, where it has demonstrated the ability to reduce microbial loads on shell surfaces without affecting internal quality parameters such as Haugh unit value or yolk color (Harikrishna et al., 2023). In the dairy sector, CP has been explored for the decontamination of milk and cheese surfaces, with studies demonstrating reductions in total bacterial count while largely preserving protein structure and fat globule integrity (Zhang et al., 2022).

Cereal grains and legumes represent another major area of application, where CP has been used not only for decontamination and mycotoxin reduction but also for the modification of starch, protein, and fiber functional properties to improve processing characteristics (Rao et al., 2023). Particularly noteworthy is the application of CP for seed germination enhancement, where pre-treatment of seeds with CP has been shown to improve germination rates, seedling vigor, and early growth parameters, attributed to surface modifications that improve water imbibition and the stimulation of metabolic pathways associated with germination (Rao et al., 2023). Spices and herbs, which are frequently associated with high microbial loads, have also been successfully treated with CP, achieving significant microbial reductions without compromising essential oil content, color, or aroma profile (Rao et al., 2023).

7. Cold Plasma in Food Packaging

An important and growing area of CP application is the modification and enhancement of food packaging materials. CP treatment of packaging films has been shown to improve surface wettability, adhesion properties, and printability by introducing polar functional groups such as hydroxyl, carbonyl, and carboxyl groups on polymer surfaces through oxidative reactions (Varilla et al., 2020). Beyond these physical improvements, CP can be used to impart antimicrobial properties to packaging surfaces by depositing reactive species or by facilitating the incorporation of antimicrobial agents into the packaging matrix (Harikrishna et al., 2023).

In-package CP treatment represents an especially innovative concept, in which plasma is generated within a sealed food package, allowing direct treatment of both the food surface and the internal atmosphere simultaneously (Varilla et al., 2020). This approach has the advantage of maintaining the sterility of the product throughout the treatment process, since the package remains closed and no external contamination can occur during treatment (Sharma et al., 2025). Research has shown that in-package DBD plasma treatment can generate sufficient ROS and RNS within the sealed headspace to achieve meaningful reductions in surface microbial loads

on fresh produce, meat, and ready-to-eat products, extending shelf life by up to 14 days in certain treated products (Sharma et al., 2025).

8. Sustainability and Environmental Benefits

The sustainability credentials of CP technology are among the most compelling arguments for its broader adoption in the food industry. Unlike chemical sanitizers such as chlorine, hydrogen peroxide, or peracetic acid, CP does not introduce exogenous chemical residues into food products or the food processing environment (Zhang et al., 2022). The primary inputs for CP generation are electricity and an ambient or inert gas such as air, helium, or argon, both of which are abundant, inexpensive, and non-toxic (Sharma et al., 2025). The absence of chemical residues not only reduces the risk of consumer exposure to processing chemicals but also simplifies wastewater treatment requirements associated with conventional sanitation protocols (Sharma et al., 2025). From an energy efficiency standpoint, CP technology compares favorably with thermal processing methods. CP can achieve significant microbial inactivation and chemical degradation at room temperature, eliminating the energy costs associated with heating large volumes of food material to pasteurization or sterilization temperatures (Sharma et al., 2025). This energy efficiency, combined with the shorter treatment times typical of CP applications relative to thermal methods, translates into a reduced carbon footprint for food processing operations (Sharma et al., 2025). As the food industry faces increasing pressure to reduce greenhouse gas emissions and adopt sustainable production practices, CP offers a technologically mature and environmentally aligned alternative to established thermal and chemical processing approaches.

9. Limitations and Future Perspectives

Despite its considerable promise, CP technology is not without challenges that must be addressed before widespread industrial adoption can be realized. One significant limitation is the penetration depth of reactive species, which are primarily effective at food surfaces and may not achieve adequate decontamination of internally contaminated products or foods with complex porous matrices (Harikrishna et al., 2023). Standardization of treatment protocols across different equipment configurations, food matrices, and target contaminants also remains an unresolved challenge, since the diversity of CP systems makes it difficult to establish universally applicable safety validation frameworks (Rao et al., 2023). The initial capital cost of CP equipment, the requirement for specialized technical knowledge, and the need for stringent safety protocols related to the handling of ozone and other reactive species during operation represent additional barriers to adoption, particularly for small and medium-scale food producers (Sharma et al., 2025).

Regulatory uncertainty also poses a challenge in several key markets. Unlike heat pasteurization or chemical treatments with well-established safety profiles, CP lacks comprehensive regulatory frameworks in most jurisdictions, which creates uncertainty for food manufacturers seeking to commercialize CP-treated products (Varilla et al., 2020). Toxicological evaluation of CP-treated foods is an active area of research, with studies generally indicating acceptable safety profiles; however, more comprehensive *in vivo* studies are needed to fully characterize the safety of CP-generated reactive species in complex food systems (Zhang et al., 2022). Future research should focus on the development of continuous-flow CP systems suitable for high-throughput industrial processing, the integration of CP with other non-thermal technologies for synergistic decontamination effects, and the establishment of clear regulatory pathways that will facilitate the commercialization of CP-treated food products.

Conclusion

Cold plasma technology represents a scientifically robust and practically versatile advancement in the field of food processing. By generating a complex mixture of reactive species at ambient temperatures, CP achieves effective microbial inactivation, mycotoxin degradation, pesticide removal, enzyme inactivation, and quality preservation across a wide range of food categories without the use of heat or chemical additives. Its sustainability credentials, low energy requirements, and chemical-free nature align well with the evolving priorities of the food industry and consumer expectations. While challenges related to penetration depth, process standardization, equipment cost, and regulatory approval continue to require attention, the cumulative evidence from current research strongly positions cold plasma as a foundational technology for the next generation of safe, sustainable, and high-quality food production.

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Mission Mausam: India's Race to Outsmart the Sky



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Introduction

On a February evening in Nashik's grape belt, a farmer named Vitthal saw a phone alert warning of hailstorm clouds building over his district within thirty-six hours. He netted his vines and advanced his harvest by two days. When the hail struck, his neighbour's uncovered vineyard lost a third of its fruit; Vitthal's crop survived largely intact. That quiet, routine-feeling alert sits atop an enormous scientific enterprise: Mission Mausam, India's boldest attempt yet to read the sky before it decides for us. Behind a single push notification lie new radars, satellites, supercomputers and thousands of scientists working to make weather less of a gamble for the country's farmers, fishers and city dwellers alike.

Why India Needed Mission Mausam

India's economy lives close to the sky. A delayed monsoon shrinks harvests; an unexpected cloudburst can wash away a season's work in an hour; a heatwave arriving early can strain hospitals and power grids at once. For decades, Indian forecasts were admirable but coarse, useful at the scale of a state or river basin but too broad to tell one farmer whether to irrigate today or wait. A cyclone warning for "the eastern coast" helps little if a fishing family needs to know whether their own harbour is safe that morning. Mission Mausam was built to shrink this gap, moving forecasting from the scale of a state down to a block and eventually a village cluster, so advice finally matches the size of the decision a person actually has to make.

The Growing Challenge of Climate Change

Climate change has not simply made India hotter; it has made the weather less predictable. Monsoon rainfall, which roughly half the country's farmland depends on, now arrives in short, erratic bursts rather than steady spells, sometimes dumping a month's rain in a single afternoon. Heatwaves start earlier and last longer and Arabian Sea cyclones, once rare, are becoming more frequent and intense. For a country where a large share of the workforce still earns its living from land and sea, this is not an abstract statistic; it shows up as a ruined wheat crop or a cancelled fishing trip. Better forecasting cannot stop a cyclone from forming, but it can shrink the element of surprise, giving people the one resource that matters most in a crisis: time to prepare.

What Exactly is Mission Mausam?

Mission Mausam is a nationwide programme approved by the Union Cabinet in September 2024 and formally launched by the Prime Minister in January 2025, marking the 150th anniversary of the India Meteorological Department, the country's oldest scientific institution. Run by the Ministry of Earth Sciences with a two-year outlay of roughly two thousand crore rupees, it is implemented chiefly through the India Meteorological Department, the Indian Institute of Tropical Meteorology and the National Centre for Medium-Range Weather Forecasting, with support from ocean specialists at the Indian National Centre for Ocean Information Services. Its underlying promise, in two words, is Weather Ready, Climate Smart: no significant weather system over India should go undetected and the right person on the ground, whether a farmer, fisher, pilot or city planner, should learn of it early enough to act.

Inside India's Weather Intelligence Network

Accurate forecasting begins with observing the atmosphere in extraordinary detail, everywhere, all the time. Mission Mausam is expanding a layered network of eyes and ears trained on the sky from the ground up, so that a storm forming over a remote hillside is noticed just as quickly as one over a major city.

Doppler Radars and Satellites

A Doppler Weather Radar works like a bat's echolocation for storms: it fires microwave pulses skyward and reads the echoes bouncing off raindrops and hailstones, revealing not just where rain falls but how fast wind is spinning inside a storm, information vital for spotting a severe thunderstorm in the making. New radars are being added across gap regions, including sensitive Himalayan states, so storms that once formed and vanished undetected are now caught within minutes. Overhead, India's INSAT geostationary satellites watch the whole subcontinent continuously from thirty-six thousand kilometres up, tracking cloud clusters over the Bay of Bengal and sea-surface temperatures that hint at where a cyclone might intensify. Radars and satellites work like a magnifying glass and a wide-angle lens, one for fine local detail, the other for the big picture.

Ground Stations and Ocean Buoys

Thousands of Automatic Weather Stations log temperature, humidity, wind and rainfall every few minutes without a human observer on-site, while moored ocean buoys measure waves, currents and sea temperature for fisheries and cyclone forecasting. A new atmospheric research testbed at Silkheda village, Sehore district, Madhya Pradesh, sits at the heart of the monsoon zone to fill long-standing data gaps in how central Indian rain, clouds and land-atmosphere interactions actually behave.

The Bharat Forecasting System Explained

At the centre of Mission Mausam's technical muscle is the Bharat Forecasting System, a home-grown model launched in 2025 and run on the Arka supercomputer in Pune. Older national models worked at roughly twelve-kilometre resolution, useful for a district but too coarse for a single village. The new system halves that grid to six kilometres, about the size of a cluster of neighbouring panchayats, the difference between a blurry passport photo and a sharp portrait: both show a face, but only one reveals individual features. That sharper resolution lets the model separate the fortunes of one block from its neighbour instead of lumping an entire district under one generic forecast.

How AI Makes Forecasts Smarter

Traditional Numerical Weather Prediction feeds the atmosphere's current temperature, pressure, humidity and wind into physics equations that a supercomputer solves forward in time. It is powerful but computationally expensive and not always precise at very local scales. Mission Mausam now layers artificial intelligence atop this backbone: in 2026, IMD launched its first AI-enabled system forecasting the monsoon's block-by-block advance, issuing a fresh probabilistic outlook every week for the following four weeks. A companion pilot for Uttar Pradesh generates rainfall forecasts on a one-kilometre grid up to ten days ahead, using AI to "downscale" broader outputs into hyper-local detail, much as image-enhancement software sharpens a blurry photograph. A large share of India's rainfall variability has long resisted older forecasting methods and this is precisely the uncertainty AI-assisted downscaling is designed to chip away at.

What is Ensemble Forecasting?

No single model run can perfectly capture a chaotic atmosphere, where tiny uncertainties in today's conditions snowball into very different outcomes just days later. Ensemble forecasting deals with this by running the same model dozens of times, each with slightly different starting assumptions and then studying how the different runs diverge. It is like asking fifty experienced farmers to independently guess how much rain a cloud bank will drop on their fields: if forty-five say heavy rain and five say light rain, that spread gives a calibrated probability rather than one confident but potentially wrong number, exactly what anyone needs before gambling on one more day of harvesting.

Impact-Based Forecasting

Fifty millimetres of predicted rain means little to someone who does not know whether it will flood a field, damage a roof or pass unnoticed. Impact-based forecasting asks a more practical question: not just what the weather will do, but what it will do to people, crops and property in a specific place. IMD's familiar green, yellow orange and red colour-coded warnings blend the probability of an event with its likely severity, so a red coastal alert signals serious disruption, not just heavy rain, prompting evacuation planning rather than a shrug. Mission Mausam extends this approach down to the district and block level across hazards from heatwaves and hailstorms

to lightning and flash floods, using the DAMINI lightning-tracking network alongside radar and satellite data for highly localised, time-critical alerts.

How Weather Information Reaches Farmers

None of this observation and modelling matters if the forecast never reaches the person who needs it. The Agrometeorological Advisory Service translates raw forecasts into plain-language farming advice twice a week at the district and block level: when to irrigate, when to delay spraying because rain is coming, when to harvest early. These advisories travel through the government's MAUSAM app and the farmer-focused MEGHDOOT app, SMS alerts reaching even basic phones and television, radio and community loudspeakers where internet access is patchy, because a sharp six-kilometre forecast is only as good as its ability to reach a farmer standing in a field without a smartphone.

Benefits for Agriculture and Beyond

Sharper, localised, impact-based forecasts mean fewer wasted inputs and fewer catastrophic losses: a farmer skips fertiliser that would wash away in coming rain or nets a vineyard before hail arrives, as Vitthal did. Better monsoon-onset forecasts help farmers time sowing to reliable rain rather than guesswork and multiplied across millions of small and marginal farms, these small, timely decisions add up to real protection for rural incomes. The benefits ripple well beyond farming too: fishing communities use Potential Fishing Zone advisories, built from satellite ocean data, to find catch while avoiding developing storms; disaster managers plan cyclone and flood evacuations with more lead time; and aviation, power grids managing renewable supply, urban planners and public health authorities all draw on the same underlying observation network.

Challenges Ahead

None of this is easy to build or sustain. Expanding radar and sensor networks into remote, mountainous regions is expensive and logistically difficult and a forecast helps no one if its last-mile message cannot reach someone in a language and format they can act on, a gap that remains uneven wherever connectivity or digital literacy is low. A few high-profile missed or overly cautious warnings can also erode public trust in future alerts and running ever more complex AI and physics-based models at fine resolution will demand sustained computing power, skilled scientists and funding well beyond the mission's initial two-year window.

The Road to a Climate-Ready India

Even so, the trajectory points toward forecasts that keep getting sharper, faster and more personal: block-level monsoon outlooks and kilometre-scale rainfall models trained on India's own unique monsoon behaviour rather than borrowed from other climates. As the observation network thickens and computing power grows, the ambition is a genuinely nationwide weather-ready ecosystem, where a warning reaches a farmer in Bastar or a fishing crew off Kutch as swiftly and precisely as it reaches a phone in a metro city.

Conclusion

Weather has always been something India endured rather than anticipated. Mission Mausam bets that this no longer has to be true: with radars, satellites, supercomputers and artificial intelligence working in concert and real care given to reaching ordinary hands, the country can meet its skies on more equal terms. For Vitthal in his vineyard and for millions like him, that shift may arrive not as a grand announcement but as a quiet notification on a phone, arriving just early enough to matter.

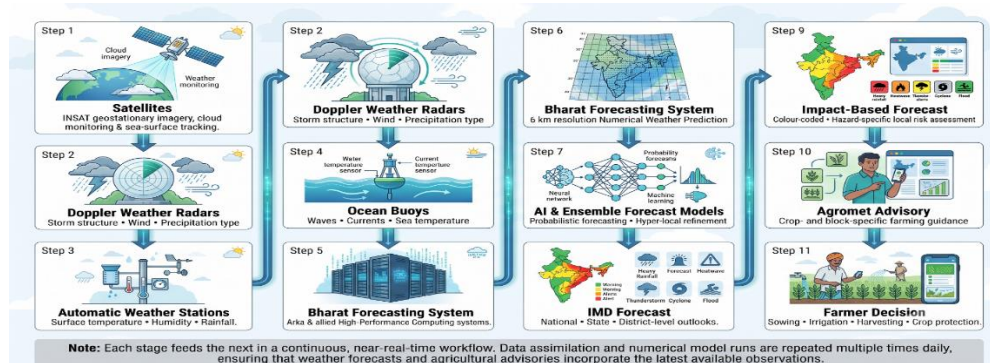


Figure 1. Workflow of Mission Mausam: From Weather Observation to Farmer Advisory

Table 1. Major Components of Mission Mausam and Their Functions

Component	Purpose	Benefit to Farmers	Example
Doppler Weather Radar	Detects storm structure, wind speed and precipitation type in real time	Early warning of hailstorms, squalls and heavy rain for crop protection	Nowcasting a thunderstorm two hours before it hits a district
INSAT Satellites	Continuously observes cloud systems, monsoon progress and sea temperature	Tracks monsoon advance so sowing dates can be planned confidently	Monitoring Bay of Bengal cloud clusters ahead of monsoon onset
Bharat Forecasting System	High-resolution (6 km) numerical weather prediction on the Arka supercomputer	Sharper block-level forecasts instead of broad district averages	Forecasting rainfall for a panchayat cluster rather than a whole district
Ensemble Forecasting	Runs multiple model simulations to quantify forecast uncertainty	Gives a probability of rain, not just a yes/no guess	70% chance of heavy rain rather than a single fixed prediction
AI Models	Downscales and refines physics-based forecasts using machine learning	Delivers kilometre-scale, near-village forecasts and monsoon-advance outlooks	AI-enabled block-level monsoon advance forecast issued weekly
Automatic Weather Stations	Continuously records temperature, humidity, wind and rainfall on the ground	Supplies the real-time ground truth that keeps forecasts accurate	Feeding minute-by-minute rainfall data from a rural weather station
Lightning Detection Network (DAMINI)	Tracks lightning strikes and thunderstorm formation across the country	Warns farm workers and herders to seek shelter before lightning strikes	Alerting villagers in Odisha of an approaching lightning-prone storm
Agromet Advisory Services (AAS)	Converts weather forecasts into plain-language, crop-specific farm advice	Tells farmers when to irrigate, spray, sow or harvest	A twice-weekly bulletin advising delayed pesticide spraying before rain
Impact-Based Forecasting	Combines hazard probability with likely on-ground consequences	Signals real-world risk, not just rainfall numbers, through colour codes	A red alert prompting evacuation ahead of a cyclone landfall

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Mud Crab Culture: A Profitable Aquaculture Venture



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Abstract

Mud crab (*Scylla spp.*) culture has emerged as a highly profitable and sustainable aquaculture enterprise due to the increasing demand for live crabs in domestic and international markets. Among the cultured species, *Scylla serrata* is the most commercially important because of its rapid growth, high meat yield, and excellent market value. Successful mud crab farming depends on proper broodstock management, seed production, larval rearing, nursery management, and suitable grow-out or fattening practices. Environmental factors such as salinity (15–30 ppt), temperature (28–32°C), dissolved oxygen (>4 mg L⁻¹), and pH (7.5–8.5) play a crucial role in ensuring optimum growth and survival. Major challenges include dependence on wild seed, cannibalism during nursery rearing, and maintaining water quality. These constraints can be minimized through hatchery seed production, regular grading, provision of shelters, and appropriate feeding management. With advances in hatchery technology and improved culture practices, mud crab farming offers significant opportunities for enhancing farmers' income, generating rural employment, and supporting sustainable coastal aquaculture development

Introduction:

Mud crab culture includes a wide range of practices, such as the use of seedstock collected from the wild or produced in hatcheries; farming systems that vary from extensive to intensive, and from monoculture to polyculture; and farm sites that range from mangrove forests to purpose-built aquaculture ponds or fattening cages. Therefore, there is no single method for farming mud crabs. However, various techniques, technologies, and principles have been developed that can be adapted to suit the specific needs of farmers and policymakers interested in promoting mud crab aquaculture.

Four species of mud crab—*Scylla serrata*, *S. tranquebarica*, *S. paramamosain*, and *S. olivacea* are the primary focus of both commercial fisheries and aquaculture across their natural range. These species are among the most valuable crabs globally, with the majority of their commercial production sold live in markets.

The mangrove crab, *Scylla serrata*, is in high demand in both domestic and international markets. It is commonly found in the mudflats and mangrove regions of India and Southeast Asia. This species has a broad, flat body covered by a fan-shaped carapace. Adult crabs migrate to the sea for spawning, and their larval stages develop in seawater. The juvenile crabs (instars) then return to brackish water for further growth and development. Although hatchery seed production technology is available at RGCA, mud crab farming still largely relies on wild seed collection.

Scylla serrata mainly cultured for its meat rich chelate legs Crab meat is sweet and tasty. It also have medicinal value and used to cure various Protein deficiency diseases. Crab meat has 20% protein, 5% fat, 2% Minerals, vitamins A and D, glycogen and free amino acids so it has high Demand as a table food all over the countries.

General Biology



Systematic position

- Phylum: Arthropoda.
- Class: Crustacea.
- Order: Decapoda
- Sub order: Brachyura
- Family: Portunidae
- Genus: Scylla
- Species: Scylla serra

Habitat and Distribution:

Mud crabs prefer mangrove areas, intertidal flats, estuarine swamps, and soft muddy bottoms suitable for burrowing (DoF Australia, 2013). They tolerate wide salinity (2–30 ppt) and temperature ranges (Huq et al., 2015; DoF Australia, 2013), and are also found in beels, gher, and ponds with muddy or sandy bottoms (Huq et al., 2015). They are widely distributed across the Indo-West Pacific—from East and South Africa to Southeast and East Asia, Japan, and Northern Australia (Masterson, 2007)—and are also found in the eastern Pacific, including the Marianas, Fiji, Samoa, and Hawaii. *Scylla serrata* is the most widely distributed species in the genus (FAO, 2012).

Food and Feeding:

Mud crabs are omnivorous and nocturnal feeders, consuming crustaceans, mollusks, small fish, detritus, sand, plant matter, and dead crabs. In ponds, they feed on algae, crustaceans, animal matter, trash fish, and eel fish, using their chelate legs to catch prey. Reproductive performance and larval production largely depend on maturation diets (Fortes, 1996). While natural diets are used for broodstock in hatcheries, they can sometimes degrade water quality (Arza, 2016).

Seed Production:

Age at first maturity

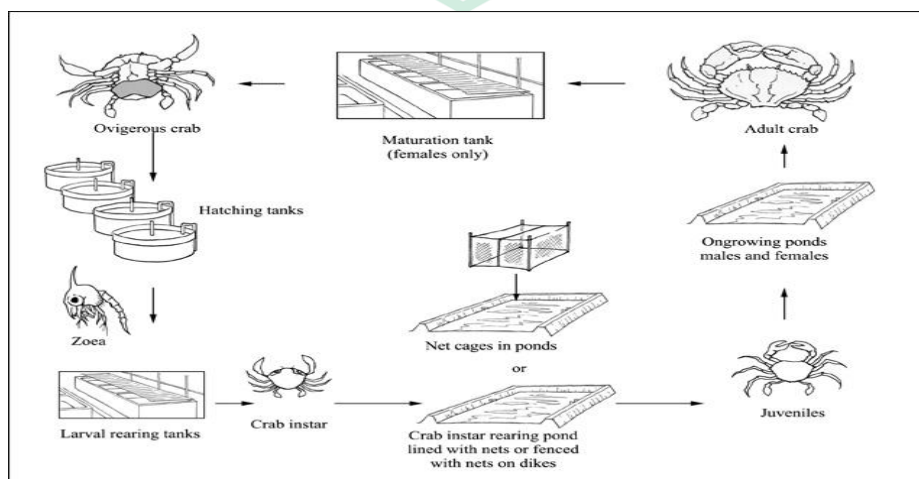
Usually, the mud crab reaches the reproductive stage when:

- shell width-greater than 7.8cm (males) and 8.5cm (female)
- Body weight over 100g and 130g respectively.

Fecundity of *Scylla tranquebarica* is 2-3 million and of *Scylla serrata* is 0.5 – 2.5 million.

Brood stock management:

Brood stock collected from wild or farm is brought with its walking legs in tied condition, disinfected with 100 ppm formalin for 30 seconds, acclimatised to hatchery condition and quarantined. Sandy substratum should be provided in the spawning tank. Half of the brood stock tank can be provided with 10 cm sand layer and another half can be bare floor for feeding purpose. Alternatively sand filled trays can be provided. Crabs can be stocked at the rate of 1-2 animals per sq. metre. Filtered sea water is maintained in the tank. It is fed with fresh wet feed @ 5-10% of the body weight. PVC pipes and tiles are kept in the tank as hideouts.



Mud crabs have separate sexes, which can be distinguished by the shape of the abdominal flap: in males, it is slender and triangular, while in females, it is broad and nearly semicircular.

Eyestalk ablation:

As the occurrence of berried crabs in nature is rare, it is essential to develop ovigerous crabs in captivity. Eyestalks are the sites of gonad inhibiting hormones and therefore the Removal of eyestalks accelerate the gonad development and spawning. One of the eyestalk is removed.

Spawning:

Spawning occurs within 10 days of eyestalk ablation. A mix of natural feeds (fish, polychaetes, shellfish, squid) is given at 5–10% of biomass, along with 1–3% formulated feed. Zoea hatchlings are stocked at 80–100/L in hatchling tanks and fed rotifers and Artemia nauplii. Early megalopae receive processed feed or 5-day-old Artemia, followed by minced mussel or fish once they settle. Feeding and water management practices vary across countries.

Larval Development:

The phototactic behaviour of the zoea larvae is used to collect them. There are five zoeal stages passing through five Molts to reach the megalopa stage. Zoea to megalopa 15 – 20 days (Each moult 3 – 4 Days) The megalopa takes 8 – 11 days before it molts Into the first crab stage the megalopa larvae gradually adapt themselves to a Benthic life.

Rearing of Larvae:

The final stage involves nursing crablets in ponds (200–800 m²) or net cages. In Phase 1, crabs <1.0 cm CW are grown to 1.5–2.0 cm at 20–50/m². In Phase 2, they are reared to 3.0–4.0 cm at 5–10/m² in net-lined ponds or dikes. Each phase lasts 3–4 weeks, depending on target size. Higher densities are possible with shorter culture periods. Crabs are fed once or twice daily with a mix of minced fish, shellfish, chicken waste, boiled corn, or formulated feeds to satiation.

Rearing of crab instar:

Crab instars (0.3–0.4 cm CW) are reared to crablets (2.5 cm CW) over 30–40 days at a density of 25–30/m² in 5×4 m HDPE or nylon nursery hapas (1.5 mm mesh) supported by bamboo poles, installed in ponds with at least 1 m water depth and 20–35 ppt salinity. Hapas can be set up before filling the pond. Fertilizers (organic/inorganic) are added to boost natural food. A catwalk is built for feeding and monitoring. Instars are fed twice daily with minced fish, mussel, or clam meat at 50% of body weight, reduced to 30% after one week, and 20% after two weeks (40% in the morning, 60% in the evening).

Cannibalism is a major challenge during nursery rearing, affecting survival rates. To reduce it, hideouts like PVC pipes or tiles are provided. Regular grading and thinning help maintain uniform size. Survival from instar to crablet stage is typically around 60%.



Harvest and transportation:

During harvesting, crablets should be protected from direct sunlight. For transport, use ventilated bamboo baskets, plastic trays, straw bags, or thermocol boxes layered with wet sand, mangrove leaves, shade net, or seaweed to reduce aggression and maintain a cool temperature.

Culture Methods:

Mud crab farming is done by two methods:

i. Grow- out culture

In this method, young crabs are grown for a period of 5 to 6 months till they attain desirable size. Mud crab grow-out systems are generally pond based, with or without mangroves. The pond size varies between 0.5-2 ha, the stocking rates are commonly between 1-3 crabs/m², with supplementary feeding. Feeding is usually with trash fish (wet weight feeding rate-5% per day of the biomass), along with other locally available items.



Water quality requirements

pH: 7.5-8.5

Salinity: 15-30 ppt

Temperature: 28-32°C

DO: >4ppm

Stocking:

Uniform-sized crablets (2.5 cm CW) are stocked at 1/m² after proper acclimation.

Feeding:

Crabs are fed chopped fish twice daily—40% in the morning and 60% in the evening. Feed is given at 10% of body weight until 6 cm CW, then reduced to 8% for 6–15 cm CW, and 6% thereafter.

ii. Fattening

Fattening is defined as the intensive feeding of water crabs to raise them to marketable size. After moulting, crab musculature takes some time to grow to fill its new shell, so the crab is referred to as “empty”, “thin” or a “water crab”. If such a crab is cooked, it will have little meat and lots of water in it which is undesirable. Mud crab fattening refers to the process whereby, “empty crabs”, identified at harvest (either from the wild or from farm stock), are held and fed for a period, often of only a few weeks, until they are full of meat and ready to market. Juvenile crabs (~200g) from brackish water areas are reared for 3–4 weeks in earthen ponds (50–500 m²), cages (4–10 m²), or pens (100–500 m²) until they reach 230–650g. Stocking density is 1–3 crabs/m². They are fed chopped low-cost fish, molluscan meat, and butchery waste at 10% of biomass. Once their shells harden, they are sold at premium prices.

Collection and stocking of lean crab in cage/pond:

Pond size should be 0.5 to 1 ha with 1-1.5m depth. The water temperature, salinity DO, and pH should be 20-30 degree C, 5-25 ppt, 4-8mg/l and 7.5-8.5 respectively (Begom et al., 2006). In case of cage the size of each cage is 2 m x 1 m x 0.3 m (length x width x height) comprising of 50 cells. The stocking density may be up to 1/cells in

communal rearing since the culture period is short. The water Crabs are fed with low-value fish, snails and chicken trash at 5-8 percent or to satiation.

Collection and grading

Generally the gonad will mature within 12-16 days. At that time the crab are harvested and separated the crab according to marketable grade (Fig 9). Sometime if it fails to reach marketable size, stock again for another time.

Harvesting and marketing:

Harvesting should be done in the early morning hours or evening hours. The harvested crabs should be washed in good brackish water to remove the dirt and mud and carefully tied without breaking its legs. The harvested crabs have to be kept in moist conditions. It has to be kept away from sunlight, which has a negative effect on survival.

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Monitoring, Management, and Emerging Threats in Sustainable Aquaculture



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Abstract

Aquaculture is the world's fastest-growing food production sector, projected to supply over 60% of global seafood consumption and support the livelihoods of more than 100 million people worldwide. However, its rapid intensification has generated escalating sustainability challenges ranging from environmental pollution and ecosystem disruption to the emergence of antimicrobial resistance (AMR), novel infectious diseases, and climate-driven threats to production stability. This comprehensive review synthesizes the most recent literature (2020–2026) across three interconnected themes: (1) the state of monitoring technologies, including IoT-based sensor networks, AI-driven analytics, and remote sensing; (2) innovative management systems such as recirculating aquaculture systems (RAS), integrated multi-trophic aquaculture (IMTA), biofloc technology (BFT), and precision aquaculture; and (3) emerging threats including AMR, climate change-mediated disease dynamics, environmental pollution, biosecurity risks, and cybersecurity vulnerabilities. The review identifies that while technological and ecological solutions offer substantial promise, a One Health framework integrating human, animal, and environmental health perspectives is essential to realise the sector's potential sustainably. Urgent interdisciplinary action, equitable policy enforcement, and sustained research investment are required to safeguard both aquaculture productivity and global food security.

Keywords: sustainable aquaculture, water quality monitoring, IoT, antimicrobial resistance, climate change, disease management.

1. Introduction

Aquaculture is the controlled cultivation of aquatic organisms, including fish, crustaceans, molluscs, and aquatic plants, that has emerged as one of the most critical components of global food security in the twenty-first century. The Food and Agriculture Organization of the United Nations (FAO) projects that global aquatic animal production will grow from 185 million tonnes in 2022 to 205 million tonnes by 2032, with the preponderance of this increase driven by aquaculture rather than capture fisheries (FAO, 2024). The sector already supplies the majority of the world's seafood for human consumption. It is projected to supply over 60% of global fish consumption, underscoring its indispensable role in meeting the protein demands of a growing world population.

Beyond food security, aquaculture supports the livelihoods of over 100 million people globally, with particular significance in developing economies across South and Southeast Asia, sub-Saharan Africa, and Latin America (Reverter *et al.*, 2020). Its contribution to poverty alleviation, rural employment, and national export revenues makes it a sector of profound socioeconomic importance. Yet this rapid expansion has been accompanied by serious sustainability concerns. Unsustainable farming methods have led to significant environmental degradation, including eutrophication of water bodies, reductions in dissolved oxygen levels, soil contamination from untreated effluents, and disruption of aquatic biodiversity (Ruben *et al.*, 2025). Concurrently, the intensive use of antibiotics to manage disease in high-density farming systems has accelerated the development and dissemination of antimicrobial resistance (AMR), posing threats that extend far beyond the

aquaculture pond into broader public health domains (Mohammed *et al.*, 2025). Climate change compounds these challenges by altering thermal regimes, precipitation patterns, and ocean chemistry in ways that favour pathogen emergence and spread (Dunshea FR *et al.*, 2024).

This provides a comprehensive and critical synthesis of three interconnected dimensions of modern sustainable aquaculture: (1) monitoring technologies, (2) management innovations, and (3) emerging threats and biosecurity challenges. By integrating all the aspects, this article aims to equip researchers, practitioners, and policymakers with a coherent overview of the current state of the field and the directions required to achieve genuinely sustainable aquaculture at scale.

2. Monitoring Technologies in Modern Aquaculture

2.1 The Centrality of Water Quality Monitoring

Water quality is the fundamental determinant of productivity, animal welfare, and disease dynamics in aquaculture systems. The maintenance of critical physicochemical parameters within biologically appropriate windows is essential to support optimal fish physiology, immune function, and growth. Key parameters include temperature, dissolved oxygen (DO), pH, salinity, turbidity, ammonia, nitrite, and electrical conductivity (EC). Deviations in these parameters, such as even transient fluctuations, can precipitate immunosuppression, mass mortality events, and cascading economic losses (Vidal-Durango *et al.*, 2025).

Traditionally, water quality assessment relied on periodic manual sampling and laboratory analysis, an approach inadequate for the real-time demands of intensive aquaculture. The limitations of this methodology are labour intensity, temporal gaps between measurements, and delayed responses to deteriorating conditions that have driven major investment in automated and continuous monitoring systems over the past decade.

2.2 IoT-Based Sensor Networks

The integration of the Internet of Things (IoT) into aquaculture monitoring represents a paradigmatic shift in how farm environments are managed. IoT sensor systems continuously measure critical water quality parameters and transmit data in real time to centralised processing platforms, enabling immediate alerts and responsive management decisions. A systematic bibliometric analysis of IoT-based water quality monitoring in aquaculture systems, which documented a 74.79% increase in research output over this period, underscoring the sector's rapid adoption trajectory (Petkovski *et al.*, 2025).

The most widely deployed sensor technologies include pH sensors (used in 98.2% of reviewed studies, with prominent models including the SEN0169, HI-98107, and pH-4502C), temperature sensors (92.9% of studies, most commonly the DS18B20), and dissolved oxygen sensors (62.5% of studies) (Petkovski *et al.*, 2025). Advances in wireless communication, mainly including Wi-Fi, LoRaWAN, and Zigbee protocols, have enabled these sensors to form distributed networks across aquaculture facilities, including remote and offshore installations.

Early implementations integrated temperature, pH, DO, and EC sensors with microcontroller platforms (such as ESP32) and Wi-Fi modules to create wireless multi-sensor water quality monitoring systems for freshwater aquaculture. These systems stream real-time data to cloud-based IoT platforms, where the information is visualised in user-friendly dashboards accessible via a browser or mobile application (Lin *et al.*, 2021). The practical value of these systems lies not merely in continuous data acquisition but in enabling data-driven decision-making that was previously unachievable.

2.3 Artificial Intelligence and the AIoT Revolution

The convergence of AI and IoT, collectively referred to as the Artificial Intelligence of Things (AIoT), represents the current frontier of aquaculture monitoring. Ten core application domains of AIoT identified in aquaculture are:

- Smart feeding systems,
- Water quality management,
- Disease detection,
- Fish biomass estimation,
- Fish behaviour monitoring,
- Organism counting,

- Species segmentation and classification,
- Breeding and growth estimation,
- Individual fish tracking, and
- Automation and Robotics.

The application of machine learning (ML) algorithms to IoT sensor data streams has yielded remarkable predictive capabilities for water quality management. Smart monitoring systems employing underwater cameras and computer vision algorithms are now capable of tracking fish behaviour in real time, detecting early signs of disease or stress, and optimising feeding schedules dynamically based on observed feeding activity (Gomes-Dias *et al.*, 2025). AI-powered sensors capable of continuously tracking dissolved oxygen, pH, temperature, and ammonia levels ensure optimal fish growth conditions while preventing ecological imbalances within the production system (Gomes-Dias *et al.*, 2025). Beyond individual farm applications, AIoT platforms are beginning to enable cross-farm data integration, supporting industry-wide benchmarking, disease early-warning networks, and regulatory compliance monitoring. These capabilities are expected to expand further as data standardisation protocols and digital infrastructure in aquaculture regions mature.

2.4 Remote Sensing and Satellite-Based Monitoring

For large-scale, landscape-level aquaculture management, satellite imaging and remote sensing have emerged as powerful complementary tools. These technologies enable continuous observation of water quality metrics, surface temperature fluctuations, harmful algal bloom (HAB) dynamics, and aquaculture facility extent across regional and national scales, those are offering capabilities far beyond what in-situ sensors alone can provide. Satellite-based monitoring is particularly valuable for open marine and coastal aquaculture systems, where in-situ sensor coverage may be sparse and environmental conditions can shift rapidly. Remote sensing data on chlorophyll-a concentrations, sea surface temperature, and turbidity indices are increasingly being integrated with farm-level IoT sensor data to provide a multi-scale view of aquaculture environments. This integrated approach supports both operational management and regulatory oversight, enabling authorities to detect illegal or unregistered aquaculture operations and monitor compliance with environmental standards.

3. Sustainable Management Approaches

3.1 Recirculating Aquaculture Systems (RAS)

Recirculating Aquaculture Systems (RAS) represent one of the most significant technological advances in sustainable aquaculture management. Unlike conventional open-flow systems that discharge treated or untreated effluent into receiving water bodies, RAS systems treat and recirculate water within a closed loop, retaining up to 99% of water volumes and dramatically reducing the environmental footprint of production (Ranjan D *et al.*, 2026).

The development of RAS technology has been enabled by concurrent advances in biofiltration (particularly nitrifying biofilm reactors), mechanical filtration (drum filters and hydrocyclones), UV disinfection, degassing, and automated control systems. These components work in concert to maintain water quality within narrow parameters despite high stocking densities, enabling intensive production in land-based facilities independent of ambient environmental conditions (Ranjan D *et al.*, 2026). This independence from environmental constraints enables locating aquaculture facilities close to consumer markets, reducing transportation distances and the supply chain's carbon footprint.

AI-driven RAS systems further enhance sustainability by enabling real-time optimisation of filtration parameters, feeding regimes, and water chemistry. Future developments are expected to incorporate blockchain technology to enhance supply chain transparency and AI-powered genetic optimisation to select disease-resistant, high-performance broodstock. Despite these advantages, the high capital expenditure, energy consumption, and technical complexity of RAS remain barriers to wider adoption, particularly among small-scale producers in developing countries.

3.2 Integrated Multi-Trophic Aquaculture (IMTA)

Integrated Multi-Trophic Aquaculture (IMTA) is an ecological farming approach that cultivates species from different trophic levels within a single system, creating a functional analogue of a natural food web. Typically, IMTA systems integrate fed species such as finfish or shrimp (which produce dissolved inorganic nutrients and

particulate organic waste) with suspension feeders such as bivalve molluscs (which filter particulate matter) and extractive species such as seaweeds or macroalgae (which absorb dissolved inorganic nutrients). This trophic complementarity transforms what would otherwise be waste products into resources, improving nutrient use efficiency and reducing environmental impacts (Ranjan D *et al.*, 2026).

A circularity assessment of IMTA demonstrated that it effectively reduces ecological footprint through nutrient cycling and water recirculation, while also enhancing resilience against harmful algal blooms and chemical contamination events.

Successful commercial IMTA implementations have been documented in Norway, Scotland, Ireland, China, Canada, and increasingly in South and Southeast Asia. Beyond environmental benefits, IMTA systems offer significant commercial advantages by diversifying the range of harvested species, providing multiple revenue streams, and reducing market-specific risk exposure. A systematic review of the productive and commercial dimensions of IMTA concluded that, beyond environmental advantages, IMTA systems positively influence the productivity, growth, survival, feed efficiency, and animal health and welfare of farmed species, while also improving the nutritional quality of harvested products.

3.3 Integrated Multi-Trophic Recirculating Aquaculture Systems (IMTRAS)

The most advanced expression of ecological aquaculture engineering is the Integrated Multi-Trophic Recirculating Aquaculture System (IMTRAS), which merges IMTA's ecological principles with the closed-loop water management of RAS. A modular IMTRAS evaluated by Huo *et al.* (2024) said that integrating California yellowtail (*Seriola dorsalis*), sea lettuce (*Ulva lactuca*), Mediterranean mussels (*Mytilus galloprovincialis*), and warty sea cucumbers (*Apostichopus parvimensis*) demonstrated efficient waste removal and optimal resource utilisation in a fully enclosed land-based system. This system offers advantages of reduced water consumption, superior biosecurity, and minimal environmental discharge while maintaining productive yields across multiple commercially valuable species.

A Vietnamese IMTRAS for intensive whiteleg shrimp (*Litopenaeus vannamei*) production, integrating tilapia, green algae (*Cladophora glomerata*), and red algae (*Gracilaria tenuistipitata*) within a closed-loop design, was evaluated over a 124-day production cycle with zero water exchange, demonstrating the system's viability as a zero-discharge aquaculture model with enhanced biosecurity. Such systems position IMTRAS as a scalable, sustainable alternative particularly suited to regions facing water scarcity and disease pressure.

3.4 Biofloc Technology (BFT)

Biofloc Technology (BFT) has emerged as a commercially mature and cost-effective sustainable production system, particularly for tilapia and shrimp farming. BFT maintains minimal water exchange by promoting the in-situ growth of heterotrophic microbial communities (biofloc) that convert toxic nitrogenous compounds, which are primarily ammonia and nitrite, into microbial biomass. This biomass simultaneously serves as a nutritional supplement for the farmed species, improving feed utilisation ratios and reducing the requirement for exogenous protein-rich feeds (Ranjan D *et al.*, 2026).

Recent developments have explored the integration of BFT with hydroponic plant production systems (FLOCponics), enabling simultaneous production of aquatic animals and crops through nutrient cycling mediated by microbial communities. These integrated systems demonstrate improved nutrient and water use efficiency and reduced effluent discharge compared to monoculture systems (Ranjan D *et al.*, 2026).

3.5 Precision Aquaculture

Precision aquaculture applies the principles of precision agriculture from data-driven, site-specific management to aquatic production environments. Through the integration of automated feeding systems calibrated to real-time behavioural observations, environmental sensors, predictive analytics, and decision support tools, precision aquaculture seeks to maximise productive efficiency while minimising resource waste, environmental impact, and disease risk (Ranjan D *et al.*, 2026).

In advanced IMTA and RAS setups, AI and data-driven decision-support technologies are already being deployed to predict nutrient flows, optimise species combinations, and improve feeding efficiency (Ranjan D *et al.*, 2026). Robotics and computer vision are enabling the automation of fish sorting, biomass estimation, and harvesting, minimising human intervention while maximising yield consistency. These advances position

precision aquaculture collectively as the dominant management paradigm for intensive, sustainable production in the coming decade.

4. Emerging Threats to Sustainable Aquaculture

4.1 Antimicrobial Resistance (AMR)

Antimicrobial resistance has emerged as arguably the most serious systemic threat to the long-term sustainability of aquaculture and, critically, one whose consequences extend well beyond the farm into broader public health domains. The extensive and often unsupervised use of antibiotics in aquaculture to manage bacterial infections under conditions of high stocking density has driven the selection and proliferation of resistant bacterial strains, the environmental contamination of sediments and water bodies with antibiotic residues, and the dissemination of resistance genes across microbial communities (Mohammed *et al.*, 2025).

Of particular clinical concern is the evidence for direct transfer of resistance elements from aquatic bacteria to human pathogens. Molecular evidence from plasmid analysis demonstrates considerable homology between plasmid backbone DNA from aquatic fish pathogens and plasmids found in terrestrial human pathogens, including *Salmonella enterica* and *Escherichia coli*. The detection of the florfenicol resistance determinant *floR*, first identified in the fish pathogen *Vibrio damsela*, in human pathogens constitutes direct evidence of horizontal resistance gene transfer from aquaculture environments to clinically relevant bacteria.

In Southeast Asian aquaculture, which dominates global production, the widespread application of beta-lactams, tetracyclines, and sulfonamides in Vietnam, Thailand, and Indonesia has generated high AMR prevalence. Drug-resistant *Vibrio* species, including *V. parahaemolyticus* resistant to oxytetracycline, pose direct threats to seafood safety and human health, particularly in association with consumption of raw or undercooked seafood (Huang & Khabusi, 2025). The global seafood trade amplifies these risks, with antibiotic residues accounting for 28% of EU rejections and 20% of US rejections of aquaculture imports, with Vietnam, China, Thailand, Bangladesh, and Indonesia identified as the principal source countries for rejected products (FAO, 2024).

Probiotics, particularly lactic acid bacteria (LAB), have gained recognition as a promising alternative or adjunct to antibiotic use in aquaculture. LAB strains can synthesise extracellular enzymes that enhance feed utilisation, modulate immune gene expression, improve stress resilience, and rebalance intestinal microbiota, collectively reducing the need for antibiotic intervention in species such as Nile tilapia (*Oreochromis niloticus*) and common carp (*Cyprinus carpio*) (Mohammed *et al.*, 2025).

4.2 Climate Change and Disease Dynamics

Climate change is fundamentally and irreversibly reshaping the disease landscape of global aquaculture. The interaction between rising water temperatures and pathogen biology creates a threat that operates on multiple levels: directly expanding the range and virulence of thermophilic pathogens and indirectly accelerating antibiotic use and resistance through increased disease incidence.

Rising sea and freshwater temperatures are particularly associated with the proliferation of *Vibrio* species in marine and estuarine environments. *Vibrio* infections in Mediterranean fish farming have increased in direct correlation with rising sea surface temperatures, with clinical disease outbreaks documented in sea bass, sea bream, and turbot farms at temperatures above historical seasonal norms. In freshwater systems, the protozoan parasite *Ichthyophthirius multifiliis*, the causative agent of white spot disease, exhibits markedly accelerated reproduction and increased host pathogenicity at elevated temperatures, driving severe economic losses in tilapia and catfish aquaculture.

The relationship between climate vulnerability and AMR risk is particularly stark for developing countries. A double meta-analysis of 460 studies spanning 40 countries demonstrated that countries with the highest climate vulnerability also exhibit the highest aquaculture AMR indices, and that infected aquatic animals show significantly higher mortality rates at elevated temperatures, creating a compound risk that will disproportionately affect food security in tropical developing nations already facing the worst impacts of climate change.

Climate-induced extreme weather events flooding, drought, and storms also compromise biosecurity in open-pen and pond aquaculture systems by physically damaging containment infrastructure, causing unplanned releases of farmed species into wild ecosystems, and facilitating the ingress of waterborne pathogens. These

events are projected to increase in frequency and severity under most climate change scenarios, demanding adaptive management strategies that incorporate resilience as a core design criterion.

4.3 Environmental Pollution and Ecosystem Disruption

Intensive aquaculture, particularly in open systems, generates substantial environmental externalities. Nutrient enrichment of receiving waters from uneaten feed, faecal matter, and metabolic excretions drives eutrophication, a process characterised by excessive algal growth, depletion of dissolved oxygen (hypoxia or anoxia), and destabilisation of aquatic food webs. Eutrophication creates inhospitable conditions for benthic communities, reduces biodiversity in aquaculture-adjacent ecosystems, and can trigger harmful algal blooms (HABs) that are themselves toxic to farmed species and human consumers.

Beyond nutrient loading, aquaculture effluents may contain antibiotic residues, disinfectants, antifoulants (including the historically used tributyltin and its successors), parasiticides, and hormone residues, all of which exert biological effects on non-target organisms. The contamination of sediments with these compounds can persist for decades, creating legacy pollution that compromises the ecosystem services of coastal and freshwater environments long after aquaculture operations cease.

The genetic contamination of wild fish populations through escapees from pen and pond aquaculture is a further, less-visible ecological threat. Escaped farmed fish — which may carry disease, compete with wild conspecifics, and introduce domesticated genotypes into wild gene pools through interbreeding — have been documented in numerous species including Atlantic salmon, rainbow trout, and various carp species. The long-term genetic implications for wild population fitness, adaptability, and evolutionary resilience are difficult to quantify but potentially severe.

4.4 Emerging Infectious Diseases and Biosecurity

Aquatic disease is recognised as one of the biggest threats to the growth and sustainability of aquaculture globally. With more than 700 species farmed across diverse production systems and aquatic environments, the sector presents an extraordinarily complex and varied landscape of biological hazards, including infectious diseases caused by bacteria, viruses, parasites, and fungi, as well as invasive alien species and non-infectious conditions associated with environmental stress.

The public health risks associated with aquatic zoonoses are expanding alongside intensifying international seafood trade and evolving dietary preferences for minimally processed seafood. The expanding detection of *Listeria monocytogenes* in aquatic products historically associated with terrestrial food environments, in addition to traditional *Vibrio* spp. and *Aeromonas* spp., reflects the growing microbial contamination pressures on the sector and underscores the need for multidisciplinary surveillance approaches that bridge aquaculture and terrestrial food safety.

Disease outbreaks in aquaculture can propagate rapidly due to the aquatic medium, high stocking densities, and the interconnected nature of coastal and river systems. The economic consequences are severe: disease losses in global aquaculture are estimated to exceed USD 10 billion annually, with bacterial infections (*Aeromonas* spp., *Edwardsiella* spp., *Pseudomonas* spp.) capable of causing 100% mortality in susceptible populations. Biosecurity frameworks encompassing farm-level hygiene practices, strategic use of vaccines, health monitoring protocols, and regulatory oversight are increasingly recognised as essential pillars of sustainable aquaculture management rather than optional additions.

4.5 Feed Sustainability and Resource Competition

The reliance of conventional aquaculture on fishmeal and fish oil derived from wild capture fisheries as primary feed ingredients represents a fundamental tension with the concept of sustainability. As aquaculture competes with both human food supply and terrestrial livestock for these limited marine resources, the sector faces increasing pressure to develop and adopt alternative feed ingredients that maintain nutritional performance without depleting wild fish stocks.

Insect farming has emerged as a particularly promising avenue for sustainable aquaculture feed production, offering a reliable and scalable supply of high-quality protein and lipids through controlled-environment farming of species such as the black soldier fly (*Hermetia illucens*). However, the sector faces substantial challenges, including scaling up production volumes, automating processing, ensuring food safety and biosecurity standards,

and navigating complex and variable regulatory frameworks across different jurisdictions. Single-cell proteins derived from bacteria, yeast, or microalgae represent additional alternatives currently under commercial development.

4.6 Cybersecurity and Data Security

As aquaculture operations become increasingly digitised by integrating IoT networks, cloud-based management platforms, AI-driven decision support systems, and electronic commerce infrastructure. Cybersecurity has emerged as an unexpected but significant threat. A 2024 report by the Aquaculture Cybersecurity Consortium documented a 156% increase in data breaches in agricultural technology over the preceding two years, with the average cost of a data breach in the aquaculture sector exceeding USD 400,000.

Data breaches and system compromises in aquaculture can have consequences extending beyond financial loss, potentially disrupting automated feeding and environmental control systems in ways that directly harm fish welfare and production outcomes. As the industry's digital dependency deepens, investment in cybersecurity infrastructure, including data encryption, access controls, system redundancy, and staff training, must be treated as an integral component of sustainable operations management rather than an optional IT consideration.

5. Governance, Policy, and the One Health Framework

The complex, cross-sectoral nature of the threats facing sustainable aquaculture is most acutely exemplified by the intersection of AMR, climate change, and global food trade, which demands governance frameworks that transcend traditional sectoral boundaries. The One Health paradigm, which recognises the inextricable interdependencies between human health, animal health, and the health of ecosystems, provides the most coherent conceptual foundation for addressing these challenges.

The World AMR Awareness Week 2025 called for united action across human, animal, and environmental health sectors, operating under the theme Act Now: Protect Our Present, Secure Our Future. Within aquaculture specifically, the One Health approach to AMR governance encompasses reducing inappropriate antibiotic use through the development of surveillance systems, supporting the uptake of vaccine-based disease prevention, promoting the development of novel antimicrobial alternatives, and integrating aquaculture AMR surveillance into national and international reporting frameworks.

At the regulatory level, significant and consequential disparities persist between regions. Major seafood-importing markets, the EU, USA, and Japan, maintain strict standards on antibiotic residues in imported aquaculture products, creating powerful market incentives for compliance in exporting nations. However, absent or weakly enforced domestic regulations in many low- and lower-middle-income countries continue to drive antibiotic misuse in local aquaculture operations, generating AMR risks that are ultimately borne not only domestically but globally through trade and ecological pathways (FAO, 2024).

A landmark policy recommendation published in 2025 called explicitly for aquaculture to be included as a distinct and specifically addressed sector within National Action Plans for Antimicrobial Resistance (NAPs-AMR) in all countries, acknowledging that generic agricultural AMR governance frameworks fail to address the unique pathways, production systems, and international trade dimensions of the aquaculture sector (Desbois et al., 2025). This recommendation is particularly pertinent given that Asian countries, expected to dominate global aquaculture growth through the 2030s, currently exhibit some of the highest AMR burdens in both aquatic and human clinical environments.

Conclusion

Sustainable aquaculture stands at a defining juncture. Its potential contribution to global food security, poverty alleviation, and nutrition is unparalleled among food production sectors, yet its realisation is contingent on the sector's capacity to confront a formidable constellation of emerging threats. The convergence of monitoring technologies, IoT sensor networks, AI-driven analytics, satellite remote sensing, and ecological management innovations such as RAS, IMTA, BFT, and precision aquaculture provides a credible technological foundation for more sustainable production. However, technology alone is insufficient. The threats of antimicrobial resistance, climate-driven disease emergence, environmental pollution, biosecurity risks, and resource competition demand responses that are simultaneously local (farm-level practice changes), national (equitable regulatory enforcement), and global (harmonised trade standards and AMR surveillance). The One Health

framework provides the most conceptually coherent and operationally practical approach to integrating these levels of response. The path forward requires sustained interdisciplinary collaboration among aquaculture scientists, ecologists, public health researchers, economists, and policymakers. It requires investment in digital infrastructure, research capacity, and extension services, particularly in developing countries where aquaculture's growth will be fastest and regulatory systems most fragile. And it requires a shared recognition that the sustainability of aquaculture is not merely a sectoral concern, but a prerequisite for the long-term health of the oceans, the food systems, and the human populations that depend upon both.

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Water Conservation Techniques for Sustainable Crop Production



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Abstract

Water is the foundation of agricultural productivity and food security. However, rapid population growth, climate change, and excessive groundwater extraction have intensified water scarcity across many agricultural regions. Sustainable crop production therefore depends on efficient water management practices that maximize crop yield while minimizing water loss. Water conservation techniques such as precision irrigation, rainwater harvesting, mulching, soil moisture management, conservation tillage, and crop diversification have emerged as effective solutions for improving water-use efficiency. These practices not only reduce irrigation requirements but also enhance soil health, improve nutrient availability, and strengthen the resilience of farming systems against drought and climate variability. Adopting integrated water conservation strategies is essential for ensuring long-term agricultural sustainability, environmental protection, and food security.

Keywords: Water conservation, precision irrigation, rainwater harvesting, mulching, soil moisture management, sustainable agriculture, crop rotation.

Introduction:

Agriculture accounts for nearly 70% of global freshwater withdrawals, making it the largest consumer of water resources. Increasing demand for food, erratic rainfall patterns, and declining groundwater levels have made efficient water management a priority for modern agriculture. Traditional irrigation practices often result in significant water losses through evaporation, runoff, and deep percolation. Consequently, there is an urgent need to adopt sustainable water conservation techniques that improve irrigation efficiency while maintaining crop productivity.

Water conservation in agriculture involves the efficient use, storage, and management of available water resources. It aims to minimize wastage, improve soil moisture retention, and ensure that crops receive adequate water throughout their growth cycle. Sustainable water management not only supports higher crop yields but also conserves natural resources for future generations.

Why Water Conservation Matters

Water scarcity has become one of the greatest challenges facing agriculture worldwide. Reduced rainfall, prolonged droughts, and excessive exploitation of groundwater threaten crop production and rural livelihoods. Efficient water management offers several important benefits:

- ✚ Improves water-use efficiency.
- ✚ Maintains crop productivity under limited water availability.
- ✚ Reduces production costs associated with irrigation.
- ✚ Conserves groundwater resources.
- ✚ Enhances soil fertility and microbial activity.
- ✚ Improves resilience to climate change.
- ✚ Supports long-term agricultural sustainability.

Major Water Conservation Techniques:

1. Precision Irrigation:

Precision irrigation delivers water according to crop requirements at the right time and in the right quantity. Advanced irrigation systems reduce water losses and improve irrigation efficiency.

➤ **Drip Irrigation:**

Drip irrigation supplies water directly to the root zone through emitters, minimizing evaporation and runoff. This method can significantly improve water-use efficiency while reducing weed growth and nutrient losses. It is particularly suitable for vegetables, fruit crops, sugarcane, and orchards.

➤ **Sprinkler Irrigation:**

Sprinkler systems distribute water uniformly across the field through pressurized nozzles, making them suitable for uneven terrain and sandy soils. These systems reduce labor requirements and provide efficient irrigation compared to traditional flooding methods.

2. Rainwater Harvesting:

Rainwater harvesting involves collecting and storing rainwater for agricultural use during dry periods. Water may be stored in farm ponds, tanks, reservoirs, or check dams for supplemental irrigation.

Major advantages include:

- ✚ Reduces dependence on groundwater.
- ✚ Recharges aquifers.
- ✚ Provides water during drought periods.
- ✚ Minimizes soil erosion and runoff.
- ✚ Enhances farm resilience during irregular rainfall.

Farm ponds have become an effective option for small and medium farmers by storing excess rainfall for critical irrigation stages.

3. Mulching:

Mulching refers to covering the soil surface with organic or inorganic materials to conserve moisture.

Common organic mulches include:

- ✚ Straw
- ✚ Crop residues
- ✚ Dry leaves
- ✚ Compost
- ✚ Grass clippings

Plastic mulch is also widely used in horticultural crops.

Mulching provides multiple benefits by:

- ✚ Reducing evaporation losses.
- ✚ Maintaining favorable soil temperature.
- ✚ Suppressing weed growth.
- ✚ Preventing soil erosion.
- ✚ Improving soil organic matter when organic mulch decomposes.

4. Soil Moisture Management:

Healthy soil stores more water and supplies it gradually to crops. Several practices improve soil moisture conservation.

➤ **Organic Matter Addition:**

Application of farmyard manure, compost, green manure, and crop residues improves soil structure and increases water-holding capacity.

➤ **Conservation Tillage:**

Minimum tillage or zero tillage minimizes soil disturbance, preserves soil moisture, reduces erosion, and improves soil organic carbon.

➤ **Laser Land Levelling:**

Uniform land levelling ensures even distribution of irrigation water, reducing runoff and saving irrigation water.

5. Crop Rotation and Diversification:

Growing different crops in rotation improves soil structure, enhances nutrient cycling, and optimizes water use. Including legumes in crop rotations improves soil fertility while reducing irrigation demand. Diversified cropping systems also reduce pest incidence and improve farm resilience against climatic stress.

6. Agroforestry:

Agroforestry integrates trees with crops and livestock to improve farm sustainability. Trees reduce wind speed, lower soil evaporation, improve infiltration, and contribute organic matter through leaf litter. Their deep roots also enhance groundwater recharge and nutrient recycling.

Modern Technologies Supporting Water Conservation:

Technological advancements are transforming agricultural water management.

1. Soil Moisture Sensors:

These sensors monitor soil moisture in real time, allowing irrigation only when necessary.

2. Weather-Based Irrigation Scheduling:

Weather forecasts help farmers schedule irrigation based on rainfall probability, temperature, humidity, and evapotranspiration.

3. Remote Sensing and Drones:

Satellite imagery and drones help identify water stress in crops, enabling timely irrigation decisions and efficient resource use.

4. Smart Irrigation Systems:

Internet of Things (IoT)-based irrigation systems automate water application according to crop requirements, significantly improving water-use efficiency.

Benefits of Water Conservation in Agriculture:

Adoption of water conservation techniques offers several economic, environmental, and social benefits:

- ✚ Increased crop productivity.
- ✚ Higher irrigation efficiency.
- ✚ Reduced water wastage.
- ✚ Improved soil health.
- ✚ Lower energy consumption for pumping groundwater.
- ✚ Reduced production costs.
- ✚ Enhanced biodiversity.
- ✚ Better climate resilience.
- ✚ Sustainable use of natural resources.
- ✚ Improved food security.

Challenges in Adoption:

Despite the advantages, several factors limit the widespread adoption of water conservation technologies:

- ✚ High initial investment for modern irrigation systems.
- ✚ Limited awareness among farmers.
- ✚ Inadequate technical knowledge.
- ✚ Small and fragmented landholdings.
- ✚ Limited access to financial support.

Government subsidies, farmer training programs, and extension services can play a significant role in overcoming these barriers.

The Way Forward:

Future agriculture must focus on maximizing “crop per drop.” Integrating precision irrigation, rainwater harvesting, mulching, conservation agriculture, and digital technologies can substantially improve water productivity. Policy support, investment in irrigation infrastructure, and farmer education are equally important for promoting sustainable water management.

Collaboration among researchers, policymakers, extension agencies, and farmers is essential to develop location-specific water conservation strategies. Strengthening community participation in water resource management and promoting climate-smart agriculture will further enhance the sustainability of agricultural production systems.

Conclusion:

Water conservation has become indispensable for sustainable crop production in the face of increasing water scarcity and climate change. Efficient water management practices such as precision irrigation, rainwater harvesting, mulching, soil moisture conservation, crop rotation, and agroforestry help improve water-use efficiency while maintaining agricultural productivity. These practices not only conserve precious water resources but also enhance soil health, reduce environmental degradation, and strengthen farmers' resilience to climatic uncertainties. Wider adoption of water-efficient technologies, supported by appropriate policies, farmer awareness, and technological innovation, will be critical for achieving long-term agricultural sustainability and ensuring food security for future generations.



Role of Plant Secondary Metabolites in Biotic Stress Tolerance



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ABSTRACT

Plants face constant challenges from herbivores and disease-causing organisms and they depend on secondary metabolites as vital parts of their defense system. Even though these compounds are not directly involved in the basic metabolic processes of plants, they play a critical role in helping plants survive when under stress. The main types of these secondary metabolites include terpenoids, phenolic compounds, sulphur-containing substances, nitrogen-containing compounds and lectins. Terpenoids function as both toxic agents and signalling molecules, while glucosinolates and phytoalexins help plants respond quickly through enzymatic actions. Alkaloids and cyanogenic glycosides prevent herbivores from feeding by being poisonous and phenolic compounds like flavonoids, tannins and lignin help plants resist damage both structurally and chemically. Lectins interfere with the digestion of insects by attaching to carbohydrates in their gut. These compounds are accumulated in specialized plant structures like trichomes, resin canals, and laticifers, where they are strategically retained and released in a regulated manner upon tissue injury. It is important to understand how these secondary metabolites are made and what roles they play, as this knowledge is essential for creating effective and sustainable methods to control pests and enhance the ability of crops to resist damage.

Keywords: Secondary metabolites; Plant secondary metabolites; Biotic stress; Plant defense mechanisms; Terpenoids; Phenolic compounds; Alkaloids; Glucosinolates; Phytoalexins; Cyanogenic glycosides; Lectins

Introduction

Plants are constantly exposed to various types of living stressors, such as insect herbivores, fungi, bacteria, nematodes and viruses. These stressors can greatly reduce plant growth and productivity. Since plants are immobile, they cannot move away from these threats. Instead, they use advanced biochemical mechanisms to defend themselves. A key part of this defense system is the production of secondary metabolites (SMs), which are a wide variety of organic compounds. These compounds are not directly involved in the basic processes plants need to survive, such as growth and reproduction. However, they play a vital role in helping plants adapt to stress and survive. Major types of SMs include alkaloids, phenolics, terpenoids, and glycosides. Each of these groups has different functions, such as deterring insects, inhibiting feeding, acting as toxins, and fighting off infections. The variety and development of these compounds are largely influenced by their interactions with herbivores and pathogens over time, which helps plants improve their ability to resist damage and thrive in their environment. Because of their vast range of structures and biological effects, plant secondary metabolites are becoming more important in areas like sustainable pest control, protecting crops, and using plants in biotechnology (War et al., 2012; Wink, 2016; Thirumurugan et al., 2018; Osman, 2020;).

♦ Major Secondary Metabolites in Biotic Stress Tolerance

Plant secondary metabolites are broadly categorized into three primary groups: terpenoids, phenolic compounds and nitrogen-containing compounds. Each group plays a distinct role in the plant's defence against stress. Phenolic compounds, often used in combination with volatile chemicals, help repel herbivores and prevent their growth.

1. Terpenes

Isopentenyl diphosphate (IDP) and dimethylallyl diphosphate (DMAPP) serve as the fundamental precursors in terpene synthesis. These building units are synthesized through two distinct metabolic pathways: the pyruvate-derived plastidial 2-C-methyl-D-erythritol-4-phosphate (MEP) pathway and the acetyl-CoA derived cytosolic mevalonate (MVA) pathway (Divekar et al., 2022). In plants, terpenes serve diverse physiological and ecological roles, including functioning as precursors of plant hormones such as gibberellins and abscisic acid, as well as contributing to defense against insects, allelopathic interactions and the attraction of pollinators.

aMenthhol, camphor, pyrethrins, artemisinin's and farnesol1 are terpenoid compounds that demonstrate important antimicrobial and antiprotozoal properties (Tiku, 2018).

❖ **Listt of terpenes with their categories and biological roles in different plants (Al-Khayri et al., 2023)**

Pyrethrin.	Monoterpenes found in <i>Chrysanthemum indicum</i> . that act as neurotoxic compounds against parasitic wasps, insects, and moths.
Hemi gossypol. activity	A sesquiterpene present in <i>Gossypium hirsutum</i> with antifungal
Gossypol	A diterpene produced by <i>G. hirsutum</i> that exhibits antifungal and antibacterial properties.
Cucurbitacin-C.	A triterpene found in Cucurbit. species that is toxic to spider mites.

2. Sulphur Containing Secondary Metabolites

Secondary metabolites that contain sulphur contribute to plant protection against pathogens, acting either as phytoalexins or Phyto anticipatory compounds. Common examples include glucosinolates, thiosulfinates (like allicin, derived from cysteine sulfoxidess) and antimicrobial peptides such as defensinss and thioninss, which are often volatile, bitter or strong-smelling (Tiku, 2018). These metabolites are synthesized via two main pathways:

a) Glucosinolate myrosinase pathway: In the glucosinolate pathway, the enzyme myrosinase breaks down glucosinolates into defensive compounds when plant tissues are damaged (e.g., cabbage, broccoli, etc.)(Ahmed et al., 2017).

b) Alliin–alliinase pathway: In the alliin pathway, the enzyme alliinase produces alliin, a compound involved in herbivore and pathogen resistance, making these pathways crucial in plant defense strategies (e.g., garlic, onion, leeks — *Allium* genus) (Sayadi et al., 1999).

2.1 Glucosinolates (GSLs)

These low-molecular-weight glycosides have a thioglucose component in their structure, and when broken down by enzymes, they release volatile compounds that help the plant respond to threats. These breakdown products can deter or kill pests and pathogens. Common examples include mustard oil glycosidess found in the Cruciferae family and allyl sulfoxides found in the *Allium* family (Leustek & Saito, 1999). These compounds are predominantly distributed in the Cruciferae family and are also reported in related families such as Resedaceaea, Moringaceaea, Capparaceae and Tovariaceae. Glucosinolates exhibit notable antibacterial. activity and can additionally function as attractants for herbivorous insects, including aphids and caterpillars (Harborne, 1998). Myrosinase is an enzyme found in plants that helps break down glucosinolates by removing the glucose portion that contains sulphur. This reaction creates unstable intermediate compounds, which quickly transform into active substances like isothiocyanates, nitriles and thiocyanates. These substances have a strong, sharp smell and act as chemical defenses to repel or harm herbivores and invading pathogens (Geu-Flores et al., 2009). In healthy plant cells, glucosinolates and myrosinase are stored separately in different parts of the cell. When the plant tissue is damaged by insects, pathogens, or mechanical injury, the enzyme and its substrates mix, triggering a chemicaldefense. For example, cabbage exhibits resistance to *Plasmodiophoraa brassicae*, whereas oilseed rape and Indian mustard demonstrate resistance to *Leptosphaeria maculanss*, largely attributed to elevated concentrations of glucosinolates. In Brassica species, the compounds formed from glucosinolate breakdown act as natural antifungal agents, helping to protect the plant from various pests and diseases (Tiku, 2018).

2.2 Sulphur Containing Phytoalexins

Phytoalexins are antimicrobial substances that plants produce as part of their natural defense mechanism to protect themselves from bacterial and fungal infections (Pedras et al., 2011). In members of the Brassicaceae, various phytoalexins including camalexinn, brassinin, and rapalexin A. are sulphur-containing indole-derived compounds synthesized from the amino acid tryptophan (Bednarek, 2012; Czerniawski & Bednarek, 2018). The process of making camalexin starts when plants experience stress and it involves specific enzymes like GSTF6 and GSTU4, as well as compounds such as indole-3-acetonitrile (IAN) and glutathione (GSH). In Arabidopsis, the cytochrome P450 enzymes CYP79B2 and CYP79B3 are important in increasing the amount of camalexin that accumulates when the plant is attacked by pathogens (Lemarié et al., 2015). Plants that lack the PAD3 gene are more likely to become infected, while those with the transporter gene AtABCG34 show higher levels of camalexin secretion

and better resistance to diseases. Some plants, such as tomato and garlic, also respond to infection by producing elemental sulfur, which acts as an inorganic form of phytoalexin (Glawischnig, 2007).

❖ Examples of phytoalexins found in various plants

Camalexin	Sulphur containing phytoalexin produced by members of the Brassicaceae.
Glycosides	Glucosinolates are characteristic defensive metabolites of the Brassicaceae.
5-(3-buten-1-ynyl)-2'-bithiophene	Dithiophene compound found in species of Tagetes.
Allicinn	Thiosulfinate compound present in Allium sativum (garlic).

3. Lectins

Lectins are widely distributed plant proteins that bind to carbohydrates and play a crucial role in protecting plants from insect herbivores. They recognize and bind specific sugar moieties on insect gut epithelial cells, leading to physiological disruption. Leguminous seeds are particularly rich sources of lectins with multiple carbohydrate-binding domains that enable agglutination of target cells. Notable examples include Wheat Germ Agglutinin (WGA), Phaseolus Hemagglutinin (PHA) and Galanthus Nivalis Agglutinin (GNA). GNA exhibits strong affinity for mannose-containing glycoconjugates, whereas PHA preferentially binds α -N-acetylgalactosamine. WGA interacts with chitin in the insect peritrophic membrane, impairing gut integrity and digestion. Lectins act as antinutritional factors by damaging the midgut epithelium and reducing nutrient absorption. Mannose-binding lectins are particularly effective against sap-sucking insects such as aphids. Transgenic expression of lectin genes, especially GNA, has enhanced resistance in crops like tobacco. Owing to their stability across a broad pH range, lectins remain active in the insect digestive system and represent promising tools for pest-resistant crop development (Yamane et al., 2010; War et al., 2012).

4. Nitrogen Containing Secondary Metabolites

Nitrogen-containing secondary metabolites are found in smaller quantities than carbon-based compounds in plants. However, they are essential components of a plant's defense system, especially against herbivorous insects and animals (Tiku, 2018). Main types of these compounds include: Alkaloids, Cyanogenic glycosides & non-protein amino acids.

4.1 Alkaloids: Alkaloids are nitrogen-based organic compounds that usually have a bitter taste. They are produced from amino acids such as tryptophan, tyrosine, lysine and aspartic acid. These compounds play a significant role in the plant's chemical defense mechanism. They help protect plants by reducing damage from herbivores and limiting the growth of harmful microorganisms. For example, caffeine found in tea, coffee and cocoa plants has toxic effects on various fungi and insect pests. Nicotine, present in tobacco, is made in the roots and then transported to and stored in leaf vacuoles, where it acts as a defensive substance (Tiku, 2018).

4.2 Cyanogenic Glycosides: Some plant compounds can release hydrogen cyanide (HCN) when their tissues are damaged by herbivores. This release serves as a quick chemical defense mechanism. When cells are broken, enzymes like glycosidases and hydroxynitrile lyases become active and help break down these compounds into their toxic forms, which prevent further herbivore attacks. Common examples: Lotaustralin and linamarin found in Trifolium repens, Linum usitatissimum and Lotus corniculatus. Dhurrin found in Sorghum bicolor. In clover plants, cyanogenic glycosides act as a protective measure for young seedlings, helping them defend against slugs and snails (Tiku, 2018).

5. Phenolic Compounds

Phenolic compounds are vital for plant growth and defense, especially against herbivory. The phenyl propanoid pathway is activated during herbivore attacks, leading to the production of various defensive phenolic compounds. Enzymes such as polyphenol oxidase and peroxidase convert phenolic compounds into quinones, which attach to insect proteins and prevent them from feeding. Onion produces catechol and protocatechuic acid to protect against Colletotrichum circinans. Wheat varieties with high phenolic content resist Rhopalosiphum padi. Strawberry leaves with high catechol levels deter Tetranychus urticae (Mostafa et al., 2022).

5.1 Coumarins: Found in plant families such as Leguminosae, Poaceae, Apiaceae and Rutaceae. These are made through the shikimate pathway and have selective toxicity against aphids (e.g., Myzus persicae) while being harmless to beneficial insects like ladybugs and earthworms (Tiku, 2018)

5.2 Furano-Coumarins: Mainly found in Umbelliferae, these compounds become toxic under UV-A light exposure. Psoralen, a common furano-coumarin, has antifungal properties, especially in untreated plants (Tiku, 2018).

5.3 Lignin: Formed from coniferyl, sinapyl and coumaryl alcohols, lignin provides mechanical strength and makes plant tissues hard to digest (Tiku, 2018). High lignin content makes it difficult for herbivores and even mammals to break down plant structures.

5.4 Flavonoids: Flavonoids are involved in plant reproduction, hormone transport, fruit ripening and defense. They act against viruses, fungi, bacteria and herbivores but also attract pollinators. These compounds are used as models for developing biopesticides due to their low environmental impact. Flavonoids inhibit insect enzyme activity and can stop larval development at an early stage. Naringin, rutin and quercetin are effective against *Eriosoma lanigerum* (Mostafa et al., 2022).

5.5 Tannins: Tannins are polyphenolic compounds with molecular weights ranging from 600 to 3000 Da. They discourage herbivores by binding to insect proteins, which reduces digestion efficiency. Plants with high tannin levels and low protein content have a stronger defense against herbivores. Tannins cause a tingling sensation in insect mouths, leading to reduced feeding behavior. Mammals like deer, cattle and apes avoid tannin-rich plants due to their unpleasant taste (Tiku, 2018).

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VERMICOMPOSTING: A LOW INVESTMENT AGRI-BUSINESS MODEL



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1. Abstract

Vermicomposting is a significant process for recycling organic waste into nutrient-rich compost called vermicompost. Vermicomposting has direct environmental & economic benefits as it contributes to the sustainable agriculture production. The present study on Vermicomposting: A Low Investment Agri -Business Model indicates the production technology, business plan, startup-cost & profit and analyzes the available subsidies and market opportunity for vermicomposting business.

2. Introduction

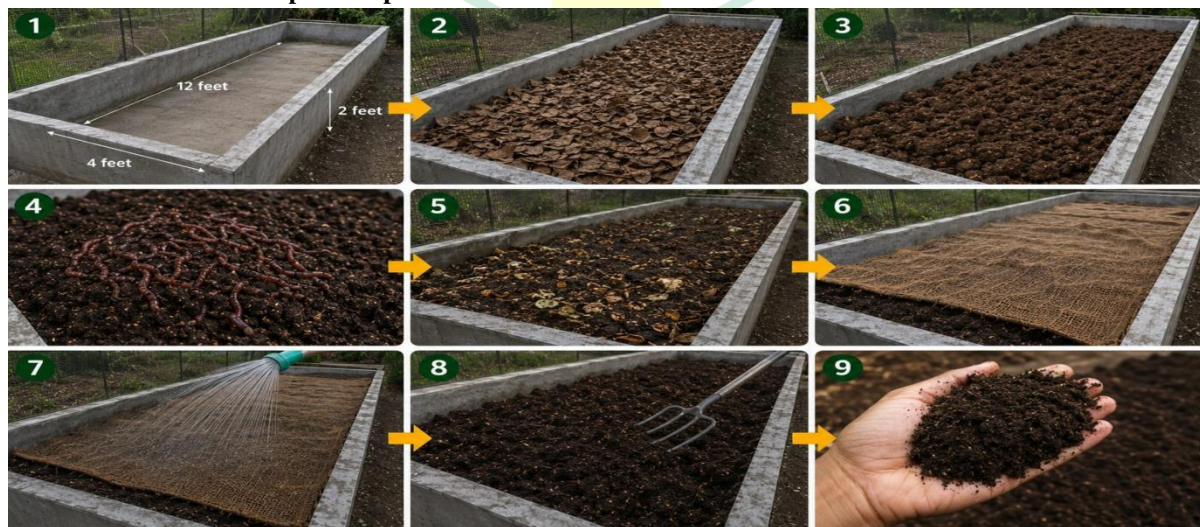
The future of sustainable agriculture begins beneath our feet—with the humble earthworm. Vermicomposting is a biological process mediated by earthworms to physically degrade and chemically convert organic material to nutrient-rich manure. It has emerged as a profitable agri-business globally. It requires low investment, simple production technology, and minimal maintenance, making it suitable for farmers, rural youth, and entrepreneurs. In addition to generating income, vermicomposting helps reduce environmental pollution and promotes efficient waste management. In this article, we explore the essential steps required to establish a successful vermicomposting business.

3. Production Technology

3.1 Vermicomposting Materials:

- A suitable container, vermi bed, or cemented pit with proper drainage.
- Partially decomposed cow dung or other animal manure.
- Organic wastes such as kitchen waste, crop residues, and dried leaves.
- Bedding materials like shredded newspaper, straw, or coconut coir.
- Red wiggler earthworms (*Eisenia fetida*).
- Clean water to maintain 60–70% moisture.
- Gunny bags or straw for covering the compost bed.
- A shaded and well-ventilated place for vermicomposting.
- A watering can or sprinkler to keep the bed moist.
- A hand shovel and sieve for harvesting and separating the compost.

3.2 Process of Vermicompost Preparation



- 1) Take a container or a bed.
- 2) Add a layer of 15–20 cm of bedding material like shredded newspaper or dried leaves.
- 3) Add partially decomposed material (like cow dung) in beds.
- 4) Introduce red wiggler earthworms.
- 5) Regularly feed them kitchen scraps (avoiding meat, dairy, and oily foods).
- 6) Maintain moisture by sprinkling water (daily) and by covering with gunny bags.
- 7) Bed should be turned once after 30 days for maintaining aeration.
- 8) Compost gets ready in 45–50 days.
- 9) The finished product is 3/4th of raw material used.

3.3 Harvesting

When raw material is completely decomposed, it appears black & granular, just like tea leaves. Earthy-smelling compost is produced at the time of harvesting. This time is suitable for harvesting.



4. Business Plan for Vermicomposting

In comparison to garden compost, vermicompost has a larger percentage — almost twice as much — of both macro & micronutrients. Depending on the type of waste, earthworm population, and environmental factors, the product is ready in 45–60 days and there are 5 to 6 possible cycles in a year.

4.1 Startup: Cost & Profit

To start a vermicomposting unit, two types of costs are required. First, fixed cost (includes land, shed, hand rake, sieving machine, weighing machine, spades, plastic troughs). Second, variable cost (includes cow dung, paddy straw, labor cost, electric charge, maintenance charge, earthworms). Fixed cost is a one-time investment, but the variable cost states the continuous investment. The initial investment can range from around ₹50,000 to ₹4,57,100 depending on the scale & infrastructure needed. A small-scale unit may cost around ₹50,000, while a larger set-up could require up to ₹4,57,100 for building, machinery, and initial earthworm purchases. The profit potential can be significant with potential annual income ranging from ₹1,35,398 to ₹6,48,000. According to the Pharma Innovation Journal authored by Shivam Singh et al, the cost of producing vermicompost is less than ₹2 per kg, while it can be sold for ₹4–₹4.5 per kg, indicating a profit margin of over 100%. A case study from The Better India authored by Shivani Gupta highlighted a farmer who, with 1000 vermicompost beds, produces five tonnes daily, earning ₹50,000 per day — translating to an annual turnover of approximately ₹1.5 crore.

4.2 Subsidies on Vermicomposting Unit

Several government schemes offer subsidies to help farmers & entrepreneurs establish vermicomposting units. Government has provisioned financial aid to farmers through state governments for adopting organic farming under various central sector schemes like: National Mission for Sustainable Agriculture (NMSA), Mission for Integrated Development of Horticulture (MIDH) and Paramparagat Krishi Vikas Yojana (PKVY). Under these

schemes, farmers can avail subsidy/grant assistance to set up vermicompost units. Some of the provisions under these schemes are as follows:

- a) **Mission for Integrated Development of Horticulture (MIDH):** Mission for Integrated Development of Horticulture (MIDH) provides financial assistance to the farmers up to 50% of the cost of vermicompost units. However, this is subject to a maximum of INR 50,000 per beneficiary for a unit of the size 30' × 8' × 2.5'.
- b) **Paramparagat Krishi Vikas Yojana (PKVY):** Paramparagat Krishi Vikas Yojana (PKVY) was launched in 2015-16 as a component of the National Mission on Sustainable Agriculture (NMSA) to promote organic farming and soil health. Under this scheme, assistance is given to the farmers to the tune of INR 5000 per unit for procurement of earthworms, construction of pits, meeting out labor charges, and procurement of other raw materials.

5. Market Opportunity for Vermicompost Fertilizer

The production of vermicompost has a good sales potential as compared to various crops related to Agriculture, Horticulture, Ornamental etc. Farmers' associations & subdivisions in nearby cities and towns are examples of direct sales to customers. Marketing in bulk quantity to companies and distributors of organic fertilizer that needs vermicompost as one of its primary components. Furthermore, more people now prefer buying organic food, which increases the demand for natural fertilizers. Selling online and partnering with local shops can also help reach a much wider audience. Finally, selling directly to plant nurseries and home gardeners provides a great opportunity to increase profits.

6. Conclusion

In conclusion, strategic planning, industrial knowledge, and continuous learning is required to start a vermicomposting business. Vermicomposting not only generates sustainable income but also promotes environmental conservation and soil health. Various cities face challenges in organic waste management and vermicomposting presents a viable solution. If this business is done on a large scale, then it will affect the GDP of the country to a great extent. So, the future of this business is very bright.

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Genetic Basis and Breeding for Brown Planthopper Resistance in Rice: Harnessing Nature's Defences for Sustainable Agriculture



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Introduction

Rice serves as the primary dietary staple for over half of the global population and is crucial for ensuring food security across Asia. Despite its importance, rice cultivation is persistently threatened by insect pests, with the brown planthopper (BPH), *Nilaparvata lugens*, being particularly destructive. This insect has repeatedly caused substantial crop damage, leading to significant economic challenges for millions of rice farmers worldwide. (Jena and Kim, 2010; Horgan et al., 2021)

Farmers have mainly relied on insecticides for Brown Planthopper (BPH) control. While this chemical method offers quick pest control, it has several long-term drawbacks, like pesticide resistance, environmental harm, damage to beneficial insects, and higher production costs. Conversely, host plant resistance offers a more sustainable and farmer-friendly option. By understanding the genetic mechanisms of BPH resistance and applying this to breeding programs, significant progress has been made in improving rice cultivation globally.

Brown Planthopper: A Persistent Threat

Brown planthoppers damage rice plants by extracting sap from the phloem tissues. When infestations are severe, they cause a condition called "hopper burn," where the plants turn yellow, wilt, and eventually perish. Additionally, BPH spreads significant viral diseases, including rice grassy stunt virus and rice ragged stunt virus, which further exacerbate yield losses. The adaptability of BPH presents a significant challenge. Emerging of new virulent biotypes overcome resistance in previously bred varieties for resistance. Therefore, continuous efforts are required to identify new resistance sources and develop improved cultivars with durable resistance.

Genetic Basis of BPH Resistance

The discovery of genetic resistance to BPH represented a significant shift in managing rice pests. Scientists have discovered that certain rice varieties and wild rice species naturally possess genes that confer resistance to planthoppers. (Brar et al., 2009).

Resistance Genes in Rice

Over the past five decades, scientists have identified more than 40 genes and quantitative trait loci (QTLs) throughout rice genome were associated with BPH resistance. These genes originated from cultivated rice varieties, landraces, and wild relatives. Key resistance genes such as Bph1, Bph3, Bph14, Bph17, Bph18, and Bph26 are located on various rice chromosomes and function through a range of defense strategies (Jena and Kim, 2010; Hu et al., 2016).

Mechanism of resistance: Resistance genes help rice plants defend themselves through several mechanisms.

Antixenosis (Non-preference): Some genes alter plant traits, which makes rice less appealing to planthoppers. As a result, these insects tend to avoid feeding on or laying eggs on plants that are resistant.

Antibiosis: Biochemical alterations induced by certain resistance genes can negatively affect the growth, survival, and reproduction of plant hoppers. Insects that consume resistant plants often exhibit diminished fitness and a decline in population growth.

Tolerance: Tolerance allows plants to withstand insect damage and recover without significant yield losses. Although planthoppers may feed on plants, they maintain crop productivity.

Activation of Plant Defence Responses

Resistance genes trigger defence signalling pathways that involve phytohormones, like jasmonic acid, salicylic acid, and ethylene. These pathways result in activation of defensive proteins and metabolites that reduce insect feeding and survival (Du et al., 2009).

Sources of Resistance: Prior studies have pinpointed important genes in traditional rice varieties, wild rice species, and local cultivars maintained by farmers. Wild relatives, including *Oryza officinalis* and *Oryza australiensis*, are important sources for harboring new resistance genes. These genetic resources act as a valuable resource for future breeding programs (Brar et al., 2009).

Breeding for BPH Resistance

Conventional Breeding: In this process, a resistant donor parent is crossed with a high-yielding but susceptible parent. Resistant progenies with desirable agronomic traits were selected through repeated selection process. This method has resulted in development of many resistant rice varieties throughout Asia. However, traditional breeding takes a long time and is frequently affected by environmental factors.

Marker-Assisted Selection (MAS): With the introduction of molecular markers, researchers can now use Marker-assisted breeding programme to identify resistant plants directly without waiting for pest infestations. MAS improves the selection efficiency, simultaneous transfer of multiple genes and improves the durable resistance while reducing the field screening costs. Molecular markers linked to genes such as Bph3, Bph14, Bph17, and Bph26 are widely used in the molecular breeding programs (Hu et al., 2016).

Gene Pyramiding: Building Durable Resistance

One of the greatest challenges in BPH management is the rapid evolution of new insect biotypes capable of overcoming the resistance of single genes (Fujita et al., 2013). To address this issue, gene pyramiding, can be employed which can integrate several resistance genes into one variety. For example, a rice variety carrying Bph14, Bph17, and Bph26 simultaneously offers stronger and more durable resistance than a variety containing only one of these genes. Gene pyramiding has several advantages.

- Broader resistance spectrum
- Enhanced durability
- Reduced risk of resistance breakdown
- Improved pest management sustainability

Molecular markers have made gene pyramiding more efficient and reliable.

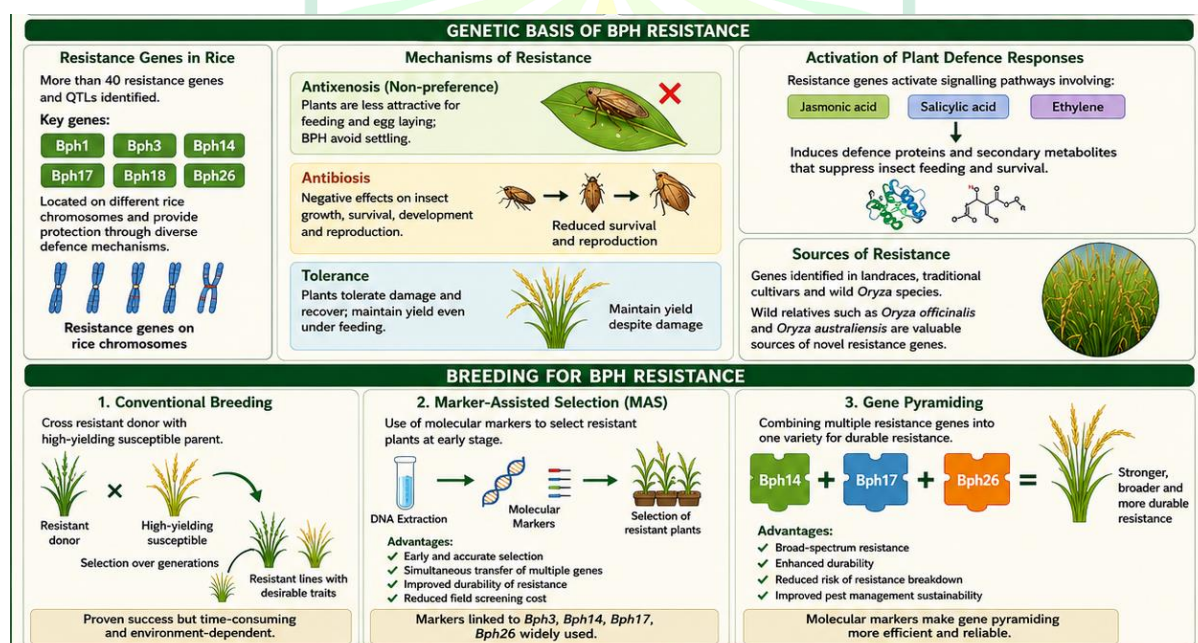


Figure 1: Genetic basis and breeding for BPH resistance

Genomics and Modern Breeding Technologies

Recent advances in genomic technologies such as genomic selection, CRISPR- Cas gene editing and precision phenotyping have accelerated the discovery of resistance genes. High-throughput sequencing, genome-wide association studies (GWAS), and transcriptome analyses have identified numerous candidate genes and defence pathways. This opens new opportunities for developing superior BPH-resistant rice varieties. Gene editing, allows researchers to precisely modify the genes involved in plant defence mechanism without introducing unwanted genetic material, offering exciting possibilities for future crop improvement (Hu et al., 2016).

Challenges

- Emergence of new BPH biotypes
- Climate change influencing pest dynamics
- Narrow genetic diversity in cultivated rice
- Need for region-specific resistance breeding

Continuous monitoring of BPH populations and exploration of new resistance sources are essential for sustaining the effectiveness of resistant varieties of rice.

Conclusion

The discovery and utilization of brown planthopper resistance genes represent one of the most successful strategies in managing BPH in rice breeding. As the global demand for rice continues to increase, breeding for durable BPH resistance will remain a cornerstone of sustainable rice production. By harnessing the rich genetic diversity present in rice and its wild relatives, breeders are building a future in which farmers can achieve higher yields, lower pesticide use, and greater environmental sustainability.

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Digital Sakhi: Empowering Women Through Technology



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Introduction

India's digital revolution is changing how people learn, earn, save, communicate, and access public services. Yet technology can only be truly transformative when everyone has the confidence and opportunity to use it. For many women, especially in rural and low-income communities, the journey from owning a mobile phone to using it independently remains difficult. The idea of the *Digital Sakhi*, meaning “digital friend,” responds to this challenge through a simple but powerful approach - women help other women become confident digital citizens. A Digital Sakhi is generally a trained woman from the community who teaches her peers how to use smartphones, internet-based services, digital payments, online banking, government portals, and cyber-safety tools. She may work through a self-help group, a non-profit organisation, a financial-inclusion programme, or a government-supported livelihood initiative. More than a trainer, she is a trusted local guide. Her role is important because she makes technology less intimidating and more relevant to everyday life.

Why Digital Sakhis?

India has rapidly expanded digital infrastructure, but access does not automatically create inclusion. A smartphone in a household may be owned by a man, shared by several family members, or used by a woman only with someone else's assistance. Many women also face barriers such as limited income, lack of digital literacy, language differences, poor connectivity, safety concerns, and social norms that discourage independent phone use.

The gender gap in mobile internet use remains a global concern. According to the GSMA's (*Mobile Gender Gap Report 2024*), women in low- and middle-income countries were 15% less likely than men to use mobile internet, while approximately 785 million women remained unconnected. Around 60% of these unconnected women lived in South Asia and Sub-Saharan Africa (GSMA, 2024). This shows that digital inclusion is not only an infrastructure issue; it is also an issue of gender equality. A Digital Sakhi may teach a woman how to make a UPI payment, check a bank balance, use WhatsApp to communicate with customers, apply for a government benefit, or recognise an online fraud attempt. These are small skills, but their effect can be life-changing. Instead of relying on someone else to withdraw money, fill an online form, or interpret a message from the bank, women can make informed decisions for themselves.

The impact reaches beyond individual users. When a woman learns digital skills, she often shares them with her family, friends, and self-help group. A Digital Sakhi thus creates a multiplier effect, one trained community leader can help many women become more confident users of technology. In Madhya Pradesh, for example, the Digital Sakhi initiative supported by L&T Financial Services and SEWA trained 100 rural women to promote digital literacy in their communities. (CSRBOX)

Financial independence is one of the most important outcomes. Digital literacy helps women use bank accounts, save securely, access insurance, understand loans, and receive payments directly. Yet financial knowledge remains uneven, an Asian Development Bank case study reported that only 24% of Indian women met the Reserve Bank of India's minimum financial-literacy standard. (Asian Development Bank) Digital Sakhi programmes address this gap by making financial concepts practical rather than abstract often using demonstrations, local examples, stories, and peer learning.

These programmes can also support women entrepreneurs. A home-based tailor can display products through WhatsApp. A farmer can access weather updates or market information. A self-help group can maintain

digital records. A small business owner can accept cashless payments. Technology does not automatically remove economic barriers, but it can widen a woman's choices and reduce her dependence on intermediaries.

From Digital Access to Digital Confidence

Digital literacy is not simply the ability to switch on a phone or open an application. It includes the ability to search for information, evaluate whether it is reliable, protect personal data, communicate safely, and complete transactions independently. For women, these skills can reduce dependence on family members or intermediaries.

A Digital Sakhi may begin with basic tasks: saving contacts, using the camera, sending WhatsApp messages, browsing in a local language, or accessing a video tutorial. Gradually, training can cover more advanced activities such as using QR codes, making digital payments, checking bank balances, booking appointments, applying for schemes, or selling products online.

The Government of India's Pradhan Mantri Gramin Digital Saksharta Abhiyan (PMGDISHA) recognised this wider meaning of digital literacy. The programme aimed to make rural households digitally literate, including women and other marginalised groups. Its definition of a digitally literate person includes the ability to use digital devices, access government services, search for information, and undertake cashless transactions ([Press Information Bureau, 2021](#)).

Financial Inclusion and Economic Independence

One of the strongest benefits of the Digital Sakhi model is its contribution to financial inclusion. A bank account is meaningful only when a person can use it safely and independently. Women may have accounts but still rely on others to withdraw money, check balances, understand transactions, or access benefits. Digital and financial literacy help change this situation.

The Reserve Bank of India has emphasised the need for both conceptual and process literacy. In other words, people need to understand financial ideas, but they must also know how to carry out the actual steps involved in using financial services. The RBI's 2025 Financial Literacy Week focused specifically on **"Financial Literacy – Women's Prosperity,"** highlighting the close connection between women's knowledge of finance and their economic well-being ([Reserve Bank of India, 2025](#)).

This effect can be seen in women-led banking models. In Bihar, digital banking kiosks run by members of women's self-help groups conducted more than US\$350 million in digital financial transactions between 2016 and 2020. This example demonstrates that women are not merely beneficiaries of digital services; they can also become trusted providers of those services in their communities ([World Bank, 2020](#)).

The Role of Self-Help Groups

Self-help groups, or SHGs, provide a natural platform for Digital Sakhi programmes. SHGs already bring women together for savings, credit, livelihood activities, and collective decision-making. Adding digital education to these groups creates a supportive learning environment. Women may feel hesitant to ask questions in a formal training centre, but they may be more comfortable learning with fellow group members. They can practise transactions together, share phones where needed, and help each other remember the steps. This peer-based model also makes training more sustainable.

The Ministry of Rural Development has used this approach through Business Correspondent Sakhis and DigiPay Sakhis. These women are trained to provide basic banking and payment services, including support for direct benefit transfers, within rural communities. In 2021, the government announced efforts to engage 50,000 women SHG members as Business Correspondents and noted that DigiPay Sakhis could offer doorstep banking facilities using mobile devices and fingerprint authentication ([Press Information Bureau, 2021](#)).

Such initiatives change the image of women in the digital economy. Instead of being viewed only as learners, women become service providers, community leaders, and entrepreneurs. Their skills earn trust and can create an independent source of income.

Cyber Safety Must Be Central

Digital participation brings opportunities, but it also brings risks. Online fraud, phishing links, fake customer-care calls, identity theft, misinformation, harassment, and financial scams can discourage women from using digital services. Therefore, cyber safety should be a core part of every Digital Sakhi programme.

Women should learn never to share OTPs, PINs, passwords, or bank details. They should know how to verify official sources, identify suspicious links, use strong passwords, update applications, and report fraud promptly. Training must also address privacy, consent, and respectful online behaviour.

This need is increasingly recognised in public policy. In April 2026, the Ministry of Electronics and Information Technology, C-DAC Hyderabad, and Reliance Foundation launched the e-SafeHER programme, with the goal of enabling one million rural women as Cyber Sakhis over three years. The programme uses localised, audio-visual, and blended learning materials to strengthen cyber-risk awareness and safe digital behaviour ([Press Information Bureau, 2026](#)).

Challenges That Remain

Despite their promise, Digital Sakhi programmes must overcome several challenges. First, many women do not own personal smartphones or cannot afford data packs. Shared-device use may limit privacy and reduce the freedom to practise. Second, connectivity and electricity remain inconsistent in some remote areas. Third, training materials are sometimes too dependent on English or written text, excluding women with limited literacy.

Social barriers are equally significant. Some women may need permission to attend training, travel outside their village, or use a phone. Others may fear making mistakes or losing money in a digital transaction. Effective programmes respond with local-language content, hands-on practice, patient follow-up, and engagement with families and community leaders. The design of technology matters as well. Voice-based tools, local-language interfaces, visual instructions, and accessible helplines can make digital services easier to use. Digital systems should be built around real users rather than expecting users to adapt to complicated systems.

Conclusion

Digital Sakhi is not only a digital-literacy programme. It is a model of women's leadership, financial inclusion, community learning, and social change. It shows that technology becomes meaningful when people can use it safely, independently, and for purposes that matter in their lives. When one woman learns to make a digital payment, access a welfare service, protect herself from cyber fraud, or sell her products online, the benefit may extend to her entire family. When she teaches other women, the effect multiplies across the community. Digital Sakhis are therefore not simply helping women enter the digital world; they are helping women shape it.

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Vertical Horticulture for Mountain Regions: Growing More in Less Space



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Vertical farming is becoming a solution for climate-smart, sustainable agricultural practices in land-scarce and fragmented mountain regions. So rather than expanding horizontally, this technology makes use of vertical space with crops grown on trellises, stacked containers, green walls as well as hanging baskets and multi-layer structures. Vertical farming is becoming the solution for climate-smart and sustainable agricultural practices in flat land scarcity and fragmented scenarios of mountain regions. So rather than expanding horizontally, this technology makes use of vertical space with crops grown on trellises, stacked containers, green walls as well as hanging baskets and multi-layer structures. When combined with drip irrigation, hydroponics, or protected cultivation, it enhances water-use efficiency, improves crop quality, and allows year-round production.

- ✦ **The need for vertical horticulture in mountain areas:** Mountain agriculture with a high relevance of vertical cultivation is facing several challenges.
- ✦ **Limited cultivable land:** Horizontal farming is limited by steep slopes and rocky landscapes.
- ✦ **Land Fragmentation:** Farmers have very small, scattered landholdings.
- ✦ **Erosion of Soil:** Heavy rain causes a large loss of topsoil.
- ✦ **Water shortage:** Efficient irrigation is a must in hilly regions.
- ✦ **Variability in Climate:** Mountain climates are subject to frost and hailstorms. There is a lot of rain and the temperature changes often.
- ✦ **High demand for fresh fruit and vegetables:** Tourism and urbanisation enhance the demand for fresh horticultural products. There is a lot to be gained by mountain farmers. Vertical systems reduce soil erosion, increase sunlight and air circulation, reduce the incidence of pests and disease and facilitate harvesting. They also provide opportunities for higher incomes by encouraging the production of high-value fruits and vegetables on small landholdings. The initial investment and technical knowledge required may be higher than those required for conventional farming, but the long-term benefits make vertical horticulture a promising option for sustainable mountain agriculture. Faced with the challenges of climate change and land scarcity to food production, upward growth rather than outward growth is a practical way to higher productivity, environmental conservation and better livelihoods in hilly areas.

Summary

Vertical horticulture is a viable and sustainable alternative to improve horticultural production in mountain areas where land resources are limited. Farmers can increase productivity and resource-use efficiency, reduce environmental degradation, and grow high-value crops throughout the year through efficient use of vertical space. The technology is capital intensive and requires some technical know-how, but the long-term economic and environmental benefits far outweigh the limitations. “Vertical horticulture, with proper government support, farmer training and technological innovation can make mountain agriculture more resilient, profitable and climate smart production system.”

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Fruit Waste to Wealth: Making Value-Added Products from Peel, Pulp and Seeds



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Introduction

A fruit is usually valued for its sweet pulp, attractive colour, pleasant aroma and nutritional benefits. However, after eating or processing fruits, a large quantity of peel, seed, rind, pomace and unused pulp is commonly thrown away. In homes, markets, juice shops and fruit-processing industries, these residues are often treated as waste. But modern fruit science is changing this view. What was once considered waste is now being recognised as a valuable raw material for food, feed, medicine, cosmetics, packaging and bioenergy.

Fruit waste is not a small problem. Globally, fruits and vegetables are among the most perishable agricultural commodities. According to FAO, fruits and vegetables show the highest food-loss rate among major food groups. In India also, government studies have reported considerable post-harvest losses in fruits due to poor handling, transport, storage and processing gaps. These losses reduce farmers' income, increase food prices, waste natural resources and create environmental problems.

The idea of "fruit waste to wealth" is therefore becoming an important trend in fruit science. It supports the circular economy, where every part of the fruit is used productively. Instead of dumping peels, seeds and pulp residues, they can be converted into value-added products such as jams, jellies, fruit bars, pectin, peel powder, seed flour, natural colourants, nutraceuticals, animal feed, compost, biofertilizers, biodegradable packaging films and biofuels.

Hidden Treasure in Fruit Waste

Fruit waste is rich in useful compounds. Peels and pomace often contain high amounts of dietary fibre, phenolic compounds, antioxidants, pigments, minerals and pectin. Seeds may contain oils, starch, protein, bioactive compounds and minerals. Citrus peels contain essential oils, flavonoids and pectin. Banana peels contain dietary fibre and bioactive compounds. Mango seed kernels contain starch, fat, fibre and minerals. Pomegranate peels are rich in phenolics with antioxidant and antimicrobial potential. Apple pomace contains fibre and polyphenols.

Research has shown that fruit by-products can be used in functional foods, nutraceuticals, edible packaging, cosmetics and pharmaceutical preparations. Thus, fruit residues are not useless materials; they are underutilized biological resources.

Peels: From Discarded Covering to Functional Ingredient

Fruit peels form a major portion of fruit waste. In many fruits, the peel protects the pulp from pests, moisture loss and microbial attack. Because of this protective role, peels are often rich in natural antioxidants, antimicrobial compounds and dietary fibre.

Citrus peel is one of the best examples. Orange, lemon, sweet lime and mandarin peels contain pectin, essential oils, flavonoids and natural aroma compounds. Pectin extracted from citrus peel is widely used as a gelling agent in jams, jellies, marmalades and confectionery products. Recent studies also show that citrus pectin can be used in biodegradable and active food-packaging films. Such packaging may help reduce dependence on petroleum-based plastics.

Banana peel is another promising by-product. It is usually discarded after eating the fruit, but studies report that banana peel flour can be incorporated into bakery products such as biscuits, cookies, muffins and bread to improve fibre content. Proper drying, grinding and safety testing are necessary before using it as a food ingredient. Banana peel can also be used for composting, animal feed, bioethanol production and the extraction of bioactive compounds.

Pomegranate peel is a rich source of phenolic compounds. These compounds show antioxidant and antimicrobial activities. Pomegranate peel extract has been studied for use in functional foods, natural preservatives, edible coatings and cosmetic products. Because consumers are increasingly looking for natural ingredients, such as fruit-peel extracts, have commercial potential.

Pulp and Pomace: The Power of Processing Residues

When fruits are processed into juice, squash, wine, cider or puree, a semi-solid residue remains. This residue is called pomace. It contains peel fragments, pulp particles, seeds and fibre. Earlier, pomace was mainly used as animal feed or discarded. Today, it is being studied as a valuable ingredient.

Apple pomace is rich in dietary fibre and polyphenols. It can be used in bakery products, breakfast cereals, health bars, fermented products and dietary supplements. Grape pomace, left after wine and juice production, contains polyphenols, anthocyanins and seed oil. It can be used in antioxidant-rich food products, natural colourants and cosmetic formulations.

Mango pulp residue, after juice or pulp extraction, can be converted into fruit leather, mango bars, chutneys, fermented beverages and dried powders. Overripe fruits that are not suitable for fresh marketing can also be processed into jam, jelly, nectar, squash, puree, dehydrated slices and candy. In this way, processing reduces waste and increases shelf life.

Seeds: Small Structures with Big Potential

Fruit seeds are often ignored, but many of them contain valuable nutrients and industrial compounds. Mango seed kernel is an important example. The hard mango stone contains an inner kernel that can be dried and processed into flour. Studies have explored mango seed kernel flour for incorporation into bakery and traditional food products. It contains starch, fat, fibre and minerals. Mango kernel fat has also been studied as a potential cocoa butter substitute in confectionery applications.

Jackfruit seeds are commonly consumed in some regions after boiling or roasting. They are rich in starch and can be converted into flour for bakery products, snacks and traditional foods. Tamarind seeds contain polysaccharides that have industrial applications as thickening and stabilizing agents. Papaya seeds contain oil and bioactive compounds, though their food use requires proper safety evaluation due to the presence of strong phytochemicals.

Seed utilization can create additional income for fruit processors and farmers. Instead of throwing seeds away, they can be collected, cleaned, dried and converted into usable products.

Value-Added Products from Fruit Waste

Fruit waste can be converted into many useful products. Some important possibilities are:

1. **Food products** – jams, jellies, fruit bars, candies, chutneys, sauces, pickles, fruit powders and bakery products.
2. **Functional ingredients** – dietary fibre powder, antioxidant extracts, natural colours, natural flavours and pectin.
3. **Nutraceuticals** – capsules, health drinks and supplements containing bioactive compounds from fruit peels and seeds.
4. **Animal feed** – dried citrus pulp, banana peel meal, mango peel powder and apple pomace can be used after proper processing.
5. **Compost and biofertilizer** – fruit residues can be converted into organic manure through composting or vermicomposting.
6. **Bioenergy** – fruit waste can be used for biogas, bioethanol and biochar production.
7. **Packaging materials** – pectin, cellulose and starch from fruit waste can be used in biodegradable films.
8. **Cosmetics** – citrus essential oils, pomegranate peel extract and fruit antioxidants can be used in soaps, creams and natural skincare products.

Waste to Wealth and Farmer Income

Fruit waste valorization has great importance for farmers, self-help groups, farmer producer organizations, startups and food-processing units. Many farmers sell fruits only in fresh form. When market prices fall, damaged

or overripe fruits are often wasted. If small-scale processing units are available, these fruits can be converted into shelf-stable products.

Mango growers can produce mango pulp, dried slices, fruit bars and seed kernel flour. Citrus growers can supply peel for pectin and essential oil extraction. Banana-growing regions can explore banana peel flour, banana fibre, vinegar and compost. Pomegranate processing units can extract peel powder for functional foods and herbal formulations. Jackfruit seeds can be processed into flour and snacks.

This approach adds value to the crop, creates rural employment and reduces pressure on the fresh-fruit market. It also supports secondary agriculture, where income is generated not only from the main produce but also from by-products.

Environmental Benefits

Fruit waste, when dumped openly, decomposes quickly and produces bad odour, leachate and greenhouse gases. It can attract insects and contaminate soil and water. Large fruit-processing units generate huge amounts of organic residues, which require proper management.

Converting fruit waste into useful products reduces environmental pollution. Composting returns nutrients to the soil. Biogas production generates renewable energy. Extraction of pectin, essential oils and antioxidants creates high-value ingredients. Biodegradable packaging from fruit waste can reduce plastic pollution. Therefore, fruit waste utilization is both an economic and environmental solution.

Scientific and Technological Approaches

Modern fruit science uses several technologies to recover useful compounds from waste. Traditional drying and grinding are used for making peel powder, seed flour and pomace powder. Hot-water extraction is commonly used for pectin. Steam distillation and cold pressing are used for essential oils. Fermentation can convert fruit waste into vinegar, enzymes, organic acids, bioethanol and single-cell protein.

Newer green technologies such as ultrasound-assisted extraction, microwave-assisted extraction, enzyme-assisted extraction and supercritical fluid extraction are gaining attention. These methods can reduce solvent use, save time and improve recovery of bioactive compounds. However, their cost, scalability and safety need to be considered before commercial use.

Challenges in Fruit Waste Utilization

Although fruit waste has great potential, some challenges must be addressed. First, waste collection is difficult because fruits are seasonal and residues are scattered across markets, households and processing units. Second, fruit waste has high moisture content and spoils quickly. Therefore, drying, refrigeration or immediate processing is necessary.

Food safety is very important. Peels may contain pesticide residues, dust, microbes or contaminants. Proper washing, drying, testing and quality standards are essential before using them in food products. Fourth, consumer acceptance is a challenge. Some people may hesitate to consume products made from “waste.” Therefore, the term “fruit by-product” or “upcycled fruit ingredient” may be more acceptable.

Finally, small entrepreneurs need training, equipment, packaging support, market linkage and regulatory guidance. Without these, fruit waste utilization may remain limited to laboratory research.

Future Scope

The future of fruit waste utilization is very promising. With increasing demand for natural foods, functional ingredients, sustainable packaging and eco-friendly products, fruit by-products can become an important industrial resource. There is scope for developing fruit-waste-based startups, rural processing units, women-led enterprises and farmer producer organization-based value chains.

Research institutions can help by developing simple, low-cost technologies suitable for rural areas. Food technologists can design safe and tasty products. Horticulturists can identify fruit varieties with better processing and by-product potential. Policymakers can support infrastructure such as cold chains, drying units, extraction facilities and common processing centres.

Conclusion

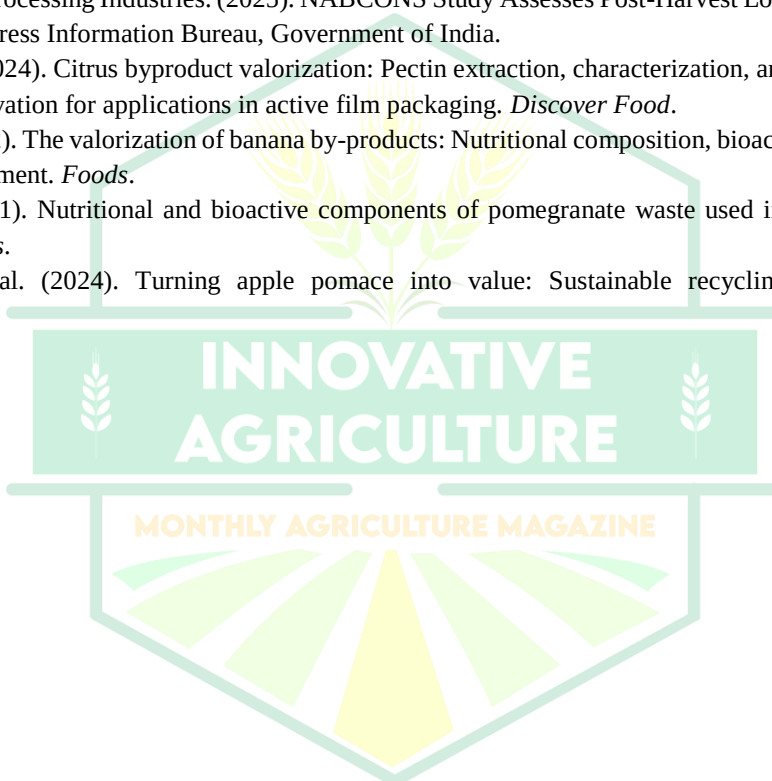
Fruit waste is not merely a disposal problem; it is an opportunity. Peels, pulp residues and seeds contain valuable nutrients, fibre, antioxidants, pectin, oils and bioactive compounds. By converting these materials into value-

added products, we can reduce post-harvest losses, increase farmer income, promote rural entrepreneurship, protect the environment and support sustainable food systems.

The concept of “Fruit Waste to Wealth” reminds us that the value of a fruit does not end with its pulp. Every peel, seed and residue has potential. With science, innovation and entrepreneurship, today’s waste can become tomorrow’s wealth.

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Integrated Land, Water and Crop Management: Recent Research Highlights



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Introduction

Watershed hydrology and conservation agronomy form the scientific foundation for sustainable management of land and water resources, particularly in regions facing increasing climatic variability, water scarcity, soil degradation, and declining agricultural productivity. Growing evidence indicates that effective watershed interventions, combined with climate-smart agronomic practices, can substantially improve water availability, reduce soil erosion, enhance groundwater recharge, increase carbon sequestration, and strengthen the resilience of agricultural production systems. Recent advances in hydrological science have expanded from conventional runoff estimation and erosion control to integrated approaches involving process-based modelling, machine learning, remote sensing, geospatial analysis, and ecosystem-based watershed management. Simultaneously, agronomic research has increasingly focused on conservation agriculture, precision nutrient management, biological soil enhancement, improved cropping systems, and carbon-smart production technologies that optimize resource-use efficiency while minimizing environmental impacts.

The research studies compiled in this section summarize significant international advances reported across the fields. Collectively, these investigations demonstrate how integrating hydrological engineering, ecological conservation, advanced monitoring technologies, and improved crop management practices can enhance watershed resilience, optimize natural resource utilization, and support sustainable agricultural development under changing climatic conditions.

Importance of the Compilation

This compilation presents a comprehensive overview of recent global research developments in watershed hydrology, conservation measures, and sustainable agronomy published during 2025–2026. It brings together multidisciplinary scientific evidence from internationally recognized journals, providing readers with current knowledge on emerging technologies, innovative conservation practices, and policy-oriented management approaches. The selected studies highlight major advances in runoff estimation, sediment transport, groundwater recharge, vegetative conservation structures, hydrological modelling, machine learning applications, climate-risk management, institutional adoption of conservation technologies, and community-based resource governance. In addition, recent agronomic innovations related to conservation tillage, precision nutrient management, UAV-based crop monitoring, biological soil enhancement, carbon sequestration, and water-efficient cropping systems are comprehensively represented.

For researchers, academicians, watershed planners, engineers, extension professionals, and policymakers, this compilation serves as a valuable reference for understanding the latest scientific trends and identifying research priorities. The documented findings are particularly relevant for rainfed and semi-arid regions such as Vidarbha, where sustainable watershed management and resource-efficient crop production are essential for improving water security, conserving soil resources, enhancing climate resilience, and increasing farmers' livelihoods. Overall, the compilation facilitates knowledge dissemination, supports evidence-based planning, promotes interdisciplinary research, and encourages the adoption of scientifically validated technologies for integrated watershed development and sustainable agricultural resource management.

Research Highlights

Field: Watershed Hydrology & Conservation Measures

1. Graded Filter Strips and Sediment Connectivity

Isotopic sediment fingerprinting of vegetative filter strips integrating deep-rooted perennial grasses into contour risers showed a reduction in surface runoff coefficient from 0.45 to 0.18 under high-intensity rainfall. Sediment connectivity to downslope water bodies declined by 42%, effectively preventing sheet wash from transitioning into ephemeral rill networks in mountainous agricultural catchments. *Water Resources Management*, Vol. 40, Issue 5, pp. 1124–1141, 2026 (Springer).

2. Revised Curve Number Framework for Forest Catchments

Re-evaluation of SCS-CN methodology in forested watersheds revealed that the standard pond and swamp adjustment factor ($F_p = 0.72$) overestimates peak discharge by up to 28%. A modified Sahu-Mishra-Eldo (SME_m) framework with a revised local abstraction coefficient (λ) was validated, offering watershed engineers a precise tool to prevent over-design of flood-attenuation structures. *Journal of Hydrology*, Vol. 642, Part A, 126840, 2026 (Elsevier).

3. Multi-Tier Check Dams and Alluvial Aquifer Recharge

A cascade arrangement of bamboo-reinforced vegetative check dams in semi-arid micro-catchments limited peak discharge routing by 34%. Extended water-sediment contact duration yielded a 22% net increase in shallow alluvial aquifer recharge over a five-year monitoring sequence, presenting a scalable model for decentralized water security. *Land Degradation and Development*, Vol. 37, Issue 6, pp. 845–859, 2026 (Wiley).

4. ML-Driven LULC Classification for Arid Flood Risk Modelling

GIS-driven machine learning paired with high-resolution satellite imagery demonstrated that input resolution and classifier selection significantly skew peak discharge estimations in data-scarce arid watersheds. A standardized high-resolution workflow was established to optimize placement and capacity of cloudburst-containment basins. *Journal of Soil and Water Conservation*, Vol. 81, Issue 3, pp. 301–315, 2026 (Taylor & Francis).

5. Streamflow Regimes Under Intensive Silviculture

Scenario-based hydrological modelling of commercial silviculture and urbanization impacts showed that native forest catchments maintained minimum seasonal streamflows up to 33% higher than altered basins. The study quantifies trade-offs between monoculture tree plantations—which increase evapotranspiration losses—and native mixed-canopy zones, providing a framework for policy-level water resource planning. *Geological Magazine (Special Hydrological Series)*, Vol. 163, Issue 4, pp. 512–527, 2026 (Cambridge University Press).

6. Water Market Efficiency and Climate Risk Mitigation

An economic modelling study demonstrates that replacing rigid, proportional water-shortage rules with active, localized water trading structures yields significant net farm-income gains. The analysis outlines a policy architecture for decentralized water markets to hedge against climate-induced hydrological volatility. Ward, F.A. (2025). *Water Resources Management: An International Journal*, Vol.39,2025.

7. Socioeconomic Barriers to Conservation Adoption

A decadal multi-way fixed-effects analysis tracking Sustainable Land and Water Management (SLWM) deployment reveals a persistent structural paradox: despite accelerating topsoil erosion and water scarcity, smallholder adoption remains suppressed owing to steep upfront capital constraints and limited equipment access. IDEAS/RePEc (2025). Adoption of sustainable land and water management practices and their impact on crop productivity among smallholder farmers in sub-Saharan Africa.

8. Incentivizing Collective Soil Health Management

A study on institutional diffusion among rural farming cohorts demonstrates that community-led compensation systems and peer knowledge networks significantly reduce social friction, accelerating adoption of multi-tier soil microbiome restoration practices. Amoabeng-Nimako, S. et al. (2026). *Land Use Policy*, Vol. 161, 2026.

9. Positive Framing in Resource Conservation Behaviour

An empirical field study from Azerbaijan shows that shifting public communication from crisis-driven warning structures to positive, outcome-linked framing yields measurably higher long-term community compliance and

persistent water conservation behaviour. Mukhtarov, F., Garayev, V., & Landa Sotomayor, L. (2026). *Water International*, Vol. 51, pp. 183–206, 2026.

10. Topographic Performance Variations of Vegetative Measures

A biophysical field appraisal of integrated soil and water conservation (SWC) interventions across degraded hillside landscapes in Tigray, Ethiopia finds water-stable aggregates increased 28% on treated tracts, while performance varied significantly ($P < 0.001$) by slope position indicating that uniform subsidies must be replaced by landscape-targeted funding models. Desta, G. et al. (2025). *BMC Environmental Science*, Vol. 2, p. 24, 2025.

Field: Agronomy

1. Long-Term Carbon Sequestration in Organic vs. Conservation Agronomy Systems

A 15-year deep-profile study (to 100 cm) shows that while organic amendments boost topsoil carbon, conservation tillage combined with diverse cover crop rotations builds stable, recalcitrant carbon in deeper subsoil layers — offering a more resilient long-term sink. *Soil and Tillage Research (Elsevier)*, Vol. 259, pp. 103–115, 2026.

2. UAV Hyperspectral Imagery for Precision Nitrogen Management in Maize

A novel algorithm separates early-season nitrogen stress from moisture stress under field conditions. Variable-rate nitrogen applications guided by drone diagnostics reduced total nitrogen input by 15% without compromising grain fill or yield. *Field Crops Research (Elsevier)*, Vol. 321, pp. 74–88, 2026.

3. Seed-Applied Biostimulants and Root Architecture in Cereal Crops

Inoculation of cereals with beneficial bacterial consortia produced a 28% increase in lateral root branching and enhanced root hair density, significantly improving nutrient uptake efficiency in low-fertility soils. *Plant and Soil (Springer)*, Vol. 502, No. 1, pp. 142–159, 2026.

4. Weed-Crop Competition Dynamics under Shifting Microclimates in Conservation Agriculture

High-density planting geometries with narrow-row configurations accelerate canopy closure, suppressing aggressive weed cohorts and reducing herbicide dependence under warming microclimate conditions. *Agronomy Journal (Wiley)*, Vol. 118, No. 4, pp. 1112–1127, 2026.

5. Strip-Intercropping for Water-Use Efficiency in Arid Tracts

Spatial separation of deep-rooted pulse and cereal root systems in strip-intercrop layouts minimises underground water competition, yielding a 22% improvement in Land Equivalent Ratio (LER) under water-deficit conditions. *European Journal of Agronomy (Elsevier)*, Vol. 175, pp. 210–224, 2026.

Conclusion

The recent scientific literature demonstrates that sustainable watershed management and conservation agronomy are increasingly evolving toward integrated, technology-driven, and ecosystem-based approaches. The studies compiled in this section provide compelling evidence that combining engineering interventions with biological conservation measures, precision agriculture, advanced modelling techniques, and community participation substantially improves watershed performance, soil health, groundwater recharge, water-use efficiency, and agricultural sustainability. Emerging technologies such as machine learning, unmanned aerial vehicle (UAV)-based sensing, remote sensing, geospatial analysis, and process-based hydrological modelling are transforming the assessment and management of watersheds by enabling more accurate planning, monitoring, and decision-making. Simultaneously, conservation-oriented agronomic practices—including reduced tillage, cover cropping, biological soil amendments, precision nutrient management, and diversified cropping systems—are enhancing carbon sequestration, resource-use efficiency, and climate resilience while maintaining agricultural productivity.

The collective findings underscore the importance of adopting integrated watershed-based land management strategies that combine scientific innovation, ecological restoration, institutional support, and farmer participation. These advances provide a strong scientific foundation for future research, technology development, policy formulation, and field implementation aimed at achieving long-term water security, sustainable agricultural intensification, environmental conservation, and resilient farming systems in both rainfed and irrigated agro-ecosystems.

Acknowledgement and Suggestions

The authors express their sincere gratitude to Dr. R. K. Singh, Chief Editor, Indian Journal of Soil Conservation (IJSC), Dehradun, for his regular dissemination of scientific research updates through the daily research bulletin. The bulletin has served as a valuable source for identifying recent advances in different fields. The information presented in this compilation has been gathered from peer-reviewed scientific journals, technical reports, conference proceedings, seminar presentations, professional communications, and other authentic scientific sources available at the time of preparation. However, scientific knowledge, technologies, management practices, and policy recommendations continue to evolve with ongoing research and field validation. Readers are therefore strongly encouraged to consult the original research publications, institutional guidelines, and subject matter experts before adopting or implementing any specific technology, methodology, recommendation, or management practice for research, teaching, extension, policy formulation, or field applications. Wherever available, the original publications should be referred to for detailed methodology, experimental conditions, limitations, and interpretation of results.

The compiler has summarized published findings solely for educational, academic, and information dissemination purposes and does not claim ownership of the original research. Nevertheless, the compiler assumes no responsibility or liability for any consequences arising from the direct application or interpretation of the information presented without independent verification. This compilation is intended to serve as a knowledge resource, reference guide, and scientific information-sharing document that promotes continuous learning, professional development, interdisciplinary collaboration, and evidence-based decision-making. It is hoped that the compiled research highlights will stimulate further research, encourage technology refinement, and support the development of sustainable and climate-resilient land and water management practices for the benefit of agriculture, natural resource conservation, and society.



Seed Trait Variability in Bamboo Species



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Abstract

Bamboos, a highly productive and ecologically important group of grasses, play a crucial role in natural ecosystems and rural economies. Even though bamboo seeds play an essential role in economic and ecological sustainability, there is little information available regarding bamboo seed characters. This study aimed at characterizing the variation in seed traits of three commercially important bamboo species, *Bambusa tulda*, *Dendrocalamus longispathus*, and *Dendrocalamus latiflorus* collected from Assam and studied at ICFRE-IWST, Bengaluru. Parameters measured include moisture content of seeds, 1000-seed weight, seed length and width, and purity of seeds. Results indicate distinct interspecific variations in these parameters, where *Bambusa tulda* had maximum moisture content and maximum seed length; *D. latiflorus* had maximum seed weight, width, and purity; whereas *D. longispathus* had minimum length, width, and purity of seeds. These results are very useful in studying bamboo seed morphology and quality variations which will be helpful in seed preservation and seedling production.

1. Introduction

Bamboo, an ecologically important and fast-growing genus of woody grasses belonging to the family Poaceae and subfamily Bambusoideae, plays a key part in natural ecosystems and rural economies in tropical and subtropical habitats (Ahmad et al., 2025; Akinlabi et al., 2017). Bamboos are referred to as the "green gold" in forestry because of their fast growth rate and high biomass yield, as well as different practical applications (Solomon et al., 2020). These plants are used in construction, manufacturing of furniture and paper, for crafting purposes, and even as a food resource (Phimmachanh et al., 2015). While scientifically studied for long periods of time, their reproduction, particularly the study of bamboo seeds and propagation, is underrepresented in scientific literature (Dutta et al., 2025; Singh et al., 2013). However, there are some specific difficulties related to the cultivation and conservation of bamboo species, such as their sporadic flowering pattern occurring only once in several decades in case of many species (Selvan, 2018). As a result, massive death of bamboo culms occurs after their reproductive phase (Franklin and Bowman, 2003; van der Hoek et al., 2019). Seed morphology, quality, and variability are thus important in devising suitable strategies for propagation, processing, and storage of seeds for conservation (Sun et al., 2023). The quality of the seed is reflected through its moisture content, shape (length and width), weight, and purity (Yang et al., 2021; Ndung'u, 2018; Kameswara et al., 2017). Variation in seed traits may be as a consequence of genetic variation, environment, or processing after harvest (Kiran Babu and Rampal, 2024). Evaluation of seed traits is very important for selection of superior bamboo varieties for plantation and ex-situ conservation (Kundu et al., 2025). This research paper deals with the variability in seed traits of three commercially and ecologically significant bamboo species namely *Bambusa tulda*, *Dendrocalamus longispathus*, and *Dendrocalamus latiflorus*. *Bambusa tulda* is used due to the long strong culms that are useful for construction purposes (Kumar et al., (2022), *D. longispathus* due to straight culms that are useful for agroforestry (Banik, R.L. (2015) and *D. latiflorus*, the clumping giant bamboo due to vigorous growth, making of furniture, and consumption of shoots (Mulatu et al, 2016). This research uses an analysis of moisture content, 1000-seed weight, seed length and width, and seed purity to get an insight into the diversity in seed morphology and quality characteristics. The results will help in seed storage, seedling production, and the understanding of reproductive biology of bamboo species. An evaluation of both intraspecific and interspecific variation in the seed

characteristics may also be helpful in genetic improvement of these species by the identification of desired traits. In conclusion, this study helps fill the gaps in knowledge regarding seeds of bamboo by comparing seed trait variation in three species.

2. Materials and Methods

2.1. Site and Seed source

The current study was carried out in June 2024 at the ICFRE-Institute of Wood Science and Technology (IWST), Bengaluru in the tropical region of South India. The study region has a humid tropical climate, with annual rainfall varying between 550 to 2000 mm. The average maximum temperature is 33.0 °C, and the average minimum temperature is 21.0 °C. The seeds of three species of bamboos belonging to two different genera *Bambusa tulda*, *Dendrocalamus longispatus*, and *Dendrocalamus latiflorus* were used in the study. These seeds were collected from Assam State by the Bamboo Society of India.

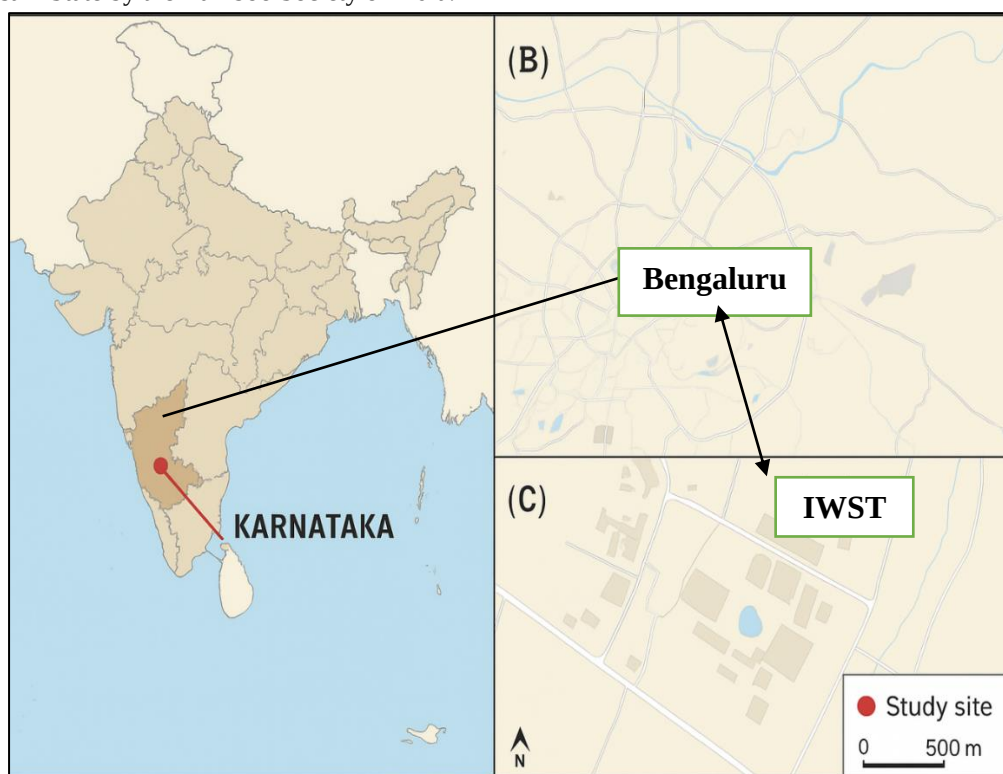


Fig. 1. Study Area Representation of ICFRE-IWST, Bengaluru

2.2. Procedure of experiment

For determining the traits of seeds, 5 replications were made for each trait:

For moisture content, 50 seeds were used in each replication FAO (1985).

For 1000-seeds weight, 5 replications were made FAO (1985).

For seed length and width, 10 seeds were used in each replication Mamo et al. (2006).

For seed purity, 35 grams of seeds were used in each replication FAO (1985).

Moisture Content (%)

The moisture content was analyzed by using the oven-drying method. The freshly weighted seeds were put in a hot air oven for 24 hours at 105°C. After that, the dried seeds were weighed and the moisture content was calculated by the formula:

$$\text{Moisture content (\%)} = \frac{\text{Fresh weight} - \text{Dry weight}}{\text{Dry weight}} \times 100$$

1000-Seed Weight

Random samples of 1000 seeds for each replicate were hand-counted and then weighed using an accurate balance. The mean and standard deviations were derived from five replicates.

Seed Length and Width

From each replicate, ten seeds were hand-picked and measured for their length and width using a digital Vernier calliper accurate to 0.01 mm.

Seed Purity (%)

Purity was evaluated by cleaning 35 g of seed sample from each replicate free of inert and non-seed material. The clean seed portion was weighed, and purity percentage was determined using the following equation:

$$\text{Seed purity (\%)} = \frac{\text{Weight of pure seeds}}{\text{Total weight of sample}} \times 100$$

Statistical analysis

The obtained information from the research was subjected to descriptive statistics to derive the mean and standard deviation for each trait. The statistical analysis was carried out using Microsoft Excel software. This helped in providing more insight into interspecies differences in seed characteristics.

Results and Discussion

Moisture Content

The moisture content in seeds is an important determinant of their storability and viability (Roberts, 1972). Out of the three bamboo species used, the *Bambusa tulda* was found to have the highest moisture content of $15.59 \pm 0.47\%$ meaning that its seeds may be vulnerable to deterioration due to higher levels of moisture. On the other hand, the *Dendrocalamus latiflorus* had the lowest moisture content of $9.94 \pm 0.62\%$ making it the best for storing since it is less prone to attacks by fungi and microbes. Moisture content of *Dendrocalamus longispatus* was determined to be $13.16 \pm 2.92\%$, which had a relatively high standard deviation. Mean viability period with the decreasing temperature and moisture content (similar to orthodox seeds (Rawat and Thapliyal, 2003), we have observed low to moderate moisture content in the studied bamboo species.

1000 Seed weight

One thousand seed weight plays a significant role as far as seed size, density, and nutrient reserves are concerned. *Dendrocalamus latiflorus* was found to have the maximum value of one thousand seed weight i.e., 152.0 ± 1.19 g owing to bigger and denser seeds. On the other hand, *Bambusa tulda* had the second highest one thousand seed weight value of 90.34 ± 2.91 g. However, *Dendrocalamus longispatus* showed the lowest value of 1000 d seed weight i.e., 4.61 ± 0.17 g, thus having smaller and lighter seeds than others.

Seed length

Seed length is a highly important morphological characteristic that can have an effect on germination and seedling development. The seeds of *Bambusa tulda* were the largest of all three bamboo species, being 26.69 ± 1.99 mm long and agreeing well with their higher 1000 seed weight. *Dendrocalamus latiflorus* had 15.06 ± 1.40 mm long seeds that belong to a medium-sized seed category. At the same time, *Dendrocalamus longispatus* had very short seeds of 4.53 ± 0.32 mm in length. This fact once again supports its status of a plant with the shortest seeds among all species considered.

Seed Width

Seed width works with seed length to determine the general shape, volume, and surface area-to-volume ratio of the seed. The widest seed was from *Dendrocalamus latiflorus*, having a width of 5.49 ± 0.45 mm, and this suggests that it is a sturdier or perhaps broad and oval seed. *Bambusa tulda* has a fairly wide seed at 3.54 ± 0.24 mm, while *Dendrocalamus longispatus* has the narrowest seed at 1.94 ± 0.26 mm.

Purity of Seeds

Purity of the seed is an important quality factor that gives the percentage of pure seeds in a given sample without any inert material, debris, or other impurities. The highest purity of seeds among the three tested species was found in *Dendrocalamus latiflorus* ($98.64 \pm 1.04\%$), which shows that it has a very pure and consistent seed population ideal for multiplication purposes on a commercial scale. Another good example of seed purity was shown by *Bambusa tulda* ($90.16 \pm 2.04\%$), which indicates efficient seed collection and processing. Conversely, *Dendrocalamus longispatus* had the lowest seed purity of $71.90 \pm 4.86\%$. This might be due to the problem in seed collection and cleaning. There is no similar information about the seed purity of the above-mentioned species

in the literature. The seed purity of *Arundinaria alpina* and *Oxytenanthera abyssinica* was reported to be 86% and 91%, respectively (Bahru et al., 2015).

Table 1: Seed Characteristics of three Bamboo Species (Mean $\pm$ SD)

Parameters	<i>Bambusa tulda</i>	<i>Dendrocalamus longispathus</i>	<i>Dendrocalamus latiflorus</i>
Moisture content	15.59 $\pm$ 0.47	13.16 $\pm$ 2.92	9.94 $\pm$ 0.62
1000 seed weight (g)	90.34 $\pm$ 2.91	4.61 $\pm$ 0.17	152.0 $\pm$ 1.19
Seed length (mm)	26.69 $\pm$ 1.99	4.53 $\pm$ 0.32	15.06 $\pm$ 1.40
Seed width (mm)	3.54 $\pm$ 0.24	1.94 $\pm$ 0.26	5.49 $\pm$ 0.45
Seed purity (%)	90.16 $\pm$ 2.04	71.90 $\pm$ 4.86	98.64 $\pm$ 1.04

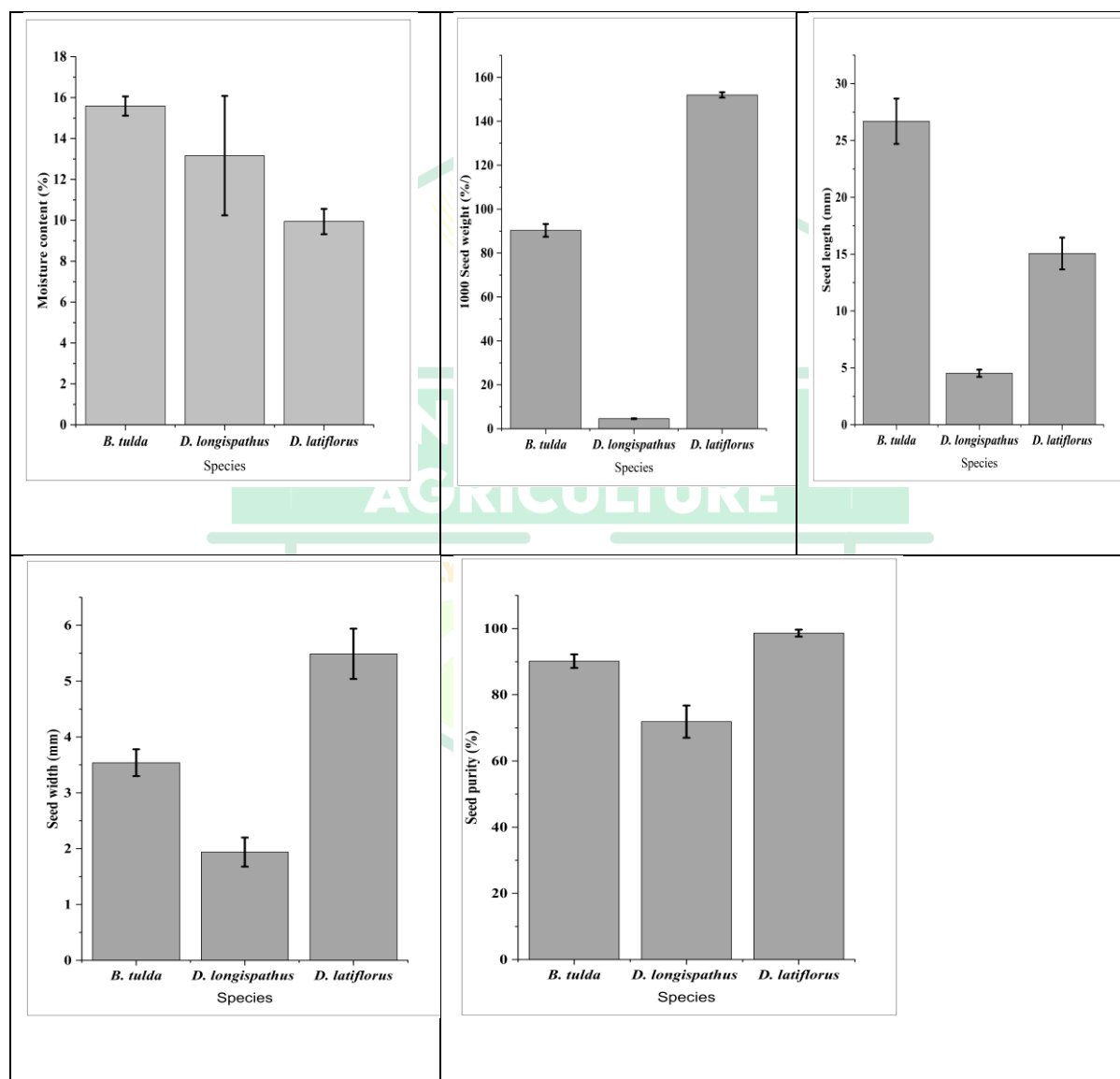


Fig. 2. Seed Trait Differences Across Three Economically Important Bamboo Species

Conclusion

The present investigation showed that there is high variation in seed characteristics among the three species of bamboo studied here. This shows great differences between them regarding their morphological and quality features. *Bambusa tulda* possessed the highest moisture content and length of seeds, which means that their seeds

have larger sizes but they require careful storage because of their moisture level. *Dendrocalamus latiflorus* proved itself to be the best among all others because of having the highest value of 1000-seed weight, the widest seeds, and the greatest purity of seeds, thus, being a good choice for propagation and storage. Finally, *Dendrocalamus longispatus* was the one possessing small seed sizes, low seed weight, and low purity of seeds.

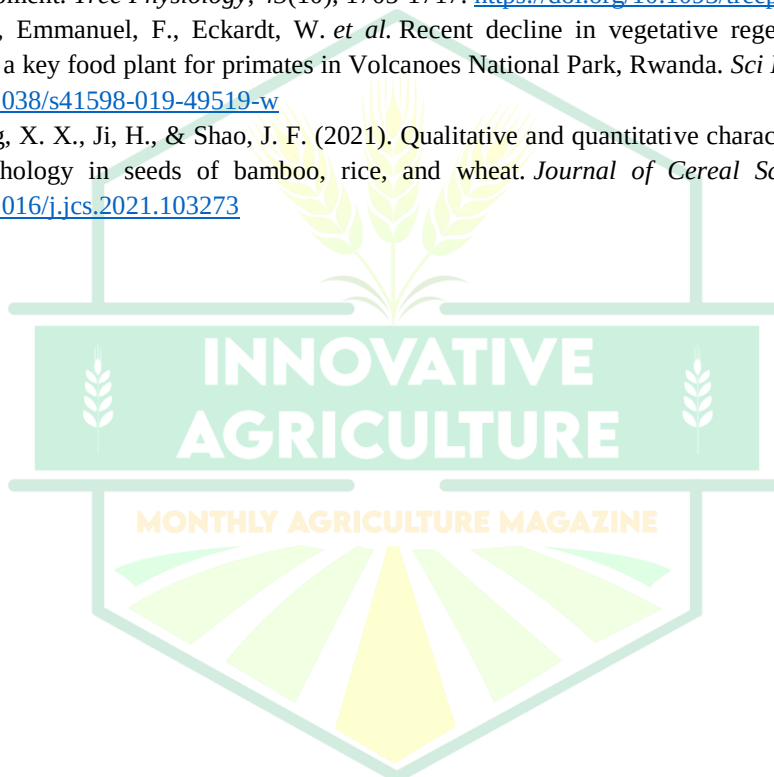
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THE FUTURE OF AGRICULTURAL EXTENSION IN THE AI ERA: TRANSFORMING KNOWLEDGE DELIVERY FOR SUSTAINABLE AGRICULTURE



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Abstract

Agricultural extension has long served as the bridge between scientific research and farming communities by facilitating the transfer of technologies, innovations, and best management practices. However, rapid advances in Artificial Intelligence (AI), digital agriculture, the Internet of Things (IoT), remote sensing, drones, and big data analytics are fundamentally reshaping agricultural advisory services. Rather than replacing extension professionals, AI is enabling more precise, timely, multilingual, and location-specific recommendations that improve farm decision-making. Recent initiatives by the Government of India and international organizations demonstrate a shift from conventional technology transfer models toward intelligent, farmer-centric digital advisory systems. AI-powered chatbots, predictive analytics, satellite-based crop monitoring, pest surveillance, and decision-support systems are enhancing productivity while promoting climate resilience and sustainable resource management. Despite these opportunities, challenges such as digital illiteracy, data privacy, infrastructure gaps, algorithmic bias, affordability, and the need for capacity building remain significant. This review examines the evolving role of agricultural extension in the AI era, highlights emerging technologies and policy initiatives, discusses opportunities and challenges, and outlines a future roadmap for AI-enabled extension systems that are inclusive, ethical, and sustainable.

Keywords: Agricultural Extension, Artificial Intelligence, Digital Agriculture, Precision Farming, Agricultural Advisory Services, Smart Farming, Climate-Smart Agriculture, Digital Extension.

Introduction

Agriculture remains the backbone of rural livelihoods and food security, particularly in developing countries such as India (FAO, 2023a). However, the agricultural sector faces numerous challenges, including climate change, shrinking landholdings, soil degradation, pest outbreaks, market volatility, labour shortages, and increasing production costs. These challenges demand timely, accurate, and location-specific information to support farmers' decision-making (World Bank, 2023c).

Traditionally, agricultural extension has relied on face-to-face interactions, demonstrations, farmer meetings, field visits, and printed advisory materials. While these methods have played a crucial role in agricultural development, they often struggle to meet the growing demand for rapid and personalized advisory services.

The emergence of Artificial Intelligence (AI) marks a transformative phase in agricultural extension. AI integrates machine learning, natural language processing, computer vision, remote sensing, and predictive analytics to deliver real-time, data-driven recommendations tailored to individual farmers' needs. AI-powered systems can analyse weather forecasts, soil characteristics, pest dynamics, crop health, and market information simultaneously, enabling more informed farm management decisions.

In India, digital agriculture is increasingly supported through initiatives such as the Digital Agriculture Mission, AgriStack, AI-enabled advisory platforms, and multilingual digital services designed to improve

farmers' access to scientific knowledge. These developments signify a shift from one-way technology dissemination to interactive, evidence-based, and farmer-centric extension systems (Ministry of Agriculture & Farmers Welfare, 2022b).

Evolution of Agricultural Extension

Agricultural extension has evolved significantly over the past century in response to changing agricultural systems, technological advancements, and the diverse needs of farming communities. Initially, extension focused on the linear transfer of technologies from research institutions to farmers through personal communication methods such as farm visits, demonstrations, training programmes, and meetings. Extension personnel acted as intermediaries, facilitating the adoption of improved agricultural practices. In India, extension services expanded after Independence through programmes like the Community Development Programme (1952) and National Extension Service (1953), and later played a crucial role during the Green Revolution by promoting high-yielding varieties, fertilizers, irrigation, and plant protection measures. The Training and Visit (T&V) system further strengthened extension delivery, although it faced criticism for its top-down approach and limited farmer participation.

Over time, extension systems shifted toward participatory and demand-driven approaches that emphasized farmer involvement, capacity building, and decentralized planning. Initiatives such as the Agricultural Technology Management Agency (ATMA) promoted collaboration among stakeholders, including research institutions, government agencies, and the private sector. A major transformation occurred with the rapid expansion of Information and Communication Technologies (ICTs), where tools like mobile phones, internet platforms, and digital advisory services enabled wider and faster dissemination of agricultural information (Trendov et al., 2019). These technologies improved communication efficiency, reduced geographical barriers, and provided farmers with timely updates on weather, crop management, market prices, and government schemes. In recent years, agricultural extension has entered a new phase driven by advanced technologies such as Artificial Intelligence (AI), the Internet of Things (IoT), remote sensing, drones, GIS, and big data analytics. These innovations enable real-time crop monitoring, predictive analysis, precision farming, and personalized advisory services. As a result, the role of extension professionals has also evolved from technology transfer agents to facilitators, knowledge managers, and digital advisors. The extension system has transitioned into a farmer-centred, technology-enabled knowledge network that integrates human expertise with digital tools. This evolution highlights the shift toward more inclusive, efficient, and sustainable agricultural extension systems capable of addressing the complexities of modern agriculture.

Why Artificial Intelligence is Transforming Agricultural Extension Services

Artificial Intelligence (AI) is transforming agricultural extension services by addressing the limitations of traditional systems, which often struggle to provide timely, personalized, and location-specific advisory services. With increasing challenges such as climate change, pest and disease outbreaks, labour shortages, and market uncertainties, extension systems require more efficient and data-driven approaches. AI enhances the speed, accuracy, and accessibility of agricultural information, enabling more responsive and farmer-centric advisory services. By integrating data from satellites, weather stations, soil sensors, drones, and mobile applications, AI systems can generate real-time recommendations tailored to individual farm conditions, including crop selection, irrigation, fertilizer use, and pest management (IFPRI, 2022a).

AI also enables predictive analytics, allowing extension services to shift from reactive problem-solving to proactive decision-making. Machine learning algorithms analyse historical and real-time data to forecast weather events, pest infestations, and crop performance (World Bank, 2023c). These early warning systems help farmers take preventive measures, reducing risks and enhancing resilience to climate variability. In addition, AI-powered chatbots and virtual assistants provide instant advisory services in local languages, significantly improving accessibility, especially in remote areas where extension personnel are limited.

Furthermore, AI enhances the efficiency of extension professionals by automating routine tasks such as data collection, monitoring, and analysis, allowing them to focus more on farmer training and capacity building. Technologies like computer vision support rapid crop diagnostics, while AI-based systems also assist in market decision-making and promote climate-smart agriculture by optimizing resource use. However, the effective

adoption of AI depends on reliable digital infrastructure, data quality, affordability, and digital literacy, along with addressing ethical concerns such as data privacy and equitable access. Overall, AI is redefining agricultural extension into a data-driven, efficient, and farmer-centric system, contributing to improved productivity, livelihoods, and food security.

AI Technologies Used in Agricultural Extension

The integration of Artificial Intelligence (AI) into agricultural extension has transformed the way advisory services are delivered to farmers. AI technologies enable extension systems to provide timely, precise, and location-specific recommendations by analysing large volumes of agricultural data from multiple sources. Unlike conventional extension approaches that rely primarily on periodic field visits and general recommendations, AI-powered systems generate personalized solutions that improve farm productivity, resource-use efficiency, and climate resilience. The major AI technologies currently being used in agricultural extension are discussed below.

1. Machine Learning (ML)

Machine Learning is a branch of AI that enables computer systems to learn from historical and real-time data without being explicitly programmed (Wolfert et al., 2017). In agricultural extension, ML algorithms analyse weather patterns, soil characteristics, crop performance, pest incidence, and management practices to generate predictive recommendations. Extension agencies use machine learning to forecast crop yields, identify disease outbreaks, optimize fertilizer application, and assess production risks. These predictive capabilities allow farmers to make informed decisions before problems become severe.

2. Natural Language Processing (NLP)

Natural Language Processing enables computers to understand, interpret, and respond to human language. This technology has significantly improved communication between farmers and digital advisory systems. AI-powered chatbots and virtual assistants equipped with NLP can answer farmers' questions in regional languages, provide recommendations on crop management, explain government schemes, and offer weather-based advisories. By overcoming language barriers, NLP enhances the accessibility and inclusiveness of agricultural extension services.

3. Computer Vision

Computer vision enables AI systems to analyse digital images and videos for agricultural decision-making. Farmers can capture photographs of diseased plants, insect pests, nutrient deficiencies, or weed infestations using smartphones. AI algorithms compare these images with extensive databases to accurately diagnose problems and recommend suitable management practices. This technology supports early detection of crop disorders, reduces diagnostic errors, and facilitates timely interventions.

4. Remote Sensing and Satellite Imagery

Remote sensing technologies combined with AI provide continuous monitoring of agricultural fields over large geographical areas. Satellite images and aerial data are analysed to assess crop health, vegetation indices, soil moisture, drought stress, flood damage, and nutrient status. Extension professionals use these insights to provide field-specific recommendations and identify areas requiring immediate intervention. Remote sensing also strengthens disaster preparedness and climate-resilient agricultural planning.

5. Internet of Things (IoT) and Smart Sensors

The Internet of Things (IoT) connects agricultural equipment and field sensors to digital platforms that continuously collect real-time information on soil moisture, temperature, humidity, rainfall, and nutrient levels. AI processes these data to generate recommendations regarding irrigation scheduling, fertilizer application, greenhouse management, and crop protection. Smart sensors reduce unnecessary input use while improving productivity and environmental sustainability.

6. AI-Powered Decision Support Systems (DSS)

Decision Support Systems integrate data from multiple sources—including weather forecasts, soil analysis, market information, crop models, and pest surveillance—to assist farmers and extension professionals in making evidence-based decisions. These systems recommend appropriate crop varieties, sowing dates, irrigation schedules, nutrient management practices, and pest control measures according to local conditions. AI-driven DSS minimizes uncertainty and enhances farm planning.

7. Predictive Analytics

Predictive analytics employs AI algorithms to identify future agricultural trends based on historical and current data. Extension agencies use predictive models to forecast weather events, pest outbreaks, disease epidemics, market prices, and crop yields. Early warning systems generated through predictive analytics enable farmers to adopt preventive measures, thereby reducing production risks and improving resilience to climate variability.

8. Drones and Unmanned Aerial Vehicles (UAVs)

Although drones themselves are not AI, they become powerful extension tools when integrated with AI-based image analysis. Drones capture high-resolution images of crop fields, which AI algorithms analyse to detect pest infestations, nutrient deficiencies, water stress, and crop damage. Drone-based surveillance enables extension workers to monitor large areas quickly and provide precise recommendations for input application and crop management.

9. Robotics and Automation

AI-powered agricultural robots are increasingly being used for precision farming operations such as planting, weeding, harvesting, spraying, and crop monitoring. These technologies improve labour efficiency, reduce production costs, and enhance operational accuracy. Extension professionals play an important role in educating farmers about the adoption, operation, and maintenance of these advanced technologies.

10. Big Data Analytics

Modern agriculture generates vast amounts of data from research institutions, weather stations, satellites, sensors, farm machinery, mobile applications, and markets. AI-based big data analytics integrates and analyses these diverse datasets to identify patterns, predict agricultural trends, and support evidence-based extension recommendations. This enables extension organizations to develop more effective policies and targeted advisory services.

AI Technologies and the Changing Role of Extension Professionals

The adoption of AI technologies is transforming the responsibilities of extension professionals. Rather than serving solely as technology disseminators, extension personnel increasingly function as digital facilitators, innovation brokers, data interpreters, and capacity builders. They assist farmers in understanding AI-generated recommendations, encourage digital literacy, validate technological solutions under local conditions, and ensure that advanced technologies remain accessible to small and marginal farmers. Human expertise remains indispensable for interpreting local socio-economic conditions, building trust, and facilitating behavioural change among farming communities.

Challenges and Ethical Concerns in AI-Enabled Agricultural Extension

Despite the transformative potential of Artificial Intelligence (AI) in agricultural extension, several challenges and ethical concerns must be addressed to ensure its effective and inclusive implementation. One of the primary challenges is the digital divide, particularly in developing countries like India, where small and marginal farmers often lack access to smartphones, reliable internet connectivity, and digital infrastructure. Limited digital literacy further restricts farmers' ability to utilize AI-powered advisory services effectively.

Another critical issue is the availability and quality of agricultural data. AI systems rely heavily on large datasets for training and decision-making. However, in many regions, data related to soil health, crop patterns, pest incidence, and weather conditions are either incomplete, outdated, or inconsistent. Poor-quality data can lead to inaccurate recommendations, thereby affecting farmers' trust in AI systems.

Affordability and accessibility of AI technologies also pose significant constraints. Advanced tools such as drones, sensors, and precision agriculture systems require substantial investment, making them less accessible to resource-poor farmers. Without adequate subsidies or institutional support, the benefits of AI may remain concentrated among large-scale farmers.

From an ethical perspective, data privacy and ownership have emerged as major concerns. Farmers' data, including land records, crop patterns, and financial information, are increasingly being collected by digital platforms. Ensuring that this data is used responsibly, securely, and with farmers' consent is essential to prevent misuse or exploitation.

Additionally, algorithmic bias and lack of transparency in AI systems can affect decision-making. If AI models are trained on biased or region-specific datasets, they may not perform accurately across diverse agro-ecological conditions. The “black-box” nature of many AI algorithms makes it difficult for farmers and extension workers to understand how recommendations are generated.

The risk of over-reliance on technology is another concern. While AI can provide valuable insights, it cannot fully replace the contextual knowledge, experience, and socio-cultural understanding of extension professionals. Excessive dependence on automated systems may reduce farmers’ critical decision-making abilities. Furthermore, ethical concerns related to employment may arise, as automation could potentially reduce the demand for traditional extension roles. However, rather than eliminating jobs, AI is more likely to redefine the roles of extension personnel.

In conclusion, addressing these challenges requires a balanced approach that combines technological innovation with policy support, capacity building, ethical governance, and inclusive digital development.

Government Initiatives in Digital Agriculture

The Government of India has undertaken several initiatives to promote digital agriculture and integrate advanced technologies, including AI, into extension services. These initiatives aim to enhance farmers’ access to timely, accurate, and location-specific information while improving agricultural productivity and sustainability.

One of the key initiatives is the Digital Agriculture Mission (2021–2025), which focuses on promoting the use of AI, machine learning, blockchain, remote sensing, and GIS technologies in agriculture (Ministry of Agriculture & Farmers Welfare, 2022b). The mission supports the development of digital platforms that provide real-time advisory services to farmers.

The AgriStack initiative aims to create a unified digital ecosystem by integrating farmers’ data, land records, crop information, and service delivery systems (Government of India, 2023b). This platform facilitates targeted delivery of subsidies, crop advisories, insurance services, and credit facilities.

The National e-Governance Plan in Agriculture (NeGPA) has played a significant role in digitizing agricultural services by supporting mobile-based applications, farmer portals, and online advisory platforms. These tools provide information on weather forecasts, pest management, input use, and government schemes.

Mobile-based platforms such as Kisan Suvidha, mKisan portal, and AI-enabled advisory services are increasingly being used to disseminate information in regional languages, thereby improving accessibility for farmers.

In addition, initiatives such as the Pradhan Mantri Fasal Bima Yojana (PMFBY) are integrating satellite imagery, drones, and AI-based analytics for crop monitoring and faster insurance claim settlement. Similarly, digital soil health cards provide farmers with precise recommendations on nutrient management.

At the state level, governments, including Gujarat, are promoting precision farming, micro-irrigation, drone usage, and digital extension services through subsidies and training programmes. Collaboration with private agri-tech companies and research institutions is further accelerating the adoption of AI technologies in agriculture.

Overall, these initiatives reflect a strategic shift toward data-driven, technology-enabled agricultural extension systems that aim to improve farmers’ livelihoods and ensure sustainable agricultural development.

Future Roadmap for AI-Enabled Extension Services

The future of agricultural extension lies in the effective integration of AI technologies with human expertise to create a more responsive, inclusive, and sustainable advisory system. A key priority is the development of farmer-centric AI platforms that provide personalized recommendations based on local agro-climatic conditions, cropping patterns, and socio-economic factors.

Strengthening digital infrastructure in rural areas is essential to ensure equitable access to AI-based services. This includes expanding internet connectivity, promoting affordable smartphones, and establishing digital service centers (World Bank, 2023c).

Enhancing digital literacy and capacity building among farmers and extension professionals is equally important. Training programmes should focus on improving farmers’ ability to use mobile applications, interpret AI-generated recommendations, and adopt modern technologies effectively.

The future extension system should emphasize human-AI collaboration, where extension workers act as facilitators and interpreters of AI-driven insights. Their role in building trust, validating recommendations, and addressing socio-cultural barriers will remain crucial.

Another important aspect is the development of ethical and regulatory frameworks to ensure data privacy, transparency, accountability, and equitable access to digital technologies. Policies should safeguard farmers' interests and promote responsible use of AI.

Promoting public-private partnerships can accelerate innovation and technology dissemination. Collaboration among government agencies, research institutions, agri-tech startups, and farmer organizations can help scale AI-based solutions effectively.

The integration of AI with climate-smart agriculture will also be a key focus area. AI-driven systems can support climate adaptation strategies, optimize resource use, and enhance resilience to environmental stresses.

Finally, the future roadmap should prioritize inclusive development, ensuring that small and marginal farmers, women farmers, and remote communities benefit from AI-enabled extension services.

Conclusion

Artificial Intelligence is ushering in a new era in agricultural extension by transforming traditional advisory systems into intelligent, data-driven, and farmer-centric platforms. By enabling real-time, location-specific, and personalized recommendations, AI has the potential to enhance agricultural productivity, improve resource-use efficiency, and strengthen climate resilience.

However, the successful integration of AI in agricultural extension depends on addressing key challenges such as digital inequality, data quality, affordability, and ethical concerns. Human expertise will continue to play a vital role in interpreting AI outputs, building trust among farmers, and ensuring the effective adoption of technologies.

The future of agricultural extension lies not in replacing human extension workers but in augmenting their capabilities through AI-powered tools. A balanced approach that combines technological innovation with inclusive policies, capacity building, and ethical governance will be essential to harness the full potential of AI in agriculture.

Thus, AI-enabled extension systems can significantly contribute to sustainable agricultural development, improved farmer livelihoods, and national food security in the years to come.

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Exploring Plant-Derived Bioactives in Animal Health: From Molecular Mechanisms to Livestock Applications



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Abstract

Plant-derived bioactive compounds have gained considerable attention as natural alternatives to conventional antibiotics and synthetic growth promoters in veterinary medicine. Their antioxidant, antimicrobial, anti-inflammatory, immunomodulatory, and metabolic regulatory properties make them valuable functional ingredients for improving animal health, productivity, and welfare. This review summarizes the current evidence regarding the mechanisms of action, veterinary applications, and production benefits of major plant bioactive compounds, including polyphenols, flavonoids, terpenoids, phenolic acids, and essential oil constituents. These compounds regulate oxidative stress, inflammatory pathways, immune responses, and gut microbial balance, thereby enhancing disease resistance, feed efficiency, reproductive performance, and overall livestock productivity. Representative compounds such as quercetin, resveratrol, curcumin, thymol, carvacrol, and rosmarinic acid have demonstrated promising effects across monogastrics, ruminants, and aquaculture. Despite their significant potential, challenges including poor bioavailability, variability in phytochemical composition, lack of standardized extraction methods, and inconsistent dosage recommendations limit their widespread application. Future research should focus on advanced formulation technologies, standardized quality control, large-scale *in vivo* veterinary studies, and the integration of omics technologies and artificial intelligence to accelerate the development of effective phytogetic feed additives and veterinary therapeutics.

Keywords: Veterinary medicine, Animal health, Livestock production, Phytogetic feed additives, Antioxidants.

1. Introduction

The livestock industry is increasingly seeking sustainable alternatives to antibiotic growth promoters following global concerns regarding antimicrobial resistance (AMR). The extensive use of antibiotics in food-producing animals has contributed to the emergence of resistant microorganisms, posing severe challenges to animal production and public healthcare within a broader One Health framework. Consequently, plant-derived bioactive compounds have emerged as promising natural feed additives capable of improving animal health, supporting welfare, and lowering environmental impacts while reducing dependence on conventional antimicrobials.

Plants produce a wide range of secondary metabolites, including polyphenols, flavonoids, terpenoids, alkaloids, and phenolic acids, which possess diverse biological activities. These compounds exhibit antioxidant, antimicrobial, anti-inflammatory, immunomodulatory, and metabolic regulatory effects that contribute to improved health and productivity in livestock species. Their multifunctional properties enable them to regulate several physiological pathways simultaneously, making them attractive candidates for sustainable veterinary applications and resource-efficient animal nutrition interventions.

2. Plant-Derived Bioactive Compounds

Plant-derived bioactive compounds are naturally occurring molecules defined by their ability to interact with living systems and trigger biological or pharmacological responses, whether synthesized by plants, microorganisms, or marine species, or produced synthetically. In plants, these secondary metabolites are biosynthesized as natural defence mechanisms against environmental stress, pathogens, and herbivores. Based on their biological roles, these molecules are broadly categorized into primary, secondary, and tertiary metabolites:

- Primary Metabolites (PMs): Indispensable for basic biological survival, cellular structure, growth, development, and reproduction. They include carbohydrates, lipids, proteins, nucleic acids, and key

growth-regulating hormones (e.g., auxins and gibberellins) essential for processes like photosynthesis and respiration.

- **Secondary Metabolites (SMs):** Biosynthesized through integrated metabolic pathways responsive to environmental stimuli. While not directly required for primary growth, SMs confer crucial ecological advantages such as pathogen defence and stress adaptation. Major classes include phenolics, flavonoids, alkaloids, terpenoids, tannins, carotenoids, glycosides, and essential oils.
- **Tertiary Metabolites (TMs):** Structural modifications or combinations of PMs and SMs with lipids, sugars, or proteins. They regulate metabolic balance and support specialized processes like seed development, embryogenesis, and long-term stress adaptation.

The plant kingdom is an extraordinary source of complex natural compounds, producing over 200,000 distinct metabolites—including carotenoids, vitamins, dietary fiber, biogenic amines, bioactive peptides, and polyphenols. Compared to synthetic molecules, plant-derived products possess superior structural diversity, higher molecular rigidity, and multiple chiral centers that contribute to enhanced biological selectivity and pharmacokinetic performance. As a result, plant natural products serve as the foundation for nearly 25% of modern pharmaceuticals and over 60% of anticancer and antimicrobial agents. Despite this immense potential, only about 15% of plant species have been phytochemically characterized, and a mere 6% pharmacologically evaluated. Furthermore, large-scale industrial exploitation is constrained by yield limitations, ecological dependencies, and high research costs, highlighting the need for metabolic engineering and biotechnological innovations. Additionally, agro-industrial residues (such as fruit pomaces, cereal bran, and oilseed cakes) represent valuable, low-cost sources of these bioactive compounds, aligning animal nutrition with circular economy schemes.

Subclasses of Polyphenols

Polyphenols represent one of the most extensively investigated groups of secondary metabolites due to their broad structural diversity, potent antioxidant capacity, and anti-inflammatory activities. They are categorized into four major subclasses:

1. **Flavonoids:** The most abundant and widely studied polyphenol subclass, found throughout fruits, vegetables, and aromatic or medicinal plants. They possess significant nutritional, therapeutic, and antioxidant properties with broad utility across food, pharmaceutical, and livestock industries.
2. **Phenolic Acids:** Abundant in whole grains, coffee, and functional plant ingredients, phenolic acids act as powerful reducing agents, hydrogen donors, and singlet oxygen quenchers. They exert strong antioxidant, anti-inflammatory, and metabolic regulatory effects.
3. **Lignans:** Documented in seeds, grains, and fruits, lignans exhibit a range of biological activities including antimicrobial, anti-aging, hepatoprotective, and cardioprotective effects.
4. **Stilbenes:** Compounds like resveratrol function naturally in plants as stress-induced phytoalexins. They exhibit broad-spectrum biological actions, including potent antimicrobial, anti-inflammatory, antioxidant, and cardiovascular protective activities.

Essential oil constituents, such as thymol, carvacrol, and eugenol, also play a crucial role alongside polyphenols due to their strong antimicrobial effects against major veterinary pathogens.

3. Mechanisms of Action

Plant bioactive compounds exert their biological effects through multiple molecular pathways rather than a single target. They regulate oxidative stress by scavenging reactive oxygen species (ROS) and activating endogenous antioxidant enzymes through the Nrf2 signaling pathway. Simultaneously, they suppress inflammatory mediators by inhibiting NF- κ B and MAPK pathways, thereby reducing the production of pro-inflammatory cytokines and protecting tissues such as intestinal epithelial cells and bovine mammary cells from oxidative damage.

Many phytochemicals also improve mitochondrial function and cellular metabolism by activating AMPK and SIRT1 pathways. Furthermore, plant bioactive compounds regulate gut microbial homeostasis by promoting beneficial bacteria such as *Lactobacillus* and *Bifidobacterium* while inhibiting pathogenic microorganisms including *Escherichia coli*, *Salmonella*, *Turicibacter*, and *Clostridium perfringens*. These combined cellular and microbial effects preserve intestinal barrier function, increase villus height to crypt depth ratios, upregulate tight

junction proteins, and enhance digestive enzyme activity, leading to optimized nutrient utilization and host disease resistance.

4. Applications in Veterinary Medicine and Animal Production

4.1 Alternatives to Antibiotic Growth Promoters

The prohibition and restricted use of antibiotic growth promoters in many countries have increased the demand for phytogetic feed additives. Numerous studies demonstrate that plant-derived bioactive compounds improve growth performance, feed conversion efficiency, intestinal health, and immune responses while reducing bacterial infections across poultry, swine, ruminants, and fish. Unlike antibiotics, phytochemicals do not indiscriminately eliminate microorganisms; instead, they regulate microbial ecology, suppress pathogen colonization, and preserve beneficial gut microbiota, which lowers the risk of antimicrobial resistance.

4.2 Improvement of Gut Health

The gastrointestinal tract is the primary site where phytogetic compounds exert beneficial effects. Supplementation with plant extracts improves intestinal morphology, reinforces mucosal barrier integrity, and stimulates endogenous digestive enzyme activity. By modulating gut microbiota and elevating short-chain fatty acid (SCFA) production, these compounds prevent gut imbalances, reduce post-weaning diarrhea, and promote efficient nutrient absorption, directly improving growth performance.

4.3 Enhancement of Immune Function

Plant bioactive compounds regulate both innate and adaptive immune responses by suppressing excessive inflammatory cytokines while boosting systemic antioxidant defenses. They stimulate immunoglobulins (such as IgM and IgG) and enhance immune organ development, thereby increasing resistance against bacterial, viral, and parasitic infections while decreasing overall morbidity and mortality in production animals.

4.4 Improvement of Productivity and Product Quality

Dietary supplementation with plant bioactive compounds drives measurable improvements in average daily gain, feed conversion ratios (FCR), carcass quality, milk yield, and egg production. In laying hens, botanical extracts and tea-derived bioactives improve laying performance, egg yolk color, and lipid metabolism. In dairy animals, plant extracts help manage clinical mastitis, lower somatic cell counts, and increase milk production without leaving chemical residues. Furthermore, plant polyphenols improve meat quality by enhancing fatty acid profiles (increasing *n*-3 PUFAs), reducing lipid oxidation, and improving meat color stability.

4.5 Reproductive Health and Perinatal Support

Plant bioactives and botanical complexes offer critical support during demanding reproductive windows, including late gestation, lactation, and embryonic development. Supplementation reduces gestational oxidative stress, enhances placental vascularization, and improves nutrient transport efficiency. These outcomes translate to higher live birth rates, reduced rates of stillbirths and intrauterine growth restriction (IUGR), increased litter sizes at weaning, and improved milk quality, which ultimately enhances post-weaning growth and resilience in offspring.

4.6 Stress Mitigation and Animal Welfare

Management-related stressors- such as high ambient temperatures, overcrowding, weaning, and transportation- trigger cellular oxidative stress and immune suppression. Compound herbal extracts and plant antioxidants mitigate transport- and heat-induced stress by reducing biomarkers like malondialdehyde (MDA) and cortisol while stabilizing physiological status. By protecting host tissues against oxidative damage and inflammation, plant bioactives support overall animal welfare and resilience.

4.7 Methane Mitigation and Environmental Sustainability

Specific plant bioactives, particularly condensed tannins, saponins, and essential oils, offer practical tools for lowering the environmental footprint of livestock. In ruminants, these compounds modulate rumen fermentation and suppress methanogenic microbial populations, leading to significant reductions in enteric methane emissions without compromising animal productivity. Additionally, plant-based diets can reduce urinary nitrogen excretion, contributing to broader environmental sustainability goals.

5. Important Plant Bioactive Compounds Used in Veterinary Medicine

- **Quercetin:** found in Red/Yellow Onions (*Allium cepa*), Moringa (*Moringa oleifera*), Guava leaves (*Psidium guajava*), Neem (*Azadirachta indica*), Buckwheat, and Capers.
Improves antioxidant status, gut health, immune function, meat quality, and growth performance while reducing intestinal pathogens.
- **Resveratrol:** Primary plant sources Indian Gooseberry / Amla (*Phyllanthus emblica* / *Embllica officinalis*), Jamun / Indian Blackberry seeds & skin (*Syzygium cumini*), Peanuts (*Arachis hypogaea*), and Black Grapes (*Vitis vinifera*).
Enhances intestinal integrity, antioxidant capacity, reproductive performance, meat quality, and disease resistance in pigs, poultry, and fish.
- **Curcumin:** Turmeric (*Curcuma longa*) and Mango Ginger (*Curcuma amada*).
Possesses strong antioxidant, anti-inflammatory, antimicrobial, and immunomodulatory properties, improving immunity, reducing oxidative stress, enhancing meat quality, and increasing resistance to enteric diseases.
- **Thymol:** Primarily found in Ajwain / Carom seeds (*Trachyspermum ammi*), Indian Thyme (*Thymus linearis*), and Wild Thyme.
Exhibits broad-spectrum antimicrobial activity, improves nutrient digestibility, enhances feed efficiency, and promotes beneficial intestinal bacteria.
- **Carvacrol:** Major plant sources are Indian Oregano / Mexican Mint (*Plectranthus amboinicus* / *Coleus aromaticus*), Wild Bergamot, ajwain (*Trachyspermum ammi*), and Thyme.
Reduces post-weaning diarrhea, suppresses enteric pathogens, improves feed conversion efficiency, and enhances overall animal performance.
- **Rosmarinic Acid:** found in Holy Basil / Tulsi (*Ocimum sanctum* / *Ocimum tenuiflorum*), Indian Mint / Pudina (*Mentha arvensis*), Rosemary (*Salvia rosmarinus*), and Sage (*Salvia officinalis*).
Enhances antioxidant defense, reduces inflammation, improves immune responses, and increases survival during infectious challenges in poultry and aquaculture species.
- **Baicalin & Macleaya cordata Extracts:**
Primary Plant Sources:
 - **Baicalin:** Indian Trumpet Flower / Shyonaka (*Oroxylum indicum*) and Chinese Skullcap (*Scutellaria baicalensis*).
 - **Macleaya cordata Extract:** Plume Poppy (*Macleaya cordata*), known for rich alkaloid extracts like sanguinarine.
Protect against mammary cell damage, reduce somatic cell counts, lower systemic inflammatory markers, and manage clinical mastitis in dairy cattle.

6. Challenges and Future Perspectives

Despite encouraging experimental findings, several limitations restrict the commercial application of plant-derived bioactive compounds. Variability in phytochemical composition due to plant species, cultivation practices, harvesting conditions, and extraction techniques leads to inconsistent biological activity. Furthermore, poor bioavailability, narrow optimal dosage windows, potential interactions among active ingredients, instability during feed processing, and limited long-term pharmacokinetic data reduce their practical effectiveness. High inclusion levels of certain bioactives or raw materials (such as microalgae) can also cause adverse physiological effects in monogastrics, emphasizing the need for precise species-specific formulations. Inconsistent global regulatory pathways further complicate product classification and market entry.

Future research should focus on developing standardized extraction procedures, nanoencapsulation delivery systems, precision dosing strategies, and species-specific formulations. Advanced multi-omics technologies (metagenomics, transcriptomics, metabolomics), artificial intelligence, and precision livestock farming can accelerate the discovery of response biomarkers and optimize bioactive delivery based on individual stress or health status. Comprehensive life-cycle assessments and large-scale *in vivo* veterinary studies are also required to

confirm safety, evaluate tissue carry-over, and prove economic feasibility before widespread adoption in commercial animal production.

7. Conclusion

Plant-derived bioactive compounds represent promising natural alternatives for improving animal health and productivity while reducing dependence on conventional antibiotics. Their antioxidant, antimicrobial, anti-inflammatory, immunomodulatory, and metabolic regulatory activities contribute to enhanced gut health, improved immune responses, better feed utilization, superior production performance, improved reproductive outcomes, and increased disease resistance across poultry, swine, ruminants, and aquaculture species. Although challenges related to standardization, bioavailability, dose optimization, and regulatory alignment remain, continued advances in phytochemistry, formulation technologies, and veterinary research are expected to facilitate their integration into modern livestock production. The adoption of phytogenic feed additives has the potential to improve animal welfare, support sustainable circular farming, reduce environmental emissions, and provide effective strategies for maintaining animal health in the post-antibiotic era.

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Artificial Intelligence and Digital Livestock Health in Animal Nutrition: Transforming Smart, Sustainable and Precision Animal Production



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Abstract

The livestock sector is undergoing a remarkable digital transformation driven by advances in artificial intelligence (AI), machine learning (ML), the internet of things (IoT), cloud computing, biosensors, robotics and big data analytics. These technologies are revolutionizing animal nutrition and health management by enabling precision feeding, early disease detection, real-time monitoring and evidence-based decision-making. Conventional livestock production relies on generalized feeding and health management practices, which often fail to account for individual animal variability in genetics, physiological status, production level and environmental conditions. Artificial intelligence and digital livestock health systems overcome these limitations by continuously collecting and analyzing large volumes of data from wearable sensors, automated feeding systems, cameras, drones, thermal imaging devices and smart farm equipment. These data-driven approaches facilitate personalized nutrition, optimize feed efficiency, improve animal welfare, reduce production costs, minimize antimicrobial usage and lower the environmental footprint of livestock farming. AI-powered decision-support systems are increasingly capable of predicting disease outbreaks, detecting nutritional deficiencies, identifying reproductive disorders, monitoring behavioral changes and forecasting production performance before visible clinical signs appear. This article discusses the principles, technologies, applications, benefits, challenges and future prospects of AI and digital livestock health in animal nutrition, highlighting their potential to transform dairy, beef, buffalo, sheep, goat, pig and poultry production into sustainable, climate-smart and profitable enterprises.

Keywords: Artificial intelligence, Biosensors, Digital livestock health, Machine learning, Precision livestock farming, Sustainable livestock production

Introduction

Livestock production plays a vital role in ensuring global food security by supplying milk, meat, eggs, wool and other animal-derived products. As the global population continues to increase and consumer demand for high-quality animal products rises, livestock producers face mounting challenges such as feed shortages, rising production costs, emerging diseases, climate change, antimicrobial resistance, and increasing public concern for animal welfare. These challenges require innovative technologies that can improve productivity while ensuring sustainability and environmental protection.

Traditionally, livestock feeding and health management have relied on visual observation, periodic veterinary examinations and uniform feeding practices. However, such conventional approaches often overlook individual animal differences in genetics, metabolism, nutrient requirements, health status and environmental adaptation. Consequently, feed resources may be used inefficiently, diseases may remain undetected until advanced stages, and production losses can occur before corrective measures are implemented.

AI and digital livestock health technologies are revolutionizing livestock farming by enabling continuous, automated and data-driven management of individual animals. AI refers to computer systems capable of performing tasks that normally require human intelligence, including learning from data, recognizing patterns, making predictions and supporting complex decision-making. When integrated with digital livestock technologies such as wearable sensors, automated feeders, biosensors, cameras, drones, cloud computing and the IoT, AI provides real-time insights into animal nutrition, health, welfare, reproduction and productivity.

Digital livestock health systems continuously monitor feed intake, rumination, body temperature, movement, respiration, milk composition, weight gain and environmental conditions. These data are analyzed using machine learning algorithms to identify abnormal patterns and predict health or nutritional problems before clinical signs become evident. Such predictive capabilities enable farmers to implement timely nutritional adjustments, veterinary interventions and management strategies, reducing disease incidence, improving feed efficiency and enhancing overall farm profitability.

The integration of AI into animal nutrition is ushering in a new era of precision livestock farming, where feeding programs are tailored to the nutritional needs of individual animals rather than entire herds or flocks. This transition from reactive to preventive and personalized livestock management is expected to play a crucial role in achieving sustainable animal production, reducing greenhouse gas emissions and improving food safety in the coming decades.

Artificial intelligence in animal nutrition

Artificial Intelligence involves the use of advanced computer algorithms that mimic human intelligence by learning from large datasets and continuously improving their performance. In animal nutrition, AI integrates nutritional models, feed composition databases, production records, weather information and health indicators to develop optimized feeding strategies. AI systems analyze multiple variables simultaneously, including:

- Breed and genetic potential
- Age and body weight
- Physiological status (growth, pregnancy, lactation)
- Feed intake patterns
- Milk yield or growth rate
- Environmental temperature and humidity
- Health status
- Feed quality
- Nutrient digestibility

Based on these analyses, AI recommends precise dietary formulations that maximize productivity while minimizing nutrient wastage.

Digital Livestock Health: A New Paradigm

Digital livestock health represents a transformative approach to animal healthcare that combines sensors, wearable devices, artificial intelligence (AI), Internet of Things (IoT), cloud computing, and data analytics to continuously monitor animal health and productivity. This technology-driven system shifts livestock management from reactive treatment to proactive prevention, enabling early disease detection, precision nutrition, timely interventions, improved welfare, enhanced productivity, and sustainable livestock production. Unlike conventional healthcare, which primarily responds to visible clinical symptoms, digital health systems focus on early detection, disease prevention and predictive management.

Key objectives include:

- Continuous health surveillance
- Early disease diagnosis
- Precision medication
- Reduced antibiotic use
- Improved welfare
- Enhanced biosecurity
- Better reproductive management
- Optimized nutritional interventions

Continuous health surveillance

Continuous health surveillance involves the real-time monitoring of physiological, behavioral and environmental parameters using wearable sensors, cameras and automated monitoring systems. Parameters such as body temperature, rumination, feed intake, heart rate, respiration, activity and movement are continuously recorded,

enabling farmers and veterinarians to detect subtle health changes early and implement preventive measures before clinical disease develops.

Early disease diagnosis

Digital health technologies facilitate early disease diagnosis by identifying deviations from normal physiological and behavioral patterns before visible clinical signs appear. Artificial intelligence analyzes data from sensors, milk analyzers, thermal imaging and activity monitors to detect conditions such as mastitis, ketosis, lameness, respiratory diseases and digestive disorders, allowing rapid intervention and minimizing production losses.

Precision medication

Precision medication uses digital health data to administer the right drug, at the correct dose, through the appropriate route and at the optimal time for individual animals. AI-supported decision systems and health monitoring devices improve treatment accuracy, reduce unnecessary medication, shorten recovery periods, minimize drug residues in animal products and enhance overall therapeutic effectiveness.

Reduced antibiotic use

Digital livestock health promotes judicious antibiotic use by emphasizing disease prevention, early diagnosis, precision nutrition, vaccination and targeted treatment strategies. Early detection of health problems reduces the need for blanket antimicrobial therapy, helping combat antimicrobial resistance (AMR), improving food safety, lowering treatment costs and supporting sustainable livestock production systems.

Improved welfare

Digital monitoring systems continuously assess indicators of animal welfare, including comfort, activity, stress levels, body temperature, feeding behavior, lying time and social interactions. Early identification of discomfort, pain, injury or environmental stress allows prompt corrective actions, improving animal well-being, reducing stress-related disorders, and enhancing productivity throughout the production cycle.

Enhanced biosecurity

Digital livestock health strengthens biosecurity by continuously monitoring animal movements, health records, environmental conditions, and disease outbreaks. Automated surveillance systems rapidly identify abnormal events, support quarantine management, improve traceability and enable timely implementation of disease control measures, thereby reducing pathogen transmission within and between livestock farms.

Better reproductive management

Digital technologies improve reproductive management by continuously monitoring estrus behavior, body temperature, activity levels, rumination, hormone-associated changes and calving indicators. Artificial intelligence accurately predicts optimal breeding and insemination times while detecting reproductive disorders early, resulting in higher conception rates, shorter calving intervals, improved fertility and enhanced reproductive efficiency.

Optimized nutritional interventions

Digital livestock health integrates sensor-derived physiological data, feed intake records, metabolic biomarkers and production performance to design individualized nutritional interventions. Real-time nutritional adjustments improve nutrient utilization, maintain metabolic balance, prevent nutritional deficiencies and metabolic disorders, enhance immune function, increase feed efficiency and maximize productivity while reducing feed costs and environmental nutrient losses.

Core technologies driving AI and digital livestock health

1. Internet of things (IoT)

The IoT connects sensors, automated feeders, environmental monitoring systems, cameras and cloud platforms into a unified digital network. Data collected from animals are transmitted in real time to cloud-based systems, enabling remote monitoring and rapid decision-making.

2. Wearable sensors

Wearable sensors are an integral component of precision livestock farming, enabling continuous, non-invasive monitoring of animal health, behavior, physiology and productivity. These smart devices collect real-time data on parameters such as activity, feed intake, rumination, body temperature, movement and location. By integrating sensor data with artificial intelligence and cloud-based platforms, farmers can detect health disorders early,

optimize nutrition, improve reproductive management and enhance overall animal welfare and farm efficiency. Modern livestock are equipped with wearable devices such as:

Smart ear tags

Smart ear tags are lightweight electronic devices attached to an animal's ear that continuously monitor body temperature, activity, feeding behavior, rumination and location. Equipped with wireless communication technologies, they transmit real-time information to farm management software, enabling early detection of diseases, heat stress, estrus and health abnormalities while reducing labor requirements and improving livestock productivity.

Neck collars

Smart neck collars are wearable monitoring devices that record rumination time, chewing activity, feeding behavior, physical movement, neck position and body temperature. Using accelerometers and motion sensors, they identify changes associated with estrus, illness, lameness, metabolic disorders and reduced feed intake. These collars support precision nutrition, reproductive management and timely veterinary interventions in dairy and beef animals.

Leg pedometers

Leg pedometers are electronic sensors attached to the animal's leg to measure walking activity, step count, standing time and resting behavior. Increased activity often indicates estrus, whereas reduced movement may signal lameness, illness, injury or metabolic disorders. Continuous monitoring enables early disease detection, improved reproductive efficiency, enhanced animal welfare and more informed management decisions.

GPS collars

GPS collars combine Global Positioning System (GPS) technology with activity sensors to continuously track animal location, grazing patterns, movement, and pasture utilization. They are particularly valuable in extensive grazing systems, allowing farmers to monitor herd distribution, detect abnormal movement patterns, prevent animal losses, optimize pasture management, and improve grazing efficiency while reducing labor costs.

Smart halters

Smart halters are advanced wearable devices fitted around the animal's head to monitor feeding behavior, rumination, jaw movements, chewing frequency, drinking activity, and head posture. Integrated sensors accurately detect changes associated with digestive disorders, nutritional deficiencies, heat stress and disease. The collected information supports precision feeding strategies, early diagnosis and improved overall herd health management.

Rumen boluses

Rumen boluses are ingestible electronic devices permanently placed in the rumen to continuously monitor internal body temperature, rumen pH, rumen motility and other physiological parameters. These sensors provide highly accurate real-time data for detecting ruminal acidosis, ketosis, heat stress, digestive disturbances and metabolic disorders. Their long operational life makes them valuable tools for precision nutrition, health monitoring and improving productivity in ruminant livestock.

These devices continuously record:

- Feed intake
- Rumination
- Activity levels
- Body temperature
- Heart rate
- Grazing behavior
- Water consumption
- Estrus activity

Abnormal changes often indicate nutritional stress or disease.

3. Machine learning algorithms

Machine learning enables computers to learn from historical data without explicit programming. These algorithms identify complex relationships between nutrition, health, and productivity, allowing prediction of:

Mastitis
Ketosis
Heat stress
Lameness
Respiratory diseases
Digestive disorders
Growth performance
Reproductive efficiency
The predictive accuracy improves as more data become available.

4. Computer vision

High-resolution cameras combined with AI analyze:
Body condition score
Feeding behavior
Walking pattern
Lameness
Social interactions
Aggression
Weight estimation
Computer vision provides non-invasive and continuous monitoring without disturbing animals.

5. Thermal imaging

Infrared cameras detect changes in surface temperature associated with inflammation or infection. Thermal imaging is widely used for identifying:

Mastitis
Hoof diseases
Heat stress
Respiratory infections
Fever
Injuries
This technology enables rapid, contact-free disease screening.

6. Biosensors

Biosensors measure biological markers in milk, blood, saliva, urine and sweat. Common indicators include:

Glucose
Ketone bodies
Cortisol
Somatic cell count
Progesterone
Lactate
pH
Electrolytes

These biomarkers help identify metabolic disorders, reproductive status and nutritional imbalances at an early stage.

7. Cloud computing and big data analytics

Livestock farms generate vast quantities of data every day. Cloud platforms securely store and analyze these data, allowing farmers and veterinarians to access dashboards, alerts, and recommendations from smart phones or computers. Big data analytics integrates nutrition, health, climate, genetics and management records to support evidence-based decisions.

Applications of AI in animal nutrition

Precision feed formulation

AI-powered software formulates diets according to:

Individual nutrient requirements

Feed ingredient availability

Ingredient costs

Digestibility

Production objectives

This reduces feed wastage and improves feed conversion efficiency.

Personalized nutrition

Not all animals require identical diets. AI uses data on genetics, metabolism, health status, and microbiome composition to recommend customized feeding strategies, improving nutrient utilization and productivity.

Feed intake monitoring

Automated feeders equipped with sensors measure:

Feeding frequency

Feeding duration

Feed refusal

Eating speed

Reduced feed intake is often one of the earliest indicators of disease or nutritional imbalance.

Prediction of nutritional disorders

Machine learning models can predict conditions such as:

Ketosis

Milk fever

Ruminal acidosis

Fatty liver

Mineral deficiencies

Farmers receive alerts before clinical symptoms appear, enabling timely dietary adjustments.

Applications in different livestock species

Dairy cattle

AI supports:

Individual concentrate allocation

Monitoring milk composition

Detecting mastitis and ketosis

Managing transition cows

Predicting reproductive events

Beef cattle

Digital systems monitor:

Grazing behavior

Weight gain

Feed efficiency

Water intake

Heat stress

Disease outbreaks

Buffaloes

AI assists in improving reproductive efficiency, optimizing feeding during lactation and monitoring heat stress, which is particularly important due to buffaloes' susceptibility to high temperatures.

Sheep and goats

Wearable sensors and GPS collars monitor grazing patterns, pregnancy, lambing/kidding, and parasite burdens, enabling better nutritional and health management in extensive production systems.

Pigs

Smart feeding systems optimize amino acid supply, while cameras and microphones detect aggression, respiratory disease, tail biting and changes in feeding behavior.

Poultry

AI-enabled poultry houses monitor:

- Feed and water intake
- Body weight
- Temperature and humidity
- Air quality
- Bird activity
- Vocalization patterns

These systems help detect heat stress, coccidiosis, respiratory diseases, and welfare problems at an early stage.

Role of AI in disease prevention

Artificial Intelligence enables a shift from treatment to prevention by:

- Detecting abnormal behavior before illness becomes visible,
- Predicting disease outbreaks using environmental and production data,
- Identifying animals requiring nutritional supplementation,
- Supporting precision vaccination and biosecurity planning,
- Reducing unnecessary antimicrobial use,
- Preventive healthcare lowers mortality, improves welfare and reduces production losses.

Artificial intelligence and sustainable animal nutrition

AI contributes to sustainability by improving nutrient utilization and reducing environmental impacts. Optimized feeding decreases nitrogen and phosphorus excretion, minimizes methane emissions through better ration formulation and reduces feed waste. Efficient feed use also lowers the demand for feed resources, supporting climate-smart livestock production and circular agriculture.

Benefits of AI and digital livestock health

The adoption of AI and digital technologies offers numerous advantages:

- Improved feed conversion efficiency,
- Higher milk, meat, and egg production,
- Early disease detection,
- Better reproductive performance,
- Reduced veterinary and medication costs,
- Lower labor requirements through automation,
- Enhanced animal welfare,
- Improved traceability and food safety,
- Reduced greenhouse gas emissions,
- Better profitability and resource-use efficiency,

Challenges

Despite their potential, several challenges limit widespread adoption:

- High initial investment costs,
- Limited internet and electricity infrastructure in rural areas,
- Lack of digital literacy among farmers,
- Integration of data from different devices,
- Data privacy and cybersecurity concerns,
- Sensor maintenance and calibration,
- Limited availability of trained personnel,
- Difficulty in adoption by smallholder farmers,

Addressing these issues requires affordable technologies, supportive government policies, training programs and public-private partnerships.

Future prospects

The future of AI and digital livestock health is promising, with emerging innovations expected to reshape animal agriculture:

Digital twins that create virtual models of individual animals,
Integration of genomics, metabolomics, and microbiome data for precision nutrition,
Autonomous robotic feeding and milking systems,
Blockchain-enabled traceability across the food supply chain,
Nanotechnology-based smart nutrient delivery systems,
AI-driven methane mitigation strategies,
Drone-assisted pasture and herd monitoring,
Smartphone applications for real-time farm management,
Predictive analytics for disease surveillance at regional and national levels,

As these technologies become more affordable and user-friendly, they are likely to become standard tools in commercial livestock farming.

Challenges and opportunities

The convergence of AI, digital livestock health, precision nutrition and advanced sensor technologies offers unprecedented opportunities for improving productivity, animal welfare and environmental sustainability. Collaboration among researchers, veterinarians, nutritionists, engineers, policymakers and farmers will be essential to develop scalable and cost-effective solutions. Investment in digital infrastructure, farmer education and research will accelerate the adoption of these innovations, particularly in developing countries such as India.

Conclusion

Artificial Intelligence and Digital Livestock Health are redefining the future of animal nutrition by enabling precision feeding, continuous health monitoring and predictive decision-making. These technologies empower farmers to manage animals on an individual basis, improving feed efficiency, disease prevention, productivity, welfare and profitability while reducing environmental impacts. Although challenges related to cost, infrastructure, and technical expertise remain, ongoing advances in AI, IoT, robotics, biosensors and big data analytics are making digital livestock farming increasingly practical and accessible. The integration of these technologies into everyday livestock management will play a central role in building resilient, sustainable and climate-smart animal production systems capable of meeting the growing global demand for safe and nutritious animal-derived foods.

CRISPR Technology in Plant Disease Management



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Abstract

Plant diseases caused by fungi, bacteria, viruses, and other pathogens pose a significant threat to global agricultural productivity and food security. Conventional disease management strategies, including chemical control and traditional breeding, often face limitations such as the emergence of resistant pathogen strains, lengthy breeding cycles, and environmental concerns. The advent of Clustered Regularly Interspaced Short Palindromic Repeats (CRISPR)-based genome editing has revolutionized plant biotechnology by providing a rapid, precise, and cost-effective approach for developing disease-resistant crops. CRISPR technology enables targeted modification of plant genomes by disrupting susceptibility genes, enhancing resistance genes, and directly targeting pathogen genomes, thereby strengthening plant defense mechanisms. This review highlights the principles of CRISPR genome editing and its applications in managing major plant diseases across economically important crops, with particular emphasis on rice. Successful examples include the editing of OsSWEET promoter regions to confer resistance against bacterial blight and the knockout of OsERF922 to improve resistance to rice blast disease. The article also discusses recent advances in CRISPR technologies, including base editing, prime editing, and multiplex genome editing, which further enhance the precision and efficiency of crop improvement. In addition, current challenges such as off-target effects, regulatory frameworks, public acceptance, and efficient delivery systems are examined. Overall, CRISPR has emerged as a transformative tool for sustainable disease management, offering significant potential to reduce crop losses, minimize pesticide use, and accelerate the development of resilient crop varieties. Continued research, responsible regulation, and integration with modern breeding approaches will be essential to fully realize the potential of CRISPR in ensuring global food security and sustainable agricultural production.

INTRODUCTION

Plant diseases caused by fungi, bacteria, viruses, and other pathogens significantly reduce crop yield and quality worldwide. Traditional disease management methods, such as chemical pesticides and conventional breeding, often require considerable time, resources, and may have environmental impacts. The development of Clustered Regularly Interspaced Short Palindromic Repeats (CRISPR) technology has transformed plant biotechnology by providing a precise, efficient, and cost-effective tool for improving disease resistance in crops. CRISPR-based genome editing enables scientists to modify specific genes associated with plant immunity or pathogen susceptibility, creating crops that are more resilient to diseases while reducing dependence on chemical control measures.

CRISPR

CRISPR is a revolutionary genome-editing technology adapted from a natural defense mechanism found in bacteria. In combination with the Cas9 enzyme or other CRISPR-associated proteins, it acts as molecular scissors that cut DNA at targeted locations. After the DNA is cut, the plant's natural repair mechanisms modify the genetic sequence, allowing researchers to delete, insert, or alter specific genes with remarkable precision. The simplicity, accuracy, and versatility of CRISPR have made it one of the most important tools in modern agricultural research.

CRISPR CAN IMPROVE PLANT DISEASE RESISTANCE THROUGH SEVERAL APPROACHES:

1. Editing Susceptibility Genes

Many pathogens exploit specific plant genes, known as susceptibility (S) genes, to infect crops. CRISPR can disable these genes, making plants resistant without affecting normal growth.

Example: Editing the MLO gene in wheat, barley, and tomato provides resistance to powdery mildew.

2. Enhancing Plant Immune Responses

Plants possess immune-related genes that recognize invading pathogens. CRISPR can strengthen these defense pathways by modifying resistance (R) genes or regulatory genes, enabling plants to respond more effectively to infections.

3. Directly Targeting Plant Viruses

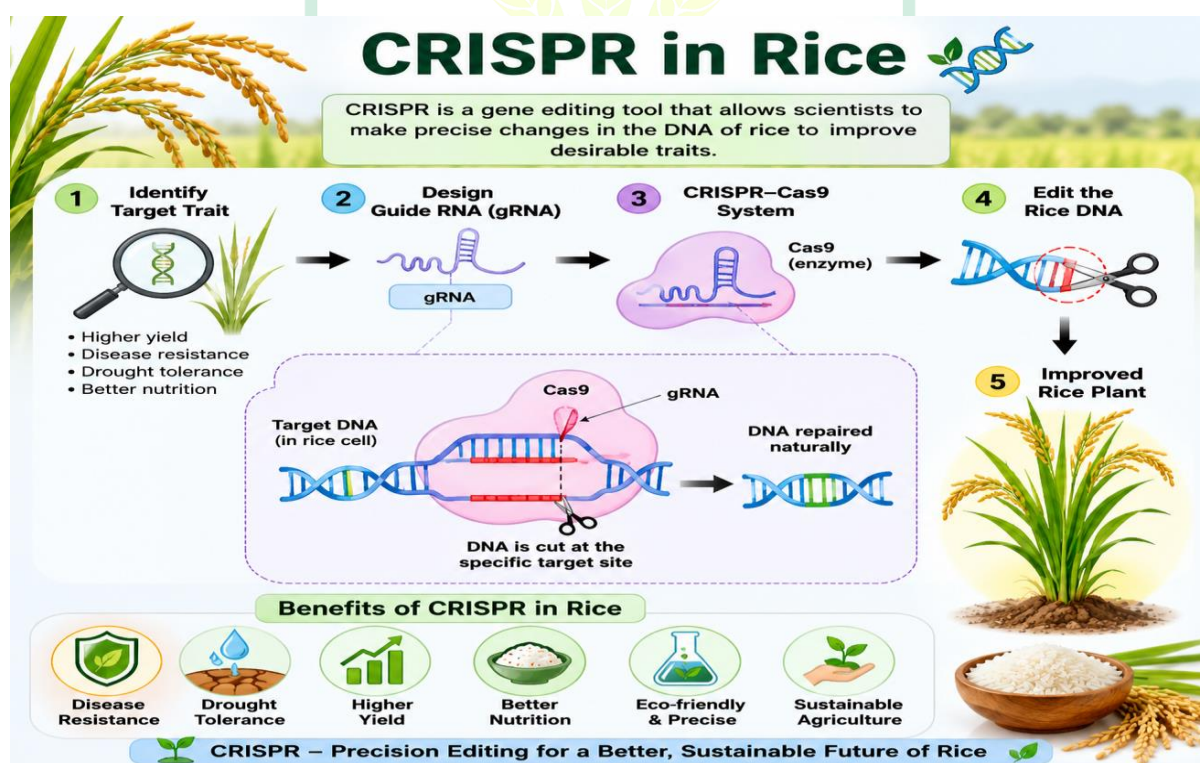
CRISPR systems such as Cas9 and Cas13 can target viral DNA or RNA, preventing viruses from multiplying inside plant cells. This strategy has shown promising results against several devastating viral diseases.

4. Improving Disease Resistance Through Gene Regulation

Advanced CRISPR technologies can regulate gene expression without permanently changing DNA sequences. This allows scientists to activate defense genes only when disease threats occur, reducing unwanted effects on plant development.

APPLICATION:

Rice (*Oryza sativa* L.) is the staple food for more than half of the world's population, making its protection against diseases a global priority. Rice production is threatened by numerous pathogens, including bacteria, fungi, viruses, and nematodes, which can cause severe yield losses ranging from 10% to over 50% under epidemic conditions. Conventional breeding for disease resistance is often slow because resistance genes may be linked to undesirable agronomic traits, and pathogens rapidly evolve to overcome resistance. CRISPR genome-editing technology has emerged as a powerful alternative, enabling precise modification of rice genes involved in disease susceptibility and immunity.



1. Bacterial Blight Resistance

Bacterial blight, caused by *Xanthomonas oryzae* pv. *oryzae* (Xoo), is one of the most destructive diseases of rice worldwide. The pathogen secretes transcription activator-like (TAL) effectors that activate members of the SWEET gene family, particularly OsSWEET11, OsSWEET13, and OsSWEET14. These genes encode sugar transporters that facilitate the movement of sugars from plant cells into the apoplast, providing nutrients for bacterial multiplication.

CRISPR/Cas9 has been successfully used to edit the promoter regions of these SWEET genes, preventing TAL effectors from binding while preserving normal gene function. As a result, the pathogen is unable to hijack

the plant's sugar transport system, leading to significantly enhanced resistance. Multiplex CRISPR editing of several SWEET promoters simultaneously has produced rice varieties with broad-spectrum and durable resistance against multiple Xoo strains without compromising grain yield or quality.

2. Rice Blast Disease

Rice blast, caused by the fungus *Magnaporthe oryzae*, is responsible for substantial yield losses worldwide and can affect leaves, stems, panicles, and grains. The disease is highly adaptable because the pathogen evolves rapidly, overcoming many resistance genes introduced through conventional breeding.

CRISPR has enabled researchers to improve blast resistance by modifying susceptibility genes and regulatory genes involved in plant defense pathways. For example, knockout of OsERF922, a negative regulator of disease resistance, resulted in enhanced resistance to rice blast without noticeable effects on plant growth or yield. Similarly, editing genes involved in immune signaling pathways has strengthened the rice defense response by promoting faster recognition and containment of fungal invasion.

3. Bacterial Leaf Streak

Bacterial leaf streak, caused by *Xanthomonas oryzae* pv. *oryzicola* (Xoc), also exploits host susceptibility genes for infection. Similar to bacterial blight, CRISPR-mediated modification of TAL effector-binding elements within susceptibility gene promoters has reduced pathogen colonization and disease severity. These studies demonstrate that promoter editing is an effective strategy for developing resistance against multiple bacterial diseases.

4. Rice Tungro Disease

Rice tungro disease results from the combined infection of Rice tungro bacilliform virus (RTBV) and Rice tungro spherical virus (RTSV). The disease causes severe stunting, yellow-orange leaf discoloration, and major yield reductions across South and Southeast Asia.

Although research is still progressing, CRISPR technologies are being explored to target viral genomes directly or modify host factors required for viral replication. Emerging CRISPR systems such as Cas13, which targets RNA viruses, offer promising opportunities for controlling viral diseases like tungro.

5. Sheath Blight

Sheath blight, caused by *Rhizoctonia solani*, is one of the most difficult rice diseases to manage because strong natural resistance sources are limited. Researchers are using CRISPR to edit genes that negatively regulate plant immunity, thereby enhancing the rice defense system against fungal infection. Although commercial varieties have not yet been released, experimental studies indicate that genome editing can improve quantitative resistance to sheath blight.

6. Broad-Spectrum Disease Resistance

One of the greatest strengths of CRISPR technology is its ability to edit multiple genes simultaneously through multiplex genome editing. Researchers have simultaneously modified several susceptibility genes and immune regulators to develop rice plants resistant to bacterial blight, blast, and other diseases. Such broad-spectrum resistance is particularly valuable because farmers often face multiple pathogens during a single growing season.

7. Improvement of Disease Resistance Without Yield Penalty

A major concern in disease-resistance breeding is that increased resistance may reduce plant growth or grain production. CRISPR enables highly precise modifications that minimize unintended effects. In many studies, CRISPR-edited rice lines maintained normal flowering time, grain size, plant height, and yield while exhibiting significantly improved disease resistance. This precision makes CRISPR superior to many conventional mutation-breeding approaches

Advantages of CRISPR in Plant Disease Management

- High precision in targeting specific genes.
- Faster development of disease-resistant crop varieties compared with conventional breeding.
- Reduced dependence on chemical pesticides.
- Lower production costs over the long term.
- Potential to improve crop productivity and food security.
- Ability to edit multiple genes simultaneously (multiplex genome editing).
- Can be applied to crops that are difficult to improve through traditional breeding methods.

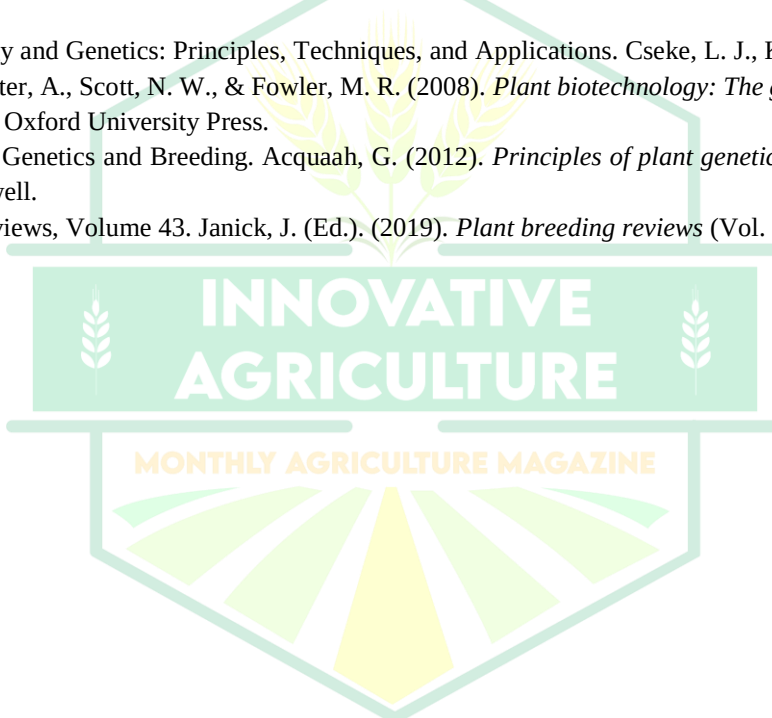
Limitations

Despite its enormous potential, several challenges remain:

- Off-target mutations may occur, although improved CRISPR systems have greatly reduced this risk.
- Many disease-resistance traits involve multiple genes, making editing more complex.
- Efficient delivery of CRISPR components into some plant species remains technically challenging.
- Regulatory frameworks differ among countries regarding genome-edited crops.
- Public acceptance and ethical considerations continue to influence commercialization

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Shielding the Bunch: A Modern Guide to Integrated Disease Management in Banana



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INTRODUCTION:

Bananas are not just a global breakfast staple; they are a economic lifeline for millions of smallholder farmers. However, the crop faces a constant barrage of invisible enemies—fungi, bacteria, and viruses that can wipe out entire plantations. Relying on heavy chemical sprays is no longer a viable option; it damages the soil, drains bank accounts, and pathogens quickly build resistance.

This is where Integrated Disease Management (IDM) comes in. Think of IDM not as a single cure, but as a holistic wellness plan for your plantation. It combines smart farming habits, nature's own defenders, and careful, targeted treatments to keep crops healthy and profitable.

THE BIG FOUR: ENEMIES TO WATCH

To fight a disease, you have to know it. Here are the four major threats every banana grower faces:

1. PANAMA WILT (*Fusarium* Wilt): A soil-borne fungus that chokes the plant from the inside out. Leaves turn yellow from the edges, droop like an umbrella, and the stem shows dark streaks when cut. Once it is in the soil, it stays for decades



Figure 1: Panama wilt

2. Sigatoka Leaf Spot: A devastating airborne fungus. It starts as tiny, dark streaks on leaves and expands into large, dead spots. This destroys the plant's ability to photosynthesize, leading to small, poorly ripened fruit.



Figure 2: Black Sigatoka

Figure 3: Yellow Sigatoka

3. Moko / Bacterial Wilt: A aggressive bacterial infection that causes leaves to collapse and turn a sickly yellow. If you cut the fruit open, the inside is dark, rotten, and completely inedible.



Figure 4: Moko wilt

4. Banana Bunchy Top Virus (BBTV): Spread by tiny black aphids, this virus causes new leaves to grow narrow, stunted, and bunched together at the top, making the plant look like a small rosette. It stops fruit production entirely.



Figure 5: Bunchy top

THE IDM STRATEGY: A FOUR-PILLAR BLUEPRINT

An effective IDM strategy relies on four layers of defense, working together like a security system.

Pillar 1: Cultural Controls (Smart Farm Hygiene)

- ✚ Start Clean: The biggest mistake is planting sick material. Always invest in tissue-cultured plantlets. They are grown in sterile labs and are guaranteed to be disease-free from day one.
- ✚ The "One-Plant, One-Clean" Tool Rule: Bacteria and viruses hitchhike on dirty machetes. Farmers should carry a bucket of disinfectant (like a 10% bleach solution) and dip their tools between working on every single plant mat.
- ✚ Give Plants Breathing Room: Crowded plantations trap moisture, creating a perfect humid greenhouse for Sigatoka fungus. Proper spacing and regular pruning of dead leaves keep air moving and leaves dry.
- ✚ Crop Rotation: If a field has a history of disease, break the cycle. Rotate the land with paddy rice or sugarcane for a few seasons to starve out soil-borne pathogens.

Pillar 2: Biological Allies (Nature's Bodyguards)

- ✚ The Power of Trichoderma: *Trichoderma viride* is a beneficial fungus that acts like a shield around banana roots. By mixing it into the soil with organic manure during planting, it aggressively blocks Panama Wilt from taking hold.
- ✚ Friendly Bacteria: Spraying or drenching fields with *Pseudomonas fluorescens* boosts the plant's natural immune system, helping it fight off leaf spots and bacterial invaders naturally.
- ✚ Organic Soil Nutrition: Adding neem cake or seasoned farmyard manure doesn't just feed the plant; it feeds beneficial microbes in the soil that crowd out harmful pathogens.

Pillar 3: Vector Management (Stopping the Carrier)

- ✚ Aphid Control: Because Banana Bunchy Top is spread by aphids, managing the virus means managing the insect. Keep weeds down (where aphids like to hide) and use targeted, systemic insecticides or neem-based oil sprays to control aphid populations early in the season.

Pillar 4: Responsible Chemical Interventions

- ✚ The Last Resort: In IDM, chemicals are a scalpel, not a sledgehammer. When Sigatoka flares up during rainy seasons, alternating between different systemic fungicides prevents the fungus from developing resistance.
- ✚ Quarantine Infected Plants: If a plant contracts Moko or Bunchy Top, it cannot be cured. It must be safely destroyed in situ (often using targeted herbicide injections) to prevent the disease from spreading to neighboring mats.

Conclusion: The Long-Term Reward

Implementing an IDM approach requires more patience and daily observation than simply spraying a field with chemicals. However, the rewards are undeniable. By building a resilient ecosystem, farmers protect their soil health, cut down on expensive chemical inputs, and ensure that their banana harvests remain abundant for generations to come.



Night shift work problems and solutions



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Doctors, nurses police personnel and night shift workers are really heroes as they sacrifice their health for the cause of society doctors and nurses work whole of the night to save the life of the patient police personnel and security guard work whole of the night that people can sleep whole of the night with safety and security. Some company official works whole of the night specially working in USA Company based in India. In essence, they are real heroes.

Women soldiers of BSF stood guard, their eyes scanning the land in front of them in fog and extreme cold in night. Works performed during hours that cross midnight often defined 10 pm to 6 am or similar. Some of the common name for night shift is third shift work generally bad for health because it disrupts circadian leading to sleep problem, mental health issues, reduced alertness and concentration and increases the risk of developing diabetes, heart disease and obesity. An increased risk of gastrointestinal issue is one of the negative effects of working at night for an extended time typically lack sleep and have strange food habits.

Night shift jobs are completely legal in India. They are regulated by the Factories Act 1948. However, employers must comply with strict rules regarding working hours, break and workplace safety. Working hours cannot exceed 9 hours per day or 48 hours per week with a mandatory 30 minutes break after every 5 hours of continuous work. Women are legally permitted to work night shift provided employers follow strict safety and welfare mandates under the occupational safety, health and working conditions code 2020. Companies must obtain voluntary written consent from female employees, provide secure door-to-door GPS, tracked transportation, adequate lighting CCTV surveillance, and secure rest room facilities. Night shift work in India is a massive sector driven primarily by global business demands, expanding its corridor and around the clock service industries. It spans diverse fields from white collar IT services position to essential public safety operations.

Work extend past the shift duration or conducted on National holidays requires double the regular wage. It is mandatory. There is some jobs portal to find night shift openings:

- A. LINKEDIN: Excellent for corporate night shift.
- B. INDEED: Features level operations, Logistics and customer service.
- C. NAUKARI: Offers localised filters for MNC operations Backend process and walk-in drives.
- D. APANA: Best platform for entry level positions Security Guards Delivery personnel and drives role.

According to Economic Times India has seen a 15% rise in people adopting to work night shift. Additionally the Growth of Indian Economy has led to an increase in demand for workers in various industries. According to a survey conducted by Indian Institute of Management over 60% employees in India are working night shift. The study also found that employees working night shifts reported higher level of jobs satisfaction than those who worked day shift with almost 70 percent of participants reporting well being and satisfaction with night shift. The nighttime atmosphere can provide employees with a more alarming and relaxed environment. Finally, Statistics from the same survey revealed that employee's working night shift earned an average 17% more than those who were working day shift. Overall, the night shift in India after a wide range of benefits for both employers and employees alike. The benefits of working night shift in India are:

- A. To earn and save more
- B. To understand the Global market
- C. More hours in the day to sleep
- D. Better work life balance
- E. Reduced commute time

Compared to global averages Indians women's are less likely to engage in income generating income or actively seek employment. Globally female labour force participation stands at 50% where as in India only 28.52 % of total working age women participate in labour force and 27.44% are employed.

Uttar Pradesh Government allows to women to work night shift between 7 pm to 6 am with written consent offers double pay CCTV safety and secure transport. Although specific provision vary from State to state, the core compliance obligations remain consistent. Failure to comply with statutory provisions governing women night shift employment expenses Employers to serious legal and business risks. These may be:

- A. Legal penalties
- B. Regulatory action
- C. Civil and criminal liability
- D. Reputation damage

Some effective ways to deals with the negative impact

1. Avoid eating late at night
2. Nap during breaks for 15-20 minutes
3. Seek professional help if necessary
4. Sleep in right environment
5. Enlist the help of those you live with
6. Avoid caffeine/Alcohol
7. Get some sunlight when you are not working
8. Eat healthy diet
9. Turn off electronic an hour before going to sleep
10. Avoid nicotine before bed

In addition to above, follow 10:3:2:1 rule

- A. 10 hours before no more caffeine
- B. 3 hours before bed no more food or Alcohol
- C. 2 hours before bed no more work
- D. 1hours before bed no more screen time (Shut off all phones TVand computer).

Keep a consistent sleep schedule even on your days off. Paste your work and sleep schedule on the Refrigerator so one can see when you will be working, asleep and an awake.

Tips for Do's

1. Prioritize sleep hygiene
2. Eat balance meal
3. Take regular break
4. Stay active
5. Communicate with colleague.

Don'ts

1. Rely on caffeine
2. Eat junk food
3. Work continuously without rest
4. Remain sedentary during shifts
5. Isolate yourself from coworkers

It' is advisable to consider stopping or reducing night shift around age 45-50 years as the body ability to recover deteriorates and health risks increase significantly. Studies shows increased obesity and smoking risk for those 46 plus and reduce life expectancy for long term night workers. India doesn't shine brighter when it's women work the night shift. It moves forward **BOLDLY, INCLUSIVELY AND IRREVERSIBLE.**

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Tiny Minerals, Tremendous Results: The Nano Revolution in Poultry Nutrition



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The poultry industry is constantly searching for ways to improve productivity, bird health, and sustainability. Over the years, advances in genetics, nutrition, and management have enabled remarkable improvements in growth rates, egg production, and feed efficiency. Yet, one area that continues to evolve is mineral nutrition. For decades, poultry diets have depended on inorganic mineral sources such as sulphates, oxides, and carbonates to meet the birds' requirements for essential trace minerals. While these sources are inexpensive and widely available, their utilization by the bird is often far from ideal. A significant portion of supplemented minerals passes through the digestive system unabsorbed, leading to nutrient wastage, higher feed costs, and increased environmental contamination. The introduction of organic trace minerals improved mineral availability by protecting them from antagonistic interactions in the digestive tract. However, even these advanced mineral sources do not achieve complete utilization.

What Makes Nano Minerals Different?

Nanotechnology involves the manipulation of materials at an extremely small scale, typically between 1 and 100 nanometers. To put this into perspective, a nanoparticle is thousands of times smaller than the width of a human hair. When minerals are converted into nanoparticles, their physical and chemical properties change dramatically. They possess a much larger surface area relative to their size, improved solubility, greater stability, and enhanced interaction with biological tissues. These unique characteristics allow nano minerals to be absorbed and utilized far more efficiently than conventional mineral sources.

Superior Absorption and Utilization

One of the greatest advantages of nano trace minerals is their enhanced bioavailability. Their tiny size allows them to move more easily through the intestinal lining and reach the bloodstream. Unlike conventional minerals, which may become bound to other dietary components and lose their effectiveness, nano minerals experience fewer antagonistic interactions within the digestive tract. This enables a greater proportion of the supplemented mineral to reach target tissues where it can perform its biological functions. As a result, birds receive more nutritional benefit from lower levels of supplementation.

Strengthening Gut Health

A healthy digestive system is the foundation of efficient poultry production. Nano trace minerals have been shown to improve intestinal integrity by supporting villus development and strengthening the gut barrier. Research indicates that nano minerals can stimulate the expression of proteins responsible for maintaining tight junctions between intestinal cells. This helps prevent the entry of harmful pathogens and toxins while improving nutrient absorption. Improved gut health translates directly into better feed efficiency, enhanced growth performance, and greater disease resistance.

Natural Protection Against Harmful Bacteria

The poultry industry is increasingly focused on reducing antibiotic use while maintaining flock health. Nano trace minerals may play an important role in this transition. Nano forms of zinc, copper, and manganese possess natural antimicrobial properties. Their extremely small size enables them to interact directly with bacterial cells, disrupting cell membranes and inhibiting bacterial growth. Studies have demonstrated activity against important poultry pathogens such as *Salmonella*, *Escherichia coli*, and *Clostridium perfringens*. By helping control harmful bacteria, nano minerals contribute to a healthier intestinal environment and support antibiotic-free production systems.

Enhancing Immunity and Antioxidant Defense

Modern poultry face numerous challenges, including disease pressure, vaccination stress, heat stress, and environmental fluctuations. Optimal immune function is therefore essential for maintaining productivity. Many trace minerals serve as critical components of antioxidant enzymes that protect cells from oxidative damage. Zinc supports Superoxide Dismutase (SOD), while selenium is required for Glutathione Peroxidase (GPx), both of which are vital for combating oxidative stress. Because nano minerals are more efficiently absorbed and retained within tissues, they can enhance the activity of these protective enzymes, leading to stronger immunity and improved disease resilience.

Supporting Strong Bones and Skeletal Health

The remarkable growth potential of modern broilers places tremendous demands on skeletal development. Weak bones and leg disorders can significantly reduce performance and welfare. Nano zinc, manganese, and copper contribute to collagen formation, cartilage development, and bone mineralization. Improved availability of these minerals has been associated with stronger bones, increased tibial strength, and a reduction in skeletal abnormalities. For producers, healthier skeletal systems mean better mobility, improved growth performance, and lower economic losses.

Improving Egg Production and Eggshell Quality

Trace minerals play an essential role in egg formation and shell development. In laying hens, inadequate mineral utilization can negatively affect egg production, shell thickness, and shell strength. Nano trace minerals enhance mineral deposition efficiency, ensuring that a greater proportion of dietary minerals reaches the reproductive system. Improved availability of zinc, manganese, and copper supports eggshell matrix formation and shell integrity. The result is better egg production, improved shell quality, and reduced egg breakage during handling and transportation.

A Sustainable Approach to Poultry Nutrition

Beyond production benefits, nano trace minerals offer significant environmental advantages. Because they are absorbed more efficiently, lower supplementation rates are often required to achieve desired responses. This reduces mineral excretion in manure, decreases soil contamination, and minimizes the accumulation of heavy metals in the environment. Such benefits are becoming increasingly important as the poultry industry faces growing pressure to adopt more sustainable production practices.

Economic Benefits for Producers

Although nano trace minerals may appear more expensive on a per-kilogram basis, their superior biological efficiency often results in a better return on investment. Improved feed conversion, enhanced growth, better egg production, lower mortality, and reduced nutrient wastage can collectively offset the higher initial cost. In many situations, producers can achieve superior performance while using lower inclusion levels than conventional mineral sources.

The Future of Precision Poultry Nutrition

The future of poultry nutrition lies in precision feeding—providing nutrients in forms that maximize biological utilization while minimizing waste. Nano trace minerals fit perfectly within this vision. By delivering minerals more efficiently to the bird's cells and tissues, nanotechnology enables nutritionists to move beyond traditional supplementation strategies toward a more targeted and sustainable approach. As research continues to expand, nano trace minerals are likely to become an increasingly important component of modern poultry diets.

Conclusion

Nano trace minerals represent one of the most exciting developments in poultry nutrition. Their ability to improve mineral absorption, strengthen gut health, enhance immunity, support skeletal development, improve egg quality, and reduce environmental impact makes them a powerful tool for modern poultry production. While tiny in size, their impact on bird health and performance can be enormous. As the industry moves toward greater efficiency, sustainability, and precision nutrition, nano trace minerals are poised to play a major role in shaping the future of poultry farming.

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Response Farming: A Smart Strategy for Climate-Resilient Agriculture



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Abstract

Climate variability has become one of the greatest challenges confronting modern agriculture, affecting crop productivity, water resources and farm profitability. Increasing occurrences of droughts, floods, heat waves and unexpected rainfall demand adaptive farming approaches that enable timely and informed decision-making. Response farming is a climate-smart agricultural strategy that integrates weather forecasting, agro-advisory services, decision support systems and digital technologies to support farm management based on prevailing and anticipated weather conditions. Unlike conventional farming, which follows fixed crop calendars, response farming encourages dynamic management of crop selection, sowing, irrigation, nutrient application, pest management and harvesting according to weather forecasts. Recent advances in artificial intelligence, remote sensing, mobile applications and precision agriculture have further strengthened the effectiveness of response farming by providing real-time, location-specific advisories. The adoption of response farming enhances resource-use efficiency, reduces climate-related risks, improves crop productivity and contributes to sustainable agricultural development. As climate change continues to intensify, response farming is emerging as an indispensable component of climate-resilient agriculture and future food security.

Keywords: Climate variability, Response farming, Components

Introduction

Agriculture has always been closely linked to weather, making it one of the most climate-sensitive sectors of the economy. Traditionally, farmers planned agricultural operations based on seasonal experience and long-established cropping calendars. However, climate change has altered rainfall distribution, increased temperatures, intensified extreme weather events and changed the occurrence of pests and diseases, making conventional farming practices increasingly unreliable. Delayed monsoon onset, prolonged dry spells, unseasonal rainfall, cyclones, floods and heat waves now occur more frequently, creating uncertainty in crop production and threatening food security.

In addition to climate variability, global phenomena such as El Nino and La Nina significantly influence monsoon behaviour, affecting rainfall distribution and crop performance across many agricultural regions. Under these changing conditions, farming decisions based solely on past experience often result in poor crop establishment, inefficient resource utilization and economic losses.

Climate-resilient agriculture has therefore emerged as a sustainable approach that enables farming systems to adapt to changing climatic conditions while maintaining productivity and conserving natural resources. Among its various adaptation strategies, response farming has gained considerable attention because it converts weather information into practical farm management decisions. By integrating meteorological observations, climate forecasts, crop information, digital technologies and scientific advisories response farming enables farmers to anticipate climatic risks and optimize agricultural operations before adverse weather events occur. This proactive approach improves farm resilience, enhances productivity and supports sustainable agricultural development.

What is Response Farming?

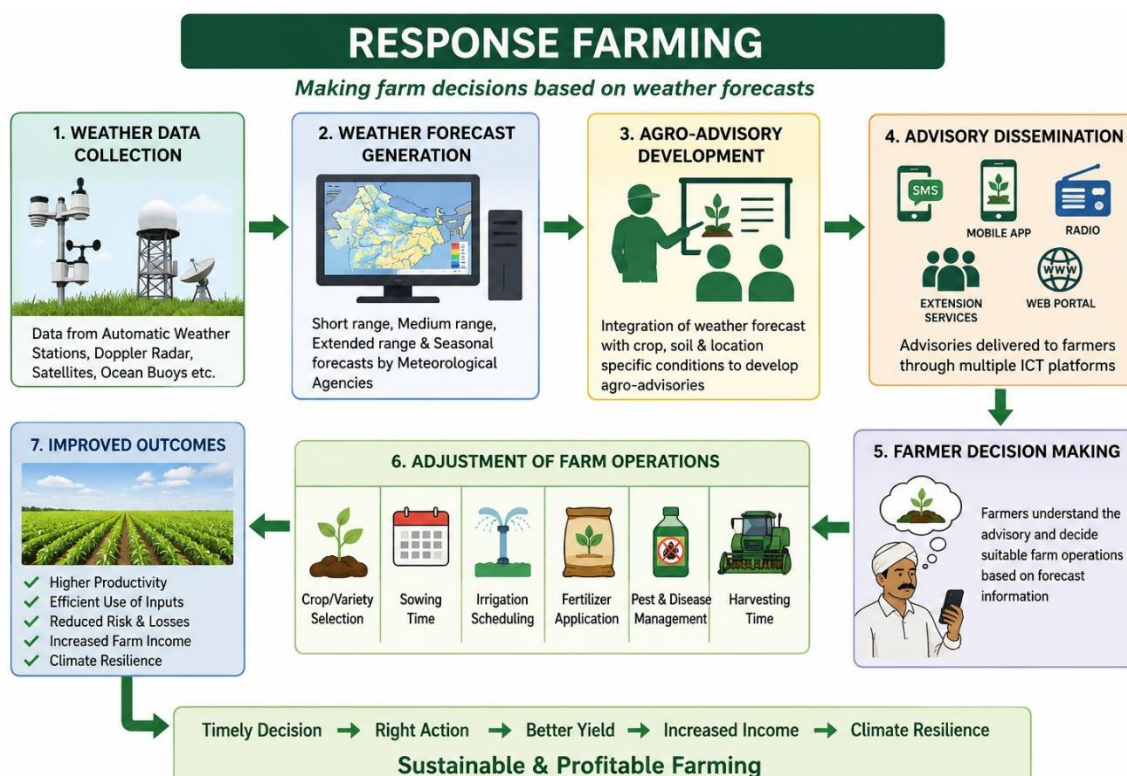
Response farming is a weather-responsive agricultural management strategy in which farmers modify farming practices according to real-time weather observations and forecasted climatic conditions instead of following fixed agricultural calendars. The concept was first introduced by J. I. Stewart (1988) to encourage farmers in rainfed regions to respond to rainfall variability through flexible crop management practices. Unlike traditional farming, where decisions are predetermined before the cropping season begins, response farming promotes

continuous decision-making throughout the crop growth period. Farmers use weather forecasts to determine suitable crop varieties, adjust sowing dates, schedule irrigation, optimize fertilizer application, implement timely pest management and plan harvesting operations. This flexibility enables agricultural systems to adapt to weather variability while minimizing production risks.

Today, response farming has evolved from simple rainfall-based decision making to an integrated climate information service supported by automatic weather stations, satellite observations, remote sensing, artificial intelligence, numerical weather prediction models and mobile-based agro-advisories. These technological advancements have significantly improved the accuracy and accessibility of weather information, making response farming an effective climate adaptation strategy for both rainfed and irrigated agriculture.

How Response Farming Works

Response farming transforms weather information into practical agricultural decisions through a systematic sequence of observation, analysis, advisory preparation, dissemination and farmer action.



Major Components of Response Farming

Weather Observation and Forecasting: Weather observation and forecasting form the foundation of response farming by providing reliable and timely climate information for agricultural decision-making.

Weather Forecast Agencies: India Meteorological Department (IMD), Institute of Tropical Meteorology (IITM), National Centre for Medium Range Weather Forecasting (NCMRWF) and Indian National Centre for Ocean Information Services (INCOIS).

Weather Data Utilization: Automatic Weather Stations (AWS), Doppler Weather Radars (DWR), satellites, rain gauges, upper-air observations.

Weather Forecasts: Now cast, Short-range, Medium range, Extended and Seasonal forecast.

Agro-Advisory Services: Agro-advisory services transform weather forecasts into practical, crop-specific recommendations for farmers. Experts gathered the forecast information viz., rainfall, temperature, humidity, wind speed, cloud cover and extreme weather analysed along with crop stage, soil moisture and local farming practices to suggest suitable actions. These advisories help farmers make timely and informed decisions while minimizing climate-related risks.

Decision Support Systems (DSS): Decision Support Systems are computer-based tools that integrate weather forecasts, soil information, crop growth models and management practices to support scientific farm planning. DSS provides location-specific recommendations that improve the timing of agricultural operations, optimize input use and enhance crop productivity. These systems reduce uncertainty and improve farm-level decision-making.

Information and Communication Technology (ICT): Information and Communication Technology (ICT) play a crucial role in delivering weather-based advisories quickly and efficiently to farmers. Mobile applications, SMS alerts, WhatsApp groups, interactive voice response systems, community radio, television and web portals ensure that real-time information reaches even remote farming communities. ICT has significantly improved the accessibility and effectiveness of climate information services.

Farm Decisions Influenced by Response Farming

Crop Selection: Seasonal weather forecasts help farmers choose suitable crops and varieties according to expected rainfall, temperature and growing conditions. During drought years, farmers can opt for short-duration or drought-tolerant crops, whereas favourable weather conditions allow cultivation of high-yielding varieties with greater production potential.

Sowing Time: Response farming enables farmers to synchronize sowing with the onset of favourable rainfall and soil moisture conditions. Timely sowing ensures better seed germination, uniform crop establishment, and improved crop growth while reducing the risk of crop failure due to delayed or erratic rainfall.

Irrigation Management: Weather forecasts assist farmers in scheduling irrigation more efficiently by avoiding unnecessary irrigation before predicted rainfall and conserving water during dry periods. This improves water-use efficiency, reduces irrigation costs and ensures adequate moisture availability during critical crop growth stages.

Nutrient Management: Weather-based advisories help farmers schedule fertilizer application under favourable weather conditions, minimizing nutrient losses caused by heavy rainfall, runoff and volatilization. Timely nutrient application enhances fertilizer-use efficiency, improves crop growth and reduces environmental pollution.

Pest and Disease Management: Response farming provides early warnings about weather conditions favourable for pest multiplication and disease development. Farmers can implement preventive crop protection measures, such as timely pesticide application or integrated pest management practices, thereby reducing crop damage and unnecessary pesticide use.

Harvesting Operations: Accurate weather forecasts enable farmers to harvest mature crops before heavy rainfall, cyclones or hailstorms. Timely harvesting minimizes post-harvest losses, preserves grain quality, reduces storage damage and improves market value, ultimately contributing to higher farm income.

Benefits of Response Farming

Response farming offers multiple benefits to farmers, agricultural institutions and society as a whole.

- ✓ Risk reduction: Farmers become better prepared for droughts, floods, heat waves, and unseasonal rainfall, reducing crop failures and income losses.
- ✓ Efficient resource usage: Management of water, fertilizers and pesticides leads to lower production costs while protecting natural resources. Better timing of farm operations also improves crop growth and increases agricultural productivity.
- ✓ Sustainable agriculture production: Weather-informed decisions reduce unnecessary pesticide applications, thereby promoting environmentally sustainable agriculture and minimizing chemical contamination.
- ✓ High Profitability: The adoption of response farming contributes to greater farm profitability by improving yield stability and reducing input wastage. It also strengthens climate resilience by enabling farming systems to recover more quickly from climatic shocks.

Digital Technologies Driving Response Farming

Rapid advances in digital agriculture have transformed response farming into a highly efficient climate service. Automatic weather stations provide continuous observations, while satellites monitor rainfall, vegetation, soil moisture and crop health across large areas.

Artificial intelligence and machine learning analyze massive weather datasets to generate increasingly accurate forecasts. Remote sensing and Geographic Information Systems (GIS) support real-time monitoring of crop conditions and environmental changes.

Mobile applications such as Meghdoot, Kisan Suvidha and various State Agricultural University advisory platforms provide farmers with personalized recommendations based on their location and crop stage. The integration of drones, IoT-based soil moisture sensors and precision agriculture technologies further enhances the effectiveness of response farming.

Challenges in Adoption

Despite its enormous potential, response farming still faces several implementation challenges. Weather forecasts are not always completely accurate, particularly for localized rainfall events. Limited internet connectivity and inadequate digital infrastructure reduce access to advisory services in remote villages. Many farmers require additional training to understand weather forecasts and adopt weather-based decision-making. The shortage of automatic weather stations and trained extension personnel also limits the effectiveness of climate advisory services. Furthermore, the successful implementation of response farming requires close collaboration among meteorological departments, agricultural universities, extension agencies and farming communities.

Future Prospects

The future of response farming is closely linked with advances in artificial intelligence, satellite technology, climate modeling and precision agriculture. Highly localized weather forecasts, real-time crop monitoring, automated decision-support systems and personalized mobile advisories are expected to become standard components of modern farming. Future response farming systems will integrate weather forecasting with pest and disease prediction, soil health monitoring, irrigation scheduling and market intelligence, providing farmers with comprehensive decision support through a single digital platform. Such integrated climate services will play a crucial role in ensuring food security under increasing climate variability.

Conclusion

Response farming represents a paradigm shift from traditional calendar-based agriculture to science-based, climate-responsive farming. By combining accurate weather forecasts, digital technologies, agro-advisory services and farmer-centred decision-making, Response farming enables agricultural communities to minimize climatic risks while improving productivity, profitability and sustainability. As climate change continues to reshape agricultural production worldwide, the widespread adoption of response farming will be essential for building resilient farming systems capable of ensuring food security and sustainable rural development. Empowering farmers with timely weather information is no longer an option it has become a necessity for the future of agriculture.

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PRAGATI: India's New National Push to Build 20,000 Agri-Entrepreneurs and Transform Smallholder Farming



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Abstract

On 7 July 2026, India's Union Minister of Agriculture and Farmers Welfare, Shivraj Singh Chouhan, launched PRAGATI (Pro-Active Governance and Timely Implementation), a nationwide initiative to build a network of 20,000 trained agri-entrepreneurs who will directly support close to 20 lakh, or two million, small and marginal farmers. Unlike a conventional centrally funded scheme, PRAGATI is structured as a multi-stakeholder partnership bringing together the Government of India with corporate foundations, global philanthropies, and rural development organizations, positioning it as one of the largest privately co-led agricultural entrepreneurship programmes in the country. This article examines what PRAGATI is, the agri-entrepreneurship model it scales up from, its stated targets for farmer income, crop yields, and financial inclusion, and the coalition of partners funding and implementing it. It also considers the questions the initiative raises: whether a network of village-level entrepreneurs can be trained and deployed at this scale within a realistic timeframe, how a privately co-funded programme sustains itself beyond an initial launch phase, and how PRAGATI will coordinate with the dozens of existing central and state missions already operating in the same districts. The article situates PRAGATI within India's broader recent policy direction toward regenerative, climate-resilient agriculture and closes by outlining the practical signals that will indicate, over the coming two to three years, whether the initiative is delivering on its scale of ambition.

Introduction

India's agriculture ministry has, over the past decade, tried a wide range of approaches to the same underlying problem: how does a country with roughly 140 million farm households, most of them small or marginal landholders, deliver modern agronomic knowledge, credit, market access, and climate resilience to millions of villages at once. Government extension services, cooperative structures, and digital advisory platforms have each made progress on pieces of this puzzle, but the last-mile gap, the distance between a scheme announced in Delhi or a state capital and a farmer's actual field, has remained difficult to close at true national scale.

PRAGATI represents the latest and, by some measures, most ambitious attempt to close that gap through a specific institutional device: the village-level agri-entrepreneur, a locally rooted individual trained to serve as a one-stop advisor connecting farmers to agronomy guidance, soil testing, mechanization, formal credit, and buyers. The model is not new; it builds directly on an existing agri-entrepreneurship network that has grown over several years to more than 26,000 entrepreneurs already supporting over 2.6 million farmers across the country. What is new is the scale and structure of PRAGATI's expansion of that model, and the unusual coalition of government, corporate, and philanthropic partners assembled to fund and deliver it.

What Was Announced, and By Whom

Speaking at the launch event in New Delhi, Chouhan framed PRAGATI as central to the government's broader Viksit Bharat, or Developed India, vision, arguing that this goal cannot be achieved without a developed agricultural sector and prosperous villages. He stressed that the government's focus extends beyond raising output

alone to reducing cultivation costs, raising farmer incomes, promoting crop diversification, and encouraging value addition through food processing and allied enterprises such as horticulture, dairy, fisheries, and beekeeping.

The initiative is being implemented through a coalition that includes, alongside the Ministry of Agriculture and Farmers Welfare, the PepsiCo Foundation, State Bank of India Foundation, the Gates Foundation, IDH, Heifer International, the Environmental Defense Fund, the Global Agri Entrepreneurship Academy, the Sustainable Agriculture Foundation's International Association, the Agri Entrepreneur Growth Foundation, and the Transform Rural India Foundation. This composition, a government ministry convening corporate foundations, an international development philanthropy, and rural livelihood organizations under a single national initiative, is itself a departure from the way most agricultural missions in India have historically been structured and funded.

The Agri-Entrepreneurship Model PRAGATI Scales Up

At the centre of PRAGATI is a model already tested at meaningful, if smaller, scale. The Agri Entrepreneur Growth Foundation and its partners have, over several years of implementation across roughly fourteen states, incubated more than 26,000 agri-entrepreneurs who collectively support over 2.6 million farmers, typically by running a village-level kiosk or micro-enterprise that bundles several services a smallholder would otherwise need to seek from multiple, often distant, sources.

Each entrepreneur under this model is trained to provide agronomy advisory tailored to local crops and soil conditions, arrange soil health testing, connect farmers to mechanization services such as tractor or harvester rental, facilitate access to formal credit and insurance products, and help farmers reach buyers on more favourable terms than an informal middleman might offer. PRAGATI aims to add 20,000 new entrepreneurs on top of this existing base, roughly doubling the network's scale, with the explicit goal of directly benefiting close to 20 lakh additional smallholder farmers across the country.

Specific Targets the Programme Has Set

PRAGATI's public targets are notably specific for an initiative of this kind. The programme aims for at least a 30 percent increase in participating farmers' incomes, a 15 to 20 percent boost in yields for key crops including paddy, maize, and potato, and adoption of regenerative agricultural practices by at least 20 percent of participating farmers. On the financial side, the initiative aims to bring at least half of all associated farmers into greater engagement with formal financial systems, including credit, savings, and insurance products, alongside a parallel push on digital inclusion.

The initial geographic rollout covers eight states: Madhya Pradesh, Uttar Pradesh, Bihar, Maharashtra, Rajasthan, West Bengal, Assam, and Jharkhand, a footprint that spans some of India's largest smallholder farming populations as well as regions with historically weaker extension and market infrastructure. The government has placed particular emphasis on the inclusion of women and rural youth, with Krishi Sakhis, women trained as agricultural extension volunteers, expected to play a significant role in the programme's village-level delivery alongside newly trained agri-entrepreneurs.

A Different Funding Model From Earlier Missions

One of the more closely watched features of PRAGATI is its funding structure. Rather than being a wholly centrally funded scheme in the mould of many earlier agricultural missions, PRAGATI is described by its own coalition as India's largest privately co-led agri-entrepreneurship programme, with corporate social responsibility arms, most visibly the PepsiCo Foundation and the State Bank of India Foundation, alongside the Gates Foundation and several development-focused non-profits, providing a substantial share of the financing and technical design alongside the government's convening role.

This structure has both an evident advantage and an open question attached to it. The advantage is access to funding, technical expertise, and delivery capacity beyond what a single ministry's budget allocation would typically support in a single year, allowing the initiative to be launched at a scale that might otherwise have taken several budget cycles to reach. The open question is durability: corporate foundation funding and philanthropic commitments, however substantial at launch, are not bound by the same multi-year budgetary planning cycle as a government scheme, and the coalition model's long-term sustainability will depend on renewed commitments from multiple independent partners rather than a single, predictable line item.

How PRAGATI Fits Alongside Existing Missions

PRAGATI does not operate in isolation. It enters a policy landscape already populated by a dense set of central and state missions, including the National Mission on Natural Farming, state-specific programmes such as Odisha's Shree Anna Abhiyan for millets, the National Mission for Edible Oils and Oilseeds, Pradhan Mantri Fasal Bima Yojana (PMFBY) for crop insurance, and numerous state agricultural extension systems built around Krishi Vigyan Kendras. Each of these programmes already engages, to varying degrees, with the same population of small and marginal farmers that PRAGATI is now targeting through its own village-level entrepreneur network. How effectively PRAGATI's agri-entrepreneurs coordinate with, rather than duplicate, this existing architecture is likely to shape much of the initiative's practical impact. A village-level entrepreneur who can point a farmer toward an existing insurance scheme, an established millet or oilseed procurement channel, or a state extension officer, rather than attempting to replace these systems, stands to add genuine value at relatively low additional cost. Where coordination is weak, there is a risk of parallel, overlapping structures competing for the same farmer's attention without a corresponding increase in the support actually reaching the field.

What to Watch Over the Next Two to Three Years

Several practical signals will indicate, well before PRAGATI's stated targets fall due, whether the initiative is on track. The pace and quality of training 20,000 new entrepreneurs is one: rushing selection and training to hit a headline number carries an evident risk of diluting the quality of advice and service farmers actually receive at the village level, a concern the underlying agri-entrepreneurship model has generally tried to avoid by emphasizing mentorship and structured curricula over rapid onboarding.

A second signal is the degree to which women and rural youth genuinely occupy leadership roles within the entrepreneur network, rather than serving primarily as a stated inclusion target. A third is whether the regenerative agriculture component, one of five core pillars of the programme's stated mission, translates into farmers actually adopting practices such as reduced tillage, cover cropping, or diversified rotation, rather than remaining a headline commitment without a clear technical delivery mechanism attached to it. Finally, the durability of the coalition's funding commitments beyond the initial launch year will determine whether PRAGATI matures into a lasting institutional feature of Indian agriculture or remains, as several earlier high-profile launches have, a strong first announcement that does not fully sustain its initial pace of expansion.

Why the Entrepreneurship Framing Matters

PRAGATI's choice of framing, positioning trained individuals as entrepreneurs running a small local enterprise rather than as government field officers or NGO volunteers, is a deliberate design decision with real consequences. An entrepreneur who earns income from the services a farmer actually uses, a paid soil test, a mechanization booking fee, a commission on a market linkage, has a direct financial incentive to keep showing up and to keep that advice genuinely useful, in a way that a purely salaried extension post does not always guarantee over the long run. This model has parallels in other last-mile service sectors in rural India, from micro-insurance agents to solar equipment dealers, where locally embedded, incentive-aligned intermediaries have often outperformed centrally dispatched staff on consistency of service.

The same framing carries a corresponding risk. An entrepreneur's income depends on farmers being able and willing to pay, even a modest fee, for services that many government schemes have historically provided free of charge. For the poorest and most marginal farmers, this could mean the entrepreneurship model reaches those with slightly more disposable income more readily than it reaches the very smallholders the programme is explicitly designed to serve. How PRAGATI's coalition addresses this affordability question, whether through subsidized service bundles, foundation-funded fee waivers for the poorest households, or bundling paid services with free government scheme referrals, will likely determine how evenly the initiative's benefits are actually distributed across the smallholder population it targets.

Early Indicators From the Existing Network

Because PRAGATI builds directly on an already operating agri-entrepreneurship base rather than starting from a blank slate, some indication of what to expect is already available from the network's track record prior to this expansion. Foundations involved in the earlier fourteen-state rollout have reported consistent gains in farmer incomes and the emergence of diverse, locally led micro-enterprises alongside the core advisory service, including

small input-supply shops, custom hiring centres for farm machinery, and produce aggregation points that improve a farmer's bargaining position relative to selling individually to a trader.

Whether this track record holds up as the network roughly doubles in size and extends into new districts with different crop patterns, market structures, and administrative capacity is the central test PRAGATI now faces. Rapid scale-up has historically been one of the harder transitions for community-based delivery models in Indian development programmes, since the quality of mentorship, curriculum, and local relationship-building that underpinned success at a smaller scale does not always transfer cleanly to a network operating at several times the size within a compressed timeframe.

PRAGATI at a Glance

Dimension	Detail
Launch date	7 July 2026, New Delhi
Lead minister	Shivraj Singh Chouhan, Union Minister of Agriculture and Farmers Welfare
New agri-entrepreneurs targeted	20,000, added to an existing base of 26,000-plus
Farmers directly targeted	Nearly 20 lakh (2 million) smallholder farmers
Income and yield targets	30% rise in farmer income; 15-20% yield increase in paddy, maize, potato
Regenerative agriculture adoption target	At least 20% of participating farmers
Financial inclusion target	At least 50% of associated farmers
Initial states covered	Madhya Pradesh, Uttar Pradesh, Bihar, Maharashtra, Rajasthan, West Bengal, Assam, Jharkhand
Key partners	PepsiCo Foundation, SBI Foundation, Gates Foundation, IDH, Heifer International, EDF, AEGF, TRIF, and others

Conclusion

PRAGATI arrives at a moment when Indian agricultural policy is increasingly organized around named, time-bound missions with specific numerical targets, and it fits that pattern closely: twenty thousand entrepreneurs, twenty lakh farmers, thirty percent income growth, twenty percent regenerative adoption. What distinguishes it is less the ambition of these numbers, several existing missions carry similarly bold targets, than the coalition assembled to deliver them, a government ministry working alongside global philanthropy and corporate foundations at a scale rarely attempted in Indian agriculture before. Whether this hybrid funding and delivery model proves more effective than a conventional centrally administered scheme, or whether it introduces new coordination and sustainability challenges of its own, will only become clear as the entrepreneur network is built out over the coming two to three years. For now, PRAGATI represents a genuinely new experiment in how India tries to close the last-mile gap between agricultural policy and the smallholder farmer, one worth watching closely alongside the country's existing portfolio of state and central missions rather than in isolation from them.

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Artificial Intelligence Tools for Smart and Sustainable Aquaculture: Innovations, Applications, and Future Prospects



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Abstract

Artificial Intelligence (AI) is emerging as an important tool for improving the efficiency and sustainability of aquaculture. AI-based technologies assist farmers in monitoring water quality, optimizing feeding practices, detecting diseases at an early stage, and supporting better farm management decisions. These innovations help enhance fish production while reducing resource use and environmental impacts. This chapter discusses the major AI tools used in aquaculture, their practical applications, associated challenges, and future prospects for promoting smart and sustainable fish farming.

Keywords: Artificial Intelligence, Aquaculture, Smart Farming, Machine Learning, IoT, Fish Health, Water Quality, Sustainable Aquaculture.

Introduction

Aquaculture has become one of the fastest-growing food production sectors in the world and plays a vital role in ensuring food security, nutritional well-being, employment, and economic growth. According to the Food and Agriculture Organization (FAO), aquaculture contributes significantly to the global supply of fish for human consumption, helping to meet the increasing demand for high-quality protein. However, the sector faces several challenges, including deteriorating water quality, disease outbreaks, inefficient feed management, climate change, and rising production costs. These issues necessitate the adoption of innovative technologies that can improve productivity while ensuring environmental sustainability.

Artificial Intelligence (AI) has emerged as a transformative technology with the potential to revolutionize aquaculture by enabling precision farming and data-driven decision-making. AI refers to the capability of computer systems to perform tasks that normally require human intelligence, such as learning from data, recognizing patterns, making predictions, and supporting complex decisions. In aquaculture, AI integrates with advanced technologies such as the Internet of Things (IoT), machine learning (ML), deep learning (DL), computer vision, cloud computing, and robotics to monitor and optimize various farming operations.

AI-powered systems enable continuous monitoring of critical water quality parameters, including temperature, dissolved oxygen, pH, ammonia, and salinity, allowing farmers to take timely corrective measures. Intelligent feeding systems optimize feed delivery based on fish behavior and appetite, thereby reducing feed wastage and production costs. Similarly, AI-based image analysis and predictive models facilitate early disease detection, fish growth estimation, biomass assessment, and behavioral monitoring, contributing to improved fish health and farm productivity.

The integration of AI into aquaculture also supports sustainable resource management by minimizing environmental impacts, enhancing operational efficiency, and promoting responsible farming practices. Furthermore, AI-driven analytics provide valuable insights for production planning, risk assessment, and supply chain management, thereby strengthening the resilience and profitability of the aquaculture sector.

This chapter presents an overview of the major Artificial Intelligence tools used in aquaculture and discusses their applications in water quality monitoring, feeding management, disease diagnosis, fish health assessment, and production optimization. It also highlights the benefits, challenges, and future prospects of AI-driven technologies in developing smart and sustainable aquaculture systems. By adopting AI-based solutions, the aquaculture industry can move towards greater efficiency, profitability, and environmental stewardship, contributing to global food security and the sustainable development of the blue economy.

Artificial Intelligence: An Overview

Artificial Intelligence (AI) refers to the simulation of human intelligence by computer systems that can learn from data, identify patterns, solve problems, and make decisions with minimal human intervention. AI combines

computational algorithms with data analysis to perform tasks such as prediction, classification, recognition, and automation. Over the past decade, rapid advances in computing power, sensor technology, and data availability have accelerated the adoption of AI across various sectors, including agriculture, healthcare, manufacturing, and aquaculture.

In aquaculture, AI facilitates **precision farming** by integrating information collected from sensors, cameras, drones, and monitoring devices to provide real-time insights into farm conditions. These systems continuously analyze environmental and biological data, enabling farmers to make informed decisions regarding water quality management, feeding schedules, disease control, and stock monitoring. As a result, AI helps improve production efficiency while reducing operational costs and environmental impacts.

Several AI technologies contribute to modern aquaculture. **Machine Learning (ML)** enables computers to learn from historical data and predict outcomes such as fish growth, feed requirements, and disease occurrence. **Deep Learning (DL)**, a specialized branch of ML, processes complex datasets and images, making it particularly useful for fish species identification, behavior analysis, and disease diagnosis. **Computer Vision** uses cameras and image-processing techniques to monitor fish movement, estimate biomass, and detect abnormal behavior without disturbing the animals. The **Internet of Things (IoT)** complements AI by providing continuous data through interconnected sensors that monitor critical water quality parameters such as temperature, dissolved oxygen, pH, salinity, and ammonia.

The integration of AI with **cloud computing**, **big data analytics**, and **robotics** has further enhanced the capabilities of smart aquaculture. Cloud platforms enable the storage and processing of large volumes of farm data, while robotics and automated systems assist in feeding, underwater inspection, and routine farm operations. These technologies support timely decision-making and improve farm management through automation and predictive analysis.

Despite its numerous advantages, AI implementation in aquaculture faces challenges such as high installation costs, limited digital infrastructure, inadequate technical expertise, and concerns regarding data quality and security. Nevertheless, continuous technological advancements and increasing accessibility of AI-based solutions are expected to overcome these barriers, making intelligent aquaculture systems more affordable and widely adopted.

Overall, Artificial Intelligence is transforming conventional aquaculture into a knowledge-driven and technology-enabled industry. By improving accuracy, efficiency, and sustainability, AI is expected to play a pivotal role in meeting the growing global demand for fish while ensuring responsible utilization of natural resources.

AI Tools Used in Aquaculture

The adoption of Artificial Intelligence (AI) in aquaculture has introduced a range of advanced tools that enable data-driven decision-making, precision farming, and sustainable resource management. These technologies work together to monitor environmental conditions, optimize production, improve fish health, and reduce operational costs. The major AI tools used in aquaculture are described below.

1. Machine Learning (ML)

Machine Learning (ML) is a branch of AI that enables computer systems to learn from historical and real-time data without being explicitly programmed. In aquaculture, ML algorithms analyze large datasets to identify patterns and predict future outcomes, helping farmers make informed management decisions. Applications of ML include predicting fish growth, estimating biomass, optimizing feeding schedules, forecasting water quality changes, and identifying disease risks. By continuously learning from new data, ML models improve their prediction accuracy over time. This results in better feed conversion efficiency, reduced production costs, and improved farm productivity.

2. Deep Learning (DL)

Deep Learning (DL) is an advanced subset of machine learning that uses artificial neural networks with multiple processing layers to analyze complex data. It is particularly effective in image and video analysis, making it highly suitable for aquaculture applications. Deep learning models can automatically identify fish species, detect diseases from external symptoms, estimate fish size and weight, and monitor fish behavior using underwater cameras.

These systems reduce dependence on manual observations and enable rapid, accurate, and non-invasive monitoring, thereby improving fish welfare and farm management.

3. Computer Vision

Computer Vision is an AI technology that enables computers to interpret and analyze visual information from images and videos. In aquaculture, computer vision systems use digital cameras and image-processing algorithms to monitor fish movement, feeding behavior, population density, and health status. These systems can detect abnormal swimming patterns that may indicate stress or disease and estimate biomass without physically handling the fish. Computer vision also supports automated grading and counting of fish, reducing labor requirements while improving accuracy and operational efficiency.

4. Internet of Things (IoT)

The Internet of Things (IoT) refers to a network of interconnected sensors and smart devices that collect and transmit real-time data. In aquaculture, IoT sensors continuously monitor important water quality parameters such as temperature, dissolved oxygen, pH, salinity, turbidity, ammonia, and water level. The collected data are transmitted to cloud platforms or mobile applications, allowing farmers to monitor farm conditions remotely. When integrated with AI, IoT systems can generate alerts, recommend corrective actions, and automate responses such as activating aerators or adjusting feeding schedules. This real-time monitoring improves farm management and minimizes production risks.

5. Big Data Analytics

Modern aquaculture generates enormous amounts of data from sensors, cameras, feeding systems, weather stations, and production records. Big Data Analytics involves collecting, processing, and analyzing these large and diverse datasets to identify trends and support decision-making. AI-powered analytical tools can integrate environmental, biological, and operational data to optimize production strategies, predict disease outbreaks, evaluate farm performance, and improve resource utilization. Big data also helps researchers develop more accurate predictive models for sustainable aquaculture management.

6. Robotics and Automation

Robotics and automation technologies are increasingly being incorporated into modern aquaculture to reduce labor dependency and improve operational efficiency. AI-powered robotic systems can perform repetitive tasks such as automated feeding, underwater inspection, cage cleaning, water sampling, and fish harvesting. Autonomous underwater vehicles (AUVs) and remotely operated vehicles (ROVs) inspect cages, monitor fish health, and assess infrastructure without disturbing cultured species. Automation ensures precision, reduces human error, and enables continuous farm operations even under challenging environmental conditions.

3.7 Cloud Computing

Cloud computing provides scalable online platforms for storing, processing, and sharing aquaculture data. Information collected through IoT devices and monitoring systems is securely stored on cloud servers, where AI algorithms analyze the data and generate recommendations for farm management. Cloud-based platforms enable farmers, researchers, and extension agencies to access real-time information from any location using computers or smartphones. These systems facilitate data sharing, remote monitoring, predictive analysis, and collaborative decision-making while reducing the need for expensive local computing infrastructure.

8. Digital Twins

A Digital Twin is a virtual representation of a physical aquaculture system that continuously updates itself using real-time data collected from sensors and monitoring devices. AI-driven digital twins simulate pond, tank, or cage environments, allowing farmers to evaluate different management strategies before implementing them in the actual farm. For example, farmers can assess the effects of changing feeding rates, stocking density, aeration, or water exchange on fish growth and water quality through simulation. Digital twin technology supports predictive management, minimizes production risks, and improves operational planning, making it one of the most promising innovations in smart aquaculture.

As summaries, the integration of Machine Learning, Deep Learning, Computer Vision, IoT, Big Data Analytics, Robotics, Cloud Computing, and Digital Twins has transformed conventional aquaculture into a smart, data-driven production system. These AI tools enable real-time monitoring, predictive analysis, automated

decision-making, and efficient resource utilization, thereby improving productivity, profitability, fish welfare, and environmental sustainability. As these technologies become more affordable and accessible, they are expected to play an increasingly important role in the future of sustainable aquaculture.

Applications of Artificial Intelligence in Aquaculture

Artificial Intelligence (AI) has transformed traditional aquaculture by introducing intelligent systems capable of monitoring, analyzing, and optimizing various farming operations. AI-based technologies enable real-time decision-making, improve production efficiency, reduce operational costs, and promote sustainable aquaculture practices. Major applications of AI in aquaculture are described below.

1. Water Quality Monitoring

Water quality is one of the most critical factors influencing fish growth, health, and survival. Conventional monitoring methods rely on manual sampling, which is often time-consuming and may fail to detect sudden environmental changes. AI integrated with the Internet of Things (IoT) enables continuous monitoring of key water quality parameters such as temperature, dissolved oxygen, pH, salinity, ammonia, turbidity, and nitrate levels through sensor networks. Machine learning algorithms analyze real-time data to identify abnormal conditions, predict water quality fluctuations, and generate early warning alerts. Automated control systems can activate aerators, water pumps, or filtration units whenever water quality deteriorates, thereby maintaining a stable culture environment and reducing fish mortality.

2. Intelligent Feeding Systems

Feed accounts for the largest operational expense in aquaculture, often representing 50–70% of total production costs. AI-powered intelligent feeding systems optimize feed management by analyzing fish appetite, swimming activity, environmental conditions, and previous feeding records. Computer vision and underwater cameras monitor feeding behavior, while machine learning algorithms determine the optimum feeding time and feed quantity. Automated feeders then deliver feed according to the actual nutritional requirements of fish, minimizing feed wastage and improving feed conversion efficiency (FCR). Intelligent feeding not only enhances fish growth but also reduces water pollution caused by uneaten feed.

3. Fish Health and Disease Diagnosis

Disease outbreaks remain one of the major constraints affecting aquaculture productivity and profitability. AI-based disease diagnosis systems use computer vision, image recognition, and deep learning algorithms to identify external signs of diseases such as lesions, fin erosion, discoloration, abnormal swimming, and parasitic infections. These systems analyze images and videos captured by underwater cameras to detect health abnormalities at an early stage, allowing timely intervention before diseases spread throughout the farm. AI can also integrate environmental and historical disease data to predict the likelihood of disease outbreaks, thereby supporting preventive health management and reducing economic losses.

4. Fish Behaviour Monitoring

Fish behavior provides valuable information about health status, stress levels, feeding response, and environmental conditions. AI-enabled computer vision systems continuously monitor fish movement and behavioral patterns using underwater cameras and video analytics. Machine learning models detect deviations from normal swimming behavior, schooling patterns, feeding activity, or surface movement that may indicate stress, oxygen deficiency, disease, or poor water quality. Continuous behavioral monitoring enables farmers to respond promptly to potential problems while reducing the need for manual observation and minimizing disturbance to cultured fish.

5. Biomass Estimation and Growth Prediction

Accurate estimation of fish biomass is essential for feeding management, stocking decisions, and harvest planning. Traditional biomass estimation methods involve manual sampling, which can stress fish and produce inaccurate results. AI-based computer vision systems estimate fish length, weight, and biomass using image analysis without physically handling the animals. Machine learning algorithms further analyze historical growth data, environmental conditions, and feeding records to predict future growth rates and harvest size. These predictive models assist farmers in optimizing feeding strategies, improving production planning, and maximizing economic returns.

6. Precision Breeding

Artificial Intelligence is increasingly being used in selective breeding programs to improve the genetic quality of cultured fish species. AI algorithms analyze genetic, phenotypic, reproductive, and environmental data to identify broodstock with desirable traits such as rapid growth, disease resistance, stress tolerance, and feed efficiency. Predictive models help optimize breeding strategies and reduce the time required to develop improved strains. Precision breeding supported by AI contributes to higher productivity, improved survival, and enhanced resilience of aquaculture species under changing environmental conditions.

7. Harvest Management

Determining the optimum harvesting time is essential for maximizing production and market value. AI systems integrate information on fish growth, biomass, market demand, weather conditions, and water quality to recommend the most suitable harvest period. Computer vision technology estimates fish size and population density, while predictive analytics evaluate economic returns under different harvesting scenarios. In large-scale aquaculture operations, AI-assisted robotic systems and automated equipment also support harvesting, grading, and sorting of fish, reducing labor costs and improving product quality.

8. Supply Chain and Traceability

AI plays an important role beyond fish production by improving supply chain management and product traceability. AI-based analytics optimize transportation routes, inventory management, demand forecasting, and cold-chain logistics, ensuring that fish products reach consumers with minimal quality loss. When integrated with blockchain and cloud-based systems, AI enables complete traceability of aquaculture products from hatchery to consumer. This improves food safety, product authenticity, regulatory compliance, and consumer confidence while reducing fraud and supply chain inefficiencies.

Moreover, Artificial Intelligence has significantly expanded the scope of modern aquaculture by enabling real-time monitoring, predictive analytics, and automated management of critical farming operations. Its applications in water quality monitoring, intelligent feeding, disease diagnosis, behavioral analysis, biomass estimation, precision breeding, harvest management, and supply chain traceability contribute to higher productivity, improved fish welfare, reduced environmental impact, and enhanced profitability. As AI technologies continue to evolve, their integration with advanced digital tools will play a central role in developing resilient, efficient, and sustainable aquaculture systems capable of meeting future global food demands.

Benefits of Artificial Intelligence in Aquaculture

Artificial Intelligence (AI) is transforming aquaculture by improving production efficiency, resource management, and environmental sustainability. The integration of AI with modern digital technologies enables aquaculture farmers to make informed decisions based on real-time data, thereby enhancing farm productivity and profitability. The major benefits of AI in aquaculture are discussed below.

1. Improved Production Efficiency

AI-based systems continuously analyze environmental and biological data to optimize farm operations. Intelligent monitoring and predictive analytics help farmers make timely decisions regarding feeding, water quality management, and disease control, resulting in increased fish growth, higher survival rates, and improved overall productivity.

2. Enhanced Water Quality Management

AI integrated with IoT sensors enables continuous monitoring of critical water quality parameters such as temperature, dissolved oxygen, pH, ammonia, and salinity. Early detection of unfavorable conditions allows farmers to take corrective measures before fish health is affected, reducing mortality and improving culture performance.

3. Optimized Feed Utilization

Feed is the largest operational cost in aquaculture. AI-powered intelligent feeding systems determine the appropriate feeding time and quantity based on fish appetite and environmental conditions. This minimizes feed wastage, improves feed conversion ratio (FCR), reduces production costs, and decreases organic pollution in culture systems.

4. **Early Disease Detection and Improved Fish Health**

AI-based computer vision and machine learning models detect abnormal fish behavior and disease symptoms at an early stage. Early diagnosis enables timely treatment, limits disease transmission, reduces mortality, and minimizes the use of antibiotics and other chemicals, thereby promoting healthier fish production.

5. **Reduced Labour Requirement**

Automation of routine activities such as feeding, water quality monitoring, biomass estimation, and environmental surveillance reduces dependence on manual labour. AI-driven systems improve operational accuracy, reduce human error, and allow farmers to manage larger aquaculture facilities more efficiently.

6. **Better Decision-Making**

AI processes large volumes of real-time and historical data to generate reliable predictions and recommendations. These insights support informed decision-making regarding stocking density, feeding schedules, disease management, harvesting time, and resource allocation, ultimately improving farm management and profitability.

7. **Environmental Sustainability**

AI promotes sustainable aquaculture by optimizing the use of water, feed, energy, and other resources. Efficient resource utilization reduces waste generation, minimizes nutrient discharge into aquatic ecosystems, and lowers the environmental footprint of aquaculture operations, supporting environmentally responsible fish farming.

8. **Increased Profitability**

By reducing production costs, minimizing losses due to disease and poor water quality, and improving production efficiency, AI significantly enhances the economic performance of aquaculture enterprises. Improved product quality and optimized harvest planning also contribute to better market returns.

9. **Improved Traceability and Food Safety**

AI integrated with cloud computing and block chain technologies strengthens traceability throughout the aquaculture supply chain. Continuous monitoring and digital record-keeping improve transparency, product quality assurance, regulatory compliance, and consumer confidence in aquaculture products.

10. **Climate Resilience**

AI assists farmers in adapting to changing environmental conditions by predicting weather patterns, monitoring climate-related risks, and recommending adaptive management strategies. This enhances the resilience of aquaculture systems against climate variability and extreme environmental events.

In conclusion, Artificial Intelligence offers numerous benefits to the aquaculture sector by improving productivity, resource efficiency, fish health, environmental sustainability, and economic returns. Through intelligent monitoring, automation, predictive analytics, and data-driven decision-making, AI enables the development of smart aquaculture systems that are more efficient, resilient, and environmentally responsible. As AI technologies become increasingly affordable and accessible, their adoption is expected to accelerate, contributing significantly to the sustainable growth of the global aquaculture industry.

Challenges and Limitations of Artificial Intelligence in Aquaculture

Despite its significant potential, the adoption of Artificial Intelligence (AI) in aquaculture is still at an early stage in many parts of the world. Several technical, economic, and infrastructural challenges limit its widespread implementation, particularly among small- and medium-scale farmers. Addressing these constraints is essential for realizing the full benefits of AI-driven aquaculture.

1. **High Initial Investment**

The installation of AI-based systems, including sensors, underwater cameras, automated feeders, robotic equipment, and data processing platforms, requires substantial capital investment. These costs may be prohibitive for small-scale aquaculture farmers, especially in developing countries.

2. **Limited Digital Infrastructure**

Successful implementation of AI depends on reliable internet connectivity, cloud computing facilities, and uninterrupted power supply. Many rural aquaculture farms lack adequate digital infrastructure, making real-time data collection and remote monitoring difficult.

3. Data Availability and Quality

AI systems require large volumes of accurate and high-quality data for model training and prediction. In many aquaculture farms, data collection is inconsistent, incomplete, or poorly documented, which reduces the accuracy and reliability of AI-based recommendations.

4. Lack of Technical Expertise

The operation and maintenance of AI technologies require knowledge of digital tools, data analysis, and sensor-based systems. Many farmers and farm managers have limited technical skills, creating a barrier to the adoption and effective use of AI applications.

5. Data Privacy and Cyber security

AI-based aquaculture systems often rely on cloud platforms for storing and processing farm data. Protecting sensitive production data from unauthorized access, cyber attacks, and data breaches has become an important concern, requiring robust cyber security measures.

6. Integration with Existing Farming Systems

Many aquaculture farms continue to use traditional production methods. Integrating AI technologies with existing infrastructure and management practices can be technically challenging and may require modifications to farm facilities and operational procedures.

7. Reliability under Diverse Environmental Conditions

AI models are often developed using datasets from specific regions or production systems. Their performance may decline when applied to different species, climatic conditions, or farming environments. Regular calibration and validation are therefore necessary to maintain prediction accuracy.

8. Ethical and Regulatory Issues

The increasing use of AI raises questions related to data ownership, transparency, accountability, and ethical use of automated decision-making. In addition, many countries lack comprehensive regulatory frameworks governing AI applications in aquaculture, which may slow their adoption.

9. Dependence on Technology

Excessive reliance on automated systems may reduce human observation and practical decision-making skills. Technical failures such as sensor malfunction, software errors, or network interruptions can disrupt farm operations if adequate backup systems are not available.

Although Artificial Intelligence offers considerable opportunities for improving aquaculture, challenges related to cost, infrastructure, technical expertise, data quality, cybersecurity, and regulatory support continue to limit its widespread adoption. Overcoming these constraints will require collaborative efforts among researchers, technology developers, policymakers, extension agencies, and aquaculture farmers. Investment in affordable AI technologies, digital infrastructure, farmer training, and standardized data management practices will be essential for promoting inclusive and sustainable AI-driven aquaculture in the future.

Future Prospects of Artificial Intelligence in Aquaculture

Artificial Intelligence (AI) is expected to play an increasingly important role in the future of aquaculture by enabling smart, efficient, and sustainable production systems. Continuous advancements in AI algorithms, sensor technologies, cloud computing, and automation are likely to improve farm management and address emerging challenges such as climate change, disease outbreaks, and increasing demand for aquatic food.

One of the major future developments will be the integration of AI with the **Internet of Things (IoT), big data analytics, robotics, blockchain, and digital twin technology**. These integrated systems will provide real-time monitoring, predictive analysis, and automated decision-making, enabling farmers to optimize water quality, feeding, fish health, and harvesting with greater accuracy and efficiency. The use of autonomous underwater vehicles (AUVs), drones, and robotic systems is also expected to expand for farm inspection, environmental monitoring, and routine management operations.

Advances in **machine learning** and **deep learning** will further improve disease diagnosis, growth prediction, biomass estimation, and fish behavior analysis. AI models trained on large datasets will become more accurate and adaptable to different species and farming systems. The integration of genomic information with AI

is also expected to accelerate precision breeding by identifying superior broodstock with desirable traits such as faster growth, disease resistance, and climate resilience.

Cloud-based platforms and mobile applications will make AI technologies more accessible to farmers by providing real-time recommendations and decision-support tools. As digital infrastructure improves and the cost of sensors and monitoring devices decreases, AI adoption is expected to increase among small- and medium-scale aquaculture enterprises. Government initiatives, public-private partnerships, and training programs will play an important role in promoting digital literacy and facilitating technology transfer to farming communities.

AI will also contribute to environmental sustainability by optimizing resource utilization, reducing feed waste, minimizing water pollution, and supporting climate-resilient aquaculture practices. Integration of AI with blockchain technology will enhance product traceability, food safety, and consumer confidence by ensuring transparent monitoring throughout the aquaculture supply chain.

Despite these promising developments, the successful implementation of AI will depend on continued research, high-quality data availability, supportive policies, standardized protocols, and capacity building among stakeholders. Collaboration among researchers, technology developers, industry, and policymakers will be essential to develop affordable, user-friendly, and scalable AI solutions suitable for diverse aquaculture systems. In conclusion, Artificial Intelligence has the potential to redefine the future of aquaculture by transforming conventional farming into an intelligent, data-driven, and sustainable production system. Its continued development and responsible adoption will improve productivity, profitability, environmental stewardship, and food security, making AI a cornerstone of next-generation aquaculture.

Conclusion

Artificial Intelligence (AI) is emerging as a transformative technology that is reshaping the aquaculture sector by enabling precision farming, real-time monitoring, and data-driven decision-making. The integration of AI tools such as machine learning, deep learning, computer vision, the Internet of Things (IoT), robotics, cloud computing, and big data analytics has significantly improved water quality management, feeding efficiency, disease diagnosis, fish health monitoring, biomass estimation, and harvest planning. These innovations enhance productivity, reduce operational costs, improve resource utilization, and support environmentally sustainable aquaculture practices.

Despite its immense potential, the adoption of AI is constrained by challenges such as high investment costs, limited digital infrastructure, inadequate technical expertise, and concerns regarding data quality and cybersecurity. Addressing these limitations through affordable technologies, capacity building, supportive policies, and collaborative research will be essential for wider adoption, particularly in developing countries.

As digital technologies continue to advance, AI is expected to become an integral component of modern aquaculture. Its ability to optimize production, strengthen climate resilience, improve traceability, and promote sustainable resource management will contribute significantly to global food security and the blue economy. The successful integration of AI with conventional aquaculture practices will not only enhance farm profitability but also ensure the long-term sustainability and resilience of the aquaculture industry.

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Integrated Fish Farming: A Sustainable Pathway to Rural Economic Development and Livelihood Enhancement



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Introduction

Integrated Aquaculture is a sustainable, synergistic farming system that combines the culture of fish/prawn with other farming systems. Instead of treating system as isolated operations, an integrated system links them together so that the by-products of one sub-system become valuable inputs for another. This approach maximizes returns from the limited land by efficiently recycling resources, lowers input costs, and generates multiple income streams from the same farm area. The most commonly observed practices include paddy-cum-fish culture (growing fish in flooded rice fields), poultry-fish farming, and cattle-fish integration. By imitating the natural ecological cycles, integrated aquaculture creates a closed-loop system that maximizes agricultural output while minimizing environmental degradation.

Impact of integrated aquaculture practices on rural communities

The impact of integrated aquaculture practices on rural communities can be observed in multi facets which include-

1. Impact on the Rural Economy: Integrated aquaculture is a best farming practice for rural economic growth, primarily by shifting farmers from subsistence agriculture to profitable, multi-commodity enterprises.

- **Income Diversification and Stability:** Due to fragmented land holdings and relying on a single crop or livestock leaves farmers vulnerable to market fluctuations, pests, or extreme weather. Since the integrated farming provides multiple revenue streams, even if one crop fails, yield from another system can act as an economic buffer.
- **Cost Reduction:** One of the advantages of integration is creation of wealth from waste. By recycling farm wastes which resulted from the unutilized feed, fertilizer, faeces etc., farmers significantly reduce their dependency on expensive external inputs like commercial fish feed and chemical fertilizers. This lowers the overall cost of production and increases profit margins.
- **Higher Yield per Unit Area:** Through integration, farmers can produce variety of farm products such as grain, meat, eggs, and fish from the same land, drastically increases the overall economic output per unit area compared to monoculture farming.

2. Impact on Livelihoods: The integrated systems not only generate additional income; in addition, they improve the day-to-day quality of life among rural communities.

- **Enhanced Food Security and Nutrition:** This system ensures balanced diet by combining carbohydrate-rich crops with high-quality protein (fish, eggs, meat) combats malnutrition and promotes better health.
- **Livelihood support:** Traditional crop farming is often seasonal, leaving farming communities without work for months. Integrated farming requires continuous management like feeding livestock, harvesting fish, and tending to crops create steady, and year-round employment for the farmers or labourers.
- **Empowerment of marginalized communities:** These systems can be easily adopted in small scale operations; therefore, they are highly accessible to limited land holding farmers and women, providing them with a steady, independent source of sustenance and income.

3. Resource Utilization: When resources like space and water are limited in availability which is the case may in majority of the rural areas, integrated aquaculture is the epitome of doing more with less.

4. Waste Utilization and the Circular Economy: Integrated aquaculture transforms potential pollutants into vital resources (Zero-Waste Loop) and Nutrient Recycling. These systems provide higher farm income through

multiple crops, make cheap protein available to rural populations, and increase productivity on small landholdings.

In this article, the economic feasibility of model fish cum cattle farming practice has been explained. It is one of the most popular and economically viable integrated systems.

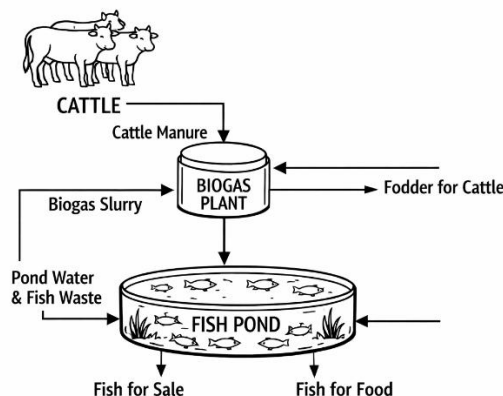


Fig. 1: Fish cum cattle farming

In fish cum cattle farming, cow dung is collected and used as an organic fertilizer in the fish pond. The dung promotes plankton growth (phytoplankton and zooplankton), which acts as natural feed for fish.

Availability of natural feed, reduce use of supplementary feed by 30-40%. The system ensures mutual benefits cattle in return get drinking water from pond whereas fish gets nutrient-rich input.

Cattle shed setup: Cattle shed is constructed on the pond embankment or adjacent to the pond. Channels are arranged to carry dung and urine into the pond. The size of the herd must be in the range of 10-15 per hectare pond.

Fish Species Recommended: The Major carps such as Rohu, Catla, Mrigal along with Tilapia and Silver carp are the ideal species for culture as they efficiently utilize plankton-based food.

Economic feasibility of fish cum cattle farming

The establishment cost varies by scale and region of operation. The cost incurred on the establishment of a model fish cum cattle farming consisting of 1 ha pond area along with 10 no.s of cattle are given as follows.

Table 1. Cost and returns in fish cum cattle farming (₹/ha/year)

Initial investment	Cost (₹)
Pond excavation/preparation	25,000-40,000
Fish fingerlings (10,000-15,000)	15,000-20,000
Cattle (10 cross-breed cows)	4,00,000-5,00,000
Cattle shed construction	50,000-75,000
Fencing & water channels	15,000-25,000
Total Initial Investment	₹5.05-6.6 lakhs
Operational Costs	
Supplemental fish feed	25,000-35,000
Cattle feed (supplement)	60,000-80,000
Labor (2 workers)	1,20,000-1,50,000
Veterinary & healthcare	15,000-20,000
Electricity & water	10,000-15,000
Total operational Cost	₹2.3-3.0 lakhs
Total cost (initial cost + operational cost)	7.35 – 9.6 lakhs
Economic benefits	
Fish Production: 6 tonnes/ha/year @ ₹90/kg	5.54 lakhs
Milk Production: 10 cattle × 5 litres/day × 250 days × ₹50/litre	6.25 lakhs
Manure Sales	25,000
Total revenue	12.04 lakhs
Net income (total revenue – total cost)	2.44 - 4.69 lakhs

Extra revenue can also be generated from the sale of calves, dry cattle, and bulls. Thus, the integrated fish cum cattle farming is economically viable.

Conclusion

Though, integrated fish and cattle farming offer high returns, safeguard livelihood, and eco-friendly farming practices, yet, it possesses several operational difficulties in the form of substantial upfront capital investment for ponds, livestock, and infrastructure, along with intense daily labour demands. Success depends heavily on technical expertise to manage ecological balance, as excessive dung can cause over-fertilization, oxygen depletion, and high fish mortality. Additionally, farmers are more often confronted with disease risks, rigorous water quality issues, and seasonal fluctuations in both milk production and winter fish growth alongside struggling to get dual-market access for their final products.

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From Ocean to Plate: Microplastics in Seafood and Their Impact on Human Health



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Abstract

Microplastics have become a major environmental issue, causing significant problems to marine ecosystems, seafood safety, and the fish processing industry. Formed through the degradation of larger plastic debris or released directly from various industrial and domestic sources, microplastics are now widely distributed in aquatic environments. These tiny plastic particles are ingested by a wide range of marine organisms, such as crustaceans, plankton, shellfish and fish, allowing them to enter the human food chain through seafood consumption. Besides the plastic particles themselves, microplastics can carry harmful chemicals and heavy metals that may pose potential health risks. This article highlights the sources of microplastics, their entry into seafood, their effects on marine organisms, challenges faced by the fish processing industry, potential human health concerns and practical strategies to reduce microplastic contamination for safer and more sustainable seafood production.

Keywords: Microplastics, Seafood, Fish Processing, Marine Pollution, Human Health, Seafood Safety

1. Introduction

Plastic pollution has become one of the biggest environmental challenges affecting marine ecosystems globally. Once plastics enter the ocean, they break down based on factors like the type of polymer, density, shape, and intended use. These properties also determine whether plastics float on the water surface, remain suspended in the water column, or sink to the seabed. Lightweight plastics are easily transported over long distances by ocean currents and wind. Based on their size, plastic debris is classified as megaplastic (>100 mm), macroplastic (>20 mm), mesoplastic (20–5 mm), microplastic (5 mm–1 µm) and nano plastics (<1 µm). When plastics are exposed to natural forces such as sunlight and wave action, they gradually degrade into microplastics—defined as plastic particles under 5 mm in size. This definition commonly includes plastic pieces in the nanoscale, < 1 µm in size. The rate of degradation varies with age, polymer type and environmental conditions like temperature, irradiation, weathering and pH. As a result, the degradation of larger plastic waste has become one of the primary sources of microplastic contamination in the marine environment. Global plastic waste generation is projected to triple by 2060, reaching approximately 155–265 million metric tons annually. These persistent plastic particles contaminate the marine ecosystem and the food chain, including foodstuffs intended for human consumption.

2. What is microplastic?

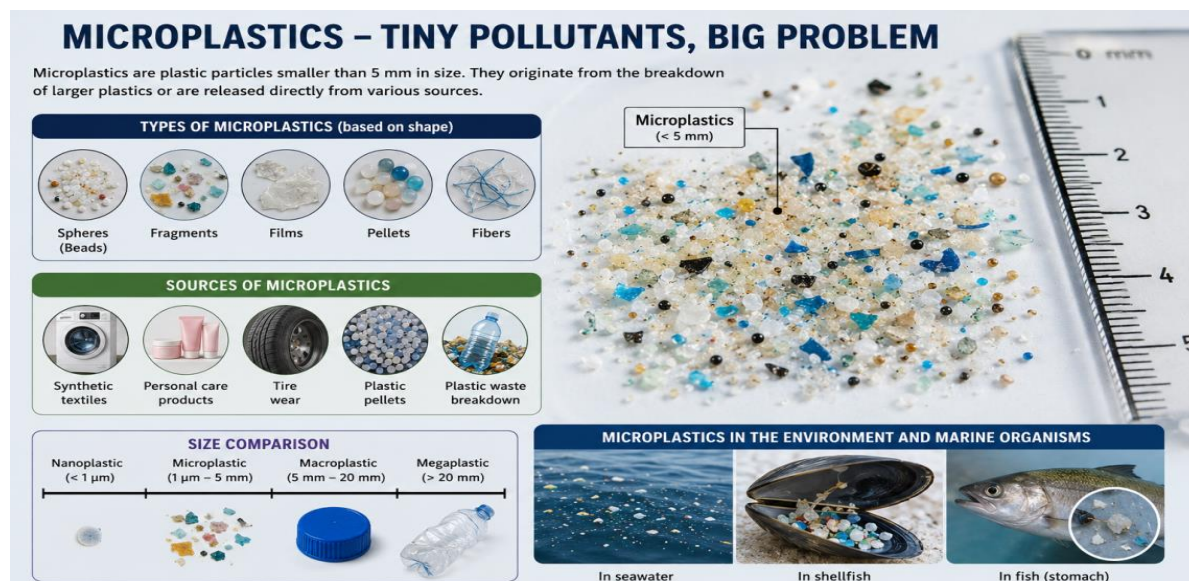
Microplastics (MPs) are tiny plastic particles smaller than 5 mm that differ in their size, shape, and chemical composition. They are now found everywhere—from oceans and rivers to sediments, beaches and even the atmosphere. The most common plastic types manufactured are polyethylene and polypropylene. Microplastics can be broadly classified into two categories: primary and secondary microplastics. Primary microplastics are very small or microscopic in structure and are directly or indirectly released into the environment through sources such as household and industrial effluents, sewage discharges, spills and wastewater. They commonly occur as spheres, films, pellets and fragments. In contrast, secondary MPs are made when larger pieces of plastic are broken down by microbial degradation, ultraviolet (UV) photo-oxidation and mechanical degradation.

In aquatic ecosystems, Microplastics originate from a variety of sources, such as domestic runoffs carrying cosmetic microbeads, industrial effluents, sewage treatment plant discharges, synthetic textile fibres, tyre wear, road markings, plastic pellets, marine coatings, and improperly managed plastic waste. Shipping and other maritime activities also contribute to marine plastic pollution through the disposal and burning of plastic materials. Besides being pollutants themselves, microplastics can adsorb toxic substances such as polychlorinated biphenyls

(PCBs), dichlorodiphenyltrichloroethane (DDT), and heavy metals including cadmium (Cd), lead (Pb), and arsenic (As), facilitating their movement through aquatic ecosystems. Most microplastics are composed of durable synthetic polymers such as polyethylene (PE), polypropylene (PP), polyamide (PA), polyvinyl chloride (PVC), polystyrene (PS), and polyethylene terephthalate (PET), which resist degradation and persist in the environment for long periods.

3. Entry of Microplastics into Seafood

The major sources of plastic waste entering the oceans include urban and industrial activities, boating, shipping, fishing, and aquaculture. Today, microplastics have been detected in almost every environment, including terrestrial ecosystems such as land, islands, cities and beaches and even the atmosphere. Once released into aquatic ecosystems including marine, river, lake, reservoir and pond environments.



A wide range of marine organisms, including phytoplankton, zooplankton, invertebrates, mollusks, corals, crustaceans, and fish, ingest microplastics either directly from the surrounding water or indirectly through contaminated food. Filter-feeding shellfish, including mussels and oysters, are particularly vulnerable because they continuously filter large volumes of water, increasing the likelihood of microplastic accumulation. Similarly, shrimps, prawns, crabs, lobsters and crayfish can absorb microplastics through their gills and mouthparts, where they accumulation in internal organs. may damage tissues, alter gut microorganisms, weaken the immune system, increase oxidative stress, and reduce survival. Small fish and bivalves that are consumed whole are considered important pathways for the transfer of microplastics from seafood to humans. Marine invertebrates with various feeding methods, including mussels (filter feeders), lugworms (deposit feeders), and sea cucumbers (detritivores), have been documented to ingest microplastics due to their particle size similarity to plankton.

Table 1. Effects of Microplastics on Marine Organisms

Marine organism	Major impacts of microplastics
Plankton	Reduces growth, photosynthesis, oxygen production, and reproductive success.
Corals	Induces bleaching, tissue necrosis and inhibits growth
Crustaceans (shrimps, prawns, crabs, lobsters, and crayfish)	Causes tissue damage, oxidative stress, impaired feeding, and reduced survival.
Other invertebrates	Blocks digestive tract, reduces growth and reproductive performance.
Seagrass	Accumulates microplastics and facilitates their transfer through the food web
Fish	Causes gut blockage, oxidative stress, immune dysfunction and behavioral changes

4. Challenges for Fish Processing

Microplastic contamination has become an emerging concern for the seafood processing industry. The presence of microplastics in fish and shellfish can affect product quality, safety, and consumer acceptance. Because these particles are extremely small, they are difficult to detect and completely remove during conventional processing methods. Filter-feeding shellfish and small fish consumed whole are more likely to accumulate microplastics, increasing the risk of human exposure. There is a need for advanced monitoring technologies in seafood processing. Therefore, seafood processors should implement effective quality control measures, routine monitoring and improved processing practices to minimize microplastic contamination and ensure the safety of seafood products.

5. Human Health Concerns

Microplastics may cause harm to humans through both physical and chemical pathways. Seafood is one of the major pathways through which humans may be exposed to microplastics. Once ingested, these tiny plastic particles may not only enter the body but also carry harmful substances such as heavy metals, bisphenol A (BPA), and persistent organic pollutants (POPs). Although long-term health effects of microplastic exposure are still being investigated, research suggests that prolonged exposure may contribute to oxidative stress, inflammation, and other adverse health effects. Therefore, continuous research and regular monitoring are essential to better understand the potential health risks associated with microplastic-contaminated seafood.

6. Strategies to Reduce Microplastic Contamination

- Strengthening plastic waste management through efficient collection, segregation, recycling, and safe disposal to prevent plastic leakage into aquatic environments.
- Reducing the use of single-use plastics by promoting reusable and environmentally friendly alternatives.
- Upgrading wastewater treatment systems to improve the removal of microplastic particles before treated water is discharged into rivers and oceans.
- Encouraging sustainable fishing and aquaculture practices, including responsible handling and disposal of plastic fishing gear and aquaculture materials.
- Implementing regular monitoring and quality control throughout the seafood supply chain to detect and minimize microplastic contamination.
- Increasing public awareness through education and community participation to encourage responsible plastic use and disposal.
- Supporting research and policy development to improve monitoring methods, establish regulatory guidelines, and develop innovative solutions for reducing microplastic pollution.

7. Conclusion

Microplastic contamination has become an emerging concern for seafood safety, fish processing, and public health. As microplastics continue to accumulate in marine ecosystems, they enter seafood through the food chain and may affect both aquatic organisms and consumers. Effective plastic waste management, sustainable fishing practices, improved wastewater treatment, and regular monitoring of seafood are essential to minimize contamination. Combined efforts from governments, industries, researchers, and the public are crucial to reduce microplastic pollution and ensure the long-term sustainability, quality, and safety of seafood resources.

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Social Media for Agricultural Knowledge Dissemination: Transforming Modern Agricultural Extension



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Introduction

The rapid advancement of information and communication technologies (ICTs) has transformed agricultural extension services worldwide. Among these technologies, **social media** has emerged as a powerful platform for disseminating agricultural knowledge, connecting farmers with experts, facilitating peer-to-peer learning, and promoting innovation. Platforms such as **WhatsApp, YouTube, Facebook, Instagram, Telegram, and X (formerly Twitter)** enable agricultural information to reach farmers quickly, cost-effectively, and interactively. In India, where smartphone penetration and internet connectivity are increasing even in rural areas, social media has become an indispensable tool for modern agricultural extension.

What is Social Media in Agricultural Extension?

Social media refers to internet-based platforms that enable users to create, share, and exchange information in real time. In agricultural extension, these platforms serve as virtual knowledge-sharing networks where farmers, scientists, extension personnel, agripreneurs, input dealers, and policymakers interact to exchange information and solve farming problems.

Unlike traditional extension methods, social media allows two-way communication, enabling farmers not only to receive information but also to ask questions, share experiences, and learn from fellow farmers.

Importance of Social Media in Agriculture

Social media has significantly reduced the gap between research institutions and farming communities. It provides farmers with timely access to scientific recommendations, market information, weather forecasts, pest and disease alerts, government schemes, and success stories.

Major benefits include:

- Rapid dissemination of agricultural technologies
- Real-time interaction between farmers and experts
- Cost-effective extension communication
- Wide geographical coverage
- Easy access to audio-visual learning materials
- Increased farmer participation
- Promotion of farmer innovations

Popular Social Media Platforms Used in Agricultural Extension

1. WhatsApp

WhatsApp is the most widely used extension platform in India. Agricultural officers and KVK scientists create farmer groups to share:

- Crop advisories
- Weather alerts
- Pest and disease management practices
- Training schedules
- Government scheme information

Farmers can also upload photographs of diseased crops for immediate expert diagnosis.

2. YouTube

YouTube has become an excellent educational platform where farmers learn through demonstration videos on:

- Crop cultivation

- Pruning techniques
- Drip irrigation
- Organic farming
- Machinery operation
- Protected cultivation

Visual demonstrations improve understanding more effectively than printed materials.

3. Facebook

Facebook groups help farmers discuss cultivation practices, market prices, success stories, and innovative technologies. Agricultural universities and KVKs regularly post extension materials through their official pages.

4. Instagram

Short educational videos (Reels) are increasingly popular among young farmers. These videos demonstrate:

- Nursery management
- Grafting techniques
- Pest identification
- Farm mechanization
- Value addition

5. Telegram

Telegram supports sharing large documents, e-books, training manuals, and recorded lectures without significant storage limitations.

6. X (Twitter)

Agricultural departments, universities, ICAR institutes, and policymakers use X for instant dissemination of:

- Weather warnings
- Government announcements
- Crop advisories
- Success stories

Role of Social Media in Agricultural Knowledge Dissemination

Social media contributes to agricultural development in several ways:

1. Technology Transfer

Latest research findings reach farmers immediately without delays associated with conventional extension methods.

2. Pest and Disease Surveillance

Farmers share crop photographs, enabling experts to provide quick diagnosis and recommendations.

3. Weather-Based Advisory

Timely weather updates help farmers make informed decisions regarding irrigation, spraying, and harvesting.

4. Market Intelligence

Daily commodity prices and marketing opportunities can be shared instantly.

5. Capacity Building

Live webinars, online training programmes, and virtual demonstrations enhance farmers' knowledge and skills.

6. Farmer-to-Farmer Learning

Farmers share successful practices, innovations, and experiences, encouraging peer learning.

Advantages of Social Media in Agricultural Extension

- Low communication cost
- Instant information sharing
- Interactive learning environment
- Wider outreach
- Improved decision-making
- Greater farmer participation
- Multimedia-based learning

- Encourages innovation
- Supports digital agriculture
- Strengthens collaboration among stakeholders

Challenges

Despite its advantages, several challenges remain:

- Digital illiteracy among elderly farmers
- Poor internet connectivity in remote villages
- Spread of misinformation
- Language barriers
- Lack of verification of online information
- Limited smartphone ownership among some farmers
- Privacy and cybersecurity concerns

Role of Extension Professionals

Extension scientists should actively utilize social media by:

- Creating verified advisory groups
- Producing localized content in regional languages
- Fact-checking agricultural information before dissemination
- Conducting online training sessions
- Sharing success stories of progressive farmers
- Encouraging digital literacy among farming communities
- Integrating social media with traditional extension methods

Future Prospects

The future of agricultural extension lies in the integration of social media with emerging technologies such as Artificial Intelligence (AI), drones, Internet of Things (IoT), remote sensing, and decision support systems. Personalized advisories, AI-powered chatbots, multilingual voice assistants, and real-time crop monitoring will further enhance the effectiveness of digital extension services.

Conclusion

Social media has revolutionized agricultural knowledge dissemination by making extension services faster, more interactive, and farmer-centric. While challenges such as misinformation and digital literacy need attention, the benefits far outweigh the limitations. By combining scientific expertise with digital communication platforms, extension professionals can bridge the gap between research and farmers, improve technology adoption, and contribute to sustainable agricultural development. The effective use of social media will play a pivotal role in shaping the future of agricultural extension and empowering farming communities in the digital age.

PLANTS AS AUTOMATIC BIOCLEANSERS



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Introduction:

With an increase in pollution level, the indoor air is not fresh as much as we thought. As documented by the Environmental Protection Agency (EPA), at certain instances, the air inside our home can be 2 to 5 times more impure than the external environment. In our home, household products like paints, furniture, carpets & other appliances release the harmful invisible toxins in to the air that we breathe every day. Plants are act as a nature's little air filters. Bio cleansing plants are the air purifying plants that naturally pulls the harmful chemicals, dust, toxins through photosynthesis & transpiration process. An experiment was conducted by NASA in 1989 to discovers the plants that are useful in absorbing the harmful toxins from the air especially in indoor conditions. The study reveals that the indoor plants can remove up to 87% of toxins present in air within a day.

The common indoor pollutants includes:

- Formaldehyde – Commonly found in furniture, paper products & plywood.
- Benzene – It is usually present in the plastics & synthetic fibres.
- Trichloroethylene – Predominantly found in the cleaning products.
- Xylene & Toluene – It stays in the rubber products & wall paints, nail paints.
- Ammonia – It is present in certain electronic devices used in our home and also found in cleaning products & fertilizers.

Potential health risk caused by indoor pollutants:

Indoor air pollution is one of the serious problems from which peoples throughout the world suffers from many health hazards. As per the World Health Organization (WHO), more than three million people die every year from diseases caused by household air toxicants. Breathing polluted indoor air, even for a short period of time, can lead to many health problems like difficulties in breathing, heart disease, poor brain function, and even causes deadliest cancer. The WHO evaluated that about 3.8 million people die each year because of sicknesses resulted from the harmful smokes released from dirty cookstoves and fuel in our home. Children, older adults, people with existing health conditions, and the families with low income status are especially at a higher risk because they are often exposed to higher levels of indoor pollutants.

Benefits of bio cleanser plants:

- They help in removing the harm full chemicals and toxins from the air.
- Helps in maintain the relative humidity.
- They help in reducing the dust particles & airborne pathogens.
- Throughout the day they provide us the fresh air.
- By the fresher environment they support the respiratory comfort.
- Certain plants are also helps in fight against the mould.
- They help in reducing the stress & improve our mental health condition.
- Along with purification they also enhance the aesthetic appearance of our house.
- They promote the sustainability, environmentally friendly living.

Some of the top bio cleanser plants include:

Sl. no.	Plant name	Scientific name	Benefits	Picture
1.	Spider plant	<i>Chlorophytum comosum</i>	These are the great air purifiers having an ability to remove the harmful pollutants like formaldehyde, xylene & toluene. They can also help in removing the carbon monoxides that generate near the stoves in our kitchen.	
2.	Snake plant	<i>Sansevieria trifasciata</i>	Like spider plant these plants are also helps in removing the common indoor toxins like formaldehyde, xylene & nitrogen oxides. They can grow easily & require very low maintenance.	
3.	Aloe vera	<i>Aloe barbadensis</i>	It is a succulent that helps in removing the formaldehyde & benzene from atmospheric air, uptake the carbon dioxide & release the lavish amount of oxygen to the atmosphere.	
4.	Peace lily	<i>Spathiphyllum wallisii</i>	These are the excellent air cleaners that removes all the common indoor toxins & pollutants like formaldehyde, xylene, ammonia, benzene & trichloroethylene. They not only purify our home but also increase the aesthetic appearance of the home space.	
5.	English Ivy	<i>Hedera helix</i>	It is a multipurpose air purifier which effectively removes the pollutants like benzene, formaldehyde, trichloroethylene, toluene and xylene. The experimental results have also shown that it reduces about 78% of the airborne mould particles.	

6.	Golden Pothos	<i>Epipremnum aureum</i>	NASA's clean air study has proven that Pothos is extremely effective at screening out indoor pollutants like toluene, benzene, formaldehyde, xylene, and trichloroethene, which are commonly found in cleaning materials in our homes.	
7.	Boston Fern	<i>Nephrolepis exaltata</i>	Its vigorous, feathery fronds which act as a natural humidifier is perfect for indoor environment. It is one of the best air purifier plants that helps in eradicate the air pollutants like formaldehyde and xylene.	
8.	Dwarf Date Palm	<i>Phoenix roebelenii</i>	It is a decorous, steady developing palm and an excellent formaldehyde and xylene absorbers. It enhances the aesthetic appearance of the living spaces.	
9.	Chinese Evergreen	<i>Aglaonema modestum</i>	This is one of the most popular houseplants for providing oxygen at home and well known for removing the toxins like formaldehyde and benzene. This gem of a plant require minimal care & maintenance.	
10.	Dracaena	<i>Dracaena</i> spp.	It is a great long-term companion like many indoor plants for better oxygen & contributes to a cleaner, healthier indoor environment. It also helps in removing the pollutants like formaldehyde, benzene, trichloroethylene, xylene, and toluene.	
11.	Areca Palm	<i>Dypsis lutescens</i>	It is a best natural humidifiers that helps in removes the toxins like formaldehyde, xylene, and toluene. It adds a natural and tropical feel to any space.	

12.	Gerbera Daisy	<i>Gerbera Jamesonii</i>	The Barberton daisy removed more benzene & trichloroethylene than any other plants. It needs more light than other air purifying plants but brighten any room with stunning colourful blooms.	
13.	Weeping Fig	<i>Ficus benjamina</i>	It is a well-liked house plant which effectively removes formaldehyde, xylene and toluene. It's been used as an indoor decor for decades.	
14.	Florist's Chrysanthemum	<i>Chrysanthemum morifolium</i>	Chrysanthemums are also one of the top air purifiers that helps in removing benzene, formaldehyde, trichloroethylene, xylene, and ammonia effectively. They add a pop of colour with their blooms to improve the view.	
15.	Rubber Plant	<i>Ficus elastica</i>	They are well known for bigger, shiny leaves that filter formaldehyde from the air. Its thick, waxy foliage also helps in increase the humidity through natural transpiration.	

Future prospect:

With growing population and industrialization the pollution is also significantly increases. To improve the air quality, these bio cleanser plants plays an important role and become essential part in our home, offices, schools, colleges, hospitals & other indoor environments. As environmental concerns continue to rise, the integration of indoor plants can provide more healthier, eco-friendly living environments & enhancing the human health and well-being. Further scientific researches and studies are conducted to identify more plant species with enhanced air-purifying abilities.

Conclusion:

Bio cleanser plants are simple, cost efficient, eco-friendly and worthwhile solution for improving the indoor air quality. They helps in removing the toxic pollutants like formaldehyde, benzene, xylene, toluene, ammonia, and trichloroethylene while provide the fresh air and maintain the relative humidity. Besides air purification, they also adds the aesthetic appeal to our indoor spaces & contribute towards better physical as well as mental health. Despite these plants are not able to fully replace with the mechanical air purification systems, but an effective step towards creating a more cleaner and sustainable living spaces.

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Bioremediation for Pesticide Residue Management



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Introduction

Rapid agricultural intensification and increased reliance on pesticides have contributed to the accumulation of pesticide residues in agricultural soils, water bodies and food commodities. Although pesticides play a vital role in protecting crops from insect pests, diseases and weeds, their extensive and indiscriminate use has resulted in the persistence of hazardous residues in the environment, making pesticide residue management an emerging environmental and public health concern.

Residual pesticides may undergo adsorption, leaching, volatilization and transformation, facilitating their movement through different environmental niches. Their accumulation in agricultural soils can adversely affect soil microbial communities, disrupt ecological processes and contaminate surface and groundwater, creating potential exposure pathways for humans, livestock and aquatic organisms. The presence of pesticide residues in food commodities is of particular concern as they may enter the human food chain. Prolonged exposure to organochlorine and organophosphate pesticides has been associated with carcinogenic effects, neurological disorders, reproductive abnormalities and endocrine disruption. Pesticides may also adversely affect beneficial organisms such as pollinators, natural enemies and soil fauna, thereby disrupting ecological balance and natural pest regulation.

Sustainable approaches for managing pesticide residues are essential. Conventional physical and chemical remediation methods may be expensive, energy-intensive and capable of generating secondary pollutants. Bioremediation, which utilizes the metabolic capabilities of microorganisms, plants and other biological agents to transform, degrade or immobilize contaminants has emerged as a promising eco-friendly alternative. Understanding the biological mechanisms and factors influencing pesticide degradation is essential for harnessing bioremediation as a sustainable strategy to reduce pesticide residues and restore contaminated agricultural ecosystems.

1. Mechanisms of Pesticide Bioremediation

Bioremediation emerges as a potent tool in the environmental pollution mitigation arsenal. Ideally aiming for the complete decomposition of pesticides into harmless molecules, bioremediation encompasses diverse approaches

1.1 Bioabsorption and bioadsorption (where the pesticide adheres or penetrates the organism)

1.2 Biotransformation (where the pesticide is converted into another molecule through enzymes and nanoenzymes) using enzymes and nanoenzymes

The degradation is facilitated by microorganisms such as bacteria, fungi, macro- and microalgae or phytoremediation.

2. Effect of Pesticides

Pesticides can persist in the environment and accumulate in living organisms through different pathways. Bioaccumulation occurs when pesticide residues build up within an individual organism faster than they are eliminated while bioconcentration occurs when chemicals are absorbed directly from the surrounding environment, particularly water at concentrations higher than those present externally. As these contaminated organisms are consumed by successive organisms in a food chain, pesticide concentrations may increase at higher trophic levels through biomagnification.

Table 1. Comparison of Biomagnification, Bioaccumulation and Bioconcentration

Bio-magnification	Bio-accumulation	Bio-concentration
Bio-amplification (or) biomagnification refers to an increase in the concentration of a substance as you move up the food chain.	Bioaccumulation occurs within an organism, where a concentration of a substance builds up in the tissues and is absorbed faster than it is removed.	Bioconcentration is the process by which a chemical's concentration in an organism becomes higher than the concentration of the chemical in the surrounding air or water.

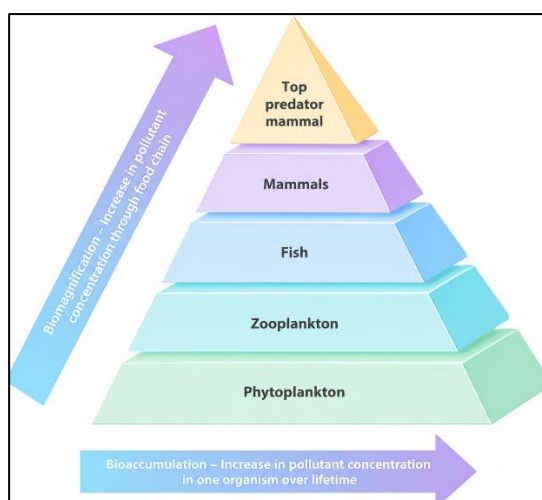


Figure 1. Accumulation of pollutants across trophic levels

3. Classification of Bioremediation

Based on transportation and removal of waste, bioremediation is classified as follows:

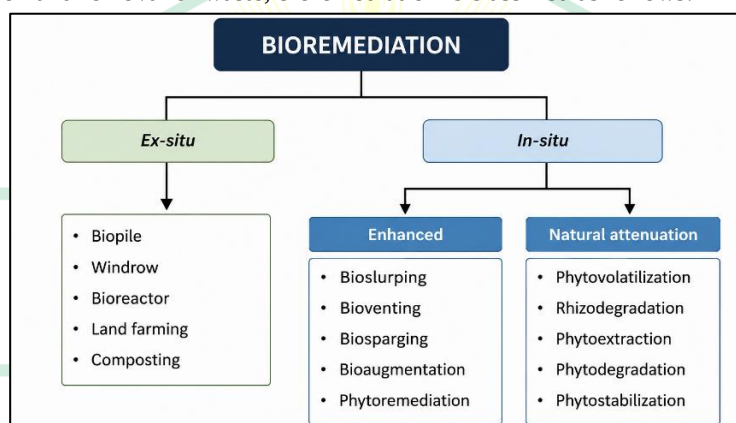


Figure 2. Classification of Bioremediation

3.1 Ex-situ bioremediation: This is a process where the treatment of pollutants is done away from the contaminated site with the help of processes like composting, bioreactors, etc. Contaminated water or soil has to be moved away from the contaminant site to the site with better conditions. Selection of technique depends on the depth of pollution, type of pollutant, degree of pollution, cost of treatment, geographical location and geological area of the site.

3.1.1 Biopile: It is a technique used to enhance bioremediation by increasing microbial activities. Contaminated soil or water is excavated, and extra nutrients are added followed by aeration. This technique can also be used to treat pollutants in extreme climates also.

3.1.2 Windrows: It is a technique used to enhance bioremediation by increasing degradation activities. Due to its tendency to remove hydrocarbon, it is more preferred to treat polluted soil compared to contaminated water.

3.1.3 Bioreactors: Bioreactors are the container in which biodegradation of pollutants is done under suitable conditions by mixing contaminants with suitable microbes. Different operating modes of bioreactors are batch, fed-batch, sequencing batch, multistage and continuous. The main advantage of a bioreactor is its excellent control over bioprocess parameters like pH, temperature, agitation, aeration rate and column concentration.

3.1.4 Land farming: It is the simplest technique owing to less cost and less equipment. There is a large debate on whether land farming is *in-situ* or *ex-situ*; it depends on pollution depth. Suppose the depth of the pollutant is less than 1 meter. In that case, it is said *in-situ* because excavation is not necessary. In contrast, if the depth of the pollutant is greater than 1 meter, it is said to be *ex-situ*.

3.1.5 Composting: It is an approach for the bioremediation of pesticides. It consists of mixing the contaminated soil with nonhazardous organic amendments to promote the development of bacterial and/or fungi population, able to degrade the pesticides through a co-metabolic pathway.

3.2 In-situ bioremediation: This is a process where the treatment of pollutants is done inside the contaminant with the help of processes like biostimulation, bio-venting, bioaugmentation, etc. It does not require excavation. Ideally, these techniques are the least expensive. Status of electron acceptor, moisture content, pH, temperature and nutrient availability are important environmental conditions for this process.

3.2.1 Enhanced bioremediation: It is the process of bioremediation in which microorganisms like fungi, bacteria and other microbe degrade contaminants found in groundwater in harmless forms. In this process, stimulating materials are added, including nutrients, nitrogen and phosphorous increasing microbial growth.

3.2.1.1 Bioslurping: It is a technique used to achieve soil and groundwater remediation. It combines vacuum pumping, bioventing, soil vapor extraction by stimulation of contaminant biodegradation. It is difficult to establish a vacuum on a deep high because it may create saturated soil lenses that are difficult to aerate.

3.2.1.2 Bioventing: It is the process of providing suitable conditions to microbes for proliferation and enhancing the degradation process of any aerobically degradable compound. The addition of nutrients and moisture is done to enhance bioremediation.

3.2.1.3 Biosparging: In this technique, the air is injected into the soil surface to increase microbial activities to promote pollutants from the contaminated site. This technique is mostly used to treat aquifers contaminated by petroleum.

3.2.1.4 Bioaugmentation: The process involves the inoculation of microbial consortia or single strains into the soil, by augmenting the microbial diversity. In this way, microorganisms with specific metabolic capabilities promote the biodegradation processes.

3.2.1.5 Phytoremediation: Phytoremediation basically refers to the use of plants and associated soil microbes to reduce the concentrations or toxic effects of contaminants in the environment. It requires a long time period, large area, climatic conditions, etc. Phytoremediation is widely accepted as a cost-effective environmental restoration technology. This can be achieved by different processes that are mentioned below:

3.2.2 Natural attenuation: It is a process which utilizes natural biodegradation of contaminated site. It makes the biological decay of pollutants easier. It is also known as passive or intrinsic remediation.

3.2.2.1 Phytovolatilization: Plants absorb contaminants from the soil and release them into the gaseous atmosphere in an unstable form through the process of transpiration.

3.2.2.2 Rhizodegradation: It is the symbiotic relationship between plants and microbes. It is the breakdown of the contaminants due to the presence of protein, enzymes by plants or soil organisms in the Rhizosphere.

3.2.2.3 Phytodegradation: Breaking down complex compounds into a simpler form by plants and microorganisms is associated with them.

3.2.2.4 Phytoextraction: Plants take up the contaminants from water and pass them from the roots to the plant's upper parts.

3.2.2.5 Phytostabilization: Certain plant species are used to bring contaminants from water and soil.

4. Role of endophytes in phytoremediation

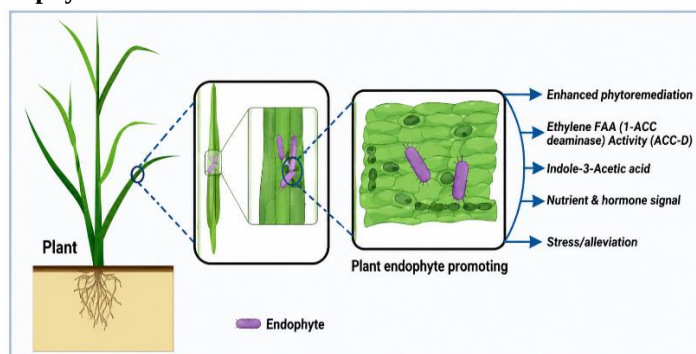


Figure 3. Plant-endophyte interaction assisted phytoremediation

The role of plant-associated microorganisms (rhizospheric microorganisms) can be considered as an alternative approach to improve plant performance for phytoremediation. Plant growth-promoting rhizobacteria (PGPR) have a key role in phytoremediation. PGPR can promote plant growth via IAA production, antimicrobial activity, increase plant tolerance against heavy metals and improved nutrient uptake through diffusion as well as uptake of heavy metal from contaminated soil, translocation etc.

Table 2. Examples of some endophytes used in bioremediation

Endophytes	Plant Source	Tissue parts used
Bacteria <i>Kocuria ascorbata</i>	<i>Prosopis laevigata</i> , <i>Sphaeralcea angustifolia</i>	Root
	<i>Solanum lycopersicum</i> , <i>Brassica napus</i>	Seed tissue
Rhizobacteria	<i>Thalaspia caerulescens</i> , <i>Alyssum bertolonii</i>	Root
Plant growth promoting bacteria and Arbuscular Mycorrhizal Fungi	<i>Populus alba</i>	Leaves
	<i>Liriodendron tulipifera</i>	Root
Microbacterium, Bacillus, Arthrobacter, Flavobacterium	<i>Solanum nigrum</i>	Roots

5. Biological Techniques for Pesticide Removal

5.1 Microbial Degradation: During biodegradation processes, pesticides are transformed into degradation products or completely mineralized by microorganisms which use the pollutant compounds as nutrients for their metabolic reactions. The degradation process of pesticides can be divided into three phases, which can be summarized as:

Phase 1: Pesticides are transformed into more water-soluble and less toxic products through oxidation, reduction, or hydrolysis reactions.

Phase 2: The Phase-1 products are converted into sugars and amino acids, which have higher water solubility and lower toxicity.

Phase 3: Conversion of the Phase-2 metabolites into less toxic secondary conjugates. The microorganisms involved in the degradation process are bacteria or fungi, which may generate intra- or extra-cellular enzymes.

5.2 Bacterial Degradation: In the years, several bacterial strains were identified as capable of degrading the pesticides present in the soils. Each bacterium has a specificity that makes it particularly suitable for a degradative process. The operative conditions, such as temperature, pH, water content and types of pollutants, affect the adaptation, development and role of a bacterial strain. **E.G:** Chlorpyrifos, an organophosphate used as an insecticide, is hydrolyzed by microorganisms, and the primary and major degradation product is 3,5,6-trichloro-2-pyridinol (TCP). TCP has greater water solubility than chlorpyrifos and causes widespread contamination in soils and aquatic environments.

5.3 Fungal Degradation: The agricultural soils are populated by many fungi, which can be exploited to biodegrade pesticides. This class of microorganisms includes yeast, molds, and filamentous fungi. Fungal degradation is promoted by its capacity to produce many enzymes involved in degradative processes. Fungi can be better degraders than bacteria due to their characteristics, such as specific bioactivity, growth morphology, and high resistance even at high concentrations of pollutants.

5.4 Enzymatic Degradation: Enzymatic biodegradation is due to the enzymes produced during the metabolic processes of microorganisms or plants. Enzymes are biological macromolecules that can catalyze biochemical reactions involved in pesticide degradation.

5.4.1 Oxidation, which is the first step of the degradation of pesticides, consists of the transfer of an electron from reductants to oxidants. Oxygenase and laccase enzymes may be involved in this reaction.

5.4.2 Hydrolysis permits the cleavage of bonds of the substrate by adding hydrogen or hydroxyl groups from water molecules. The pesticide molecules are thus divided into smaller chain compounds than the original ones. **E.g:** esterase gene from *Rhodopseudomonas palustris* PSB-S cloned was capable of decomposing several synthetic pyrethroids, such as fenpropathrin, and tolerates temperature and pH changes. The enzyme is involved in the key step of hydrolysis, namely the cleavage of the ester bond in the fenpropathrin compound.

5.4.3 Reduction permits the transformation through reductive enzymes (nitroreductase).

5.4.4 The conjugation reaction is carried out using existing enzymes, and it is typical of fungal biodegradation. It involves the addition of exogenous or endogenous natural compounds to facilitate the mineralization of pesticides. This process includes reactions such as xyloxylation, alkylation, acylation, and nitrosylation.

5.5 Mineralization: The mineralization process permits the degradation of pesticides into inorganic matter, namely, carbon dioxide, salts, minerals, and water. The microorganisms use the pesticide compounds as a source of nutrients. **E.G:** Chlorothalonil (CTN), an organochlorine fungicide, is degraded in CO₂, but if the soil microbial community is reduced, several metabolites can form, which are more toxic, persistent, and mobile than CTN itself. This is due to the absence of actively-degrading groups or the decrease in soil biodiversity that leads to low microbial activity.

5.6 Co-Metabolism: It is the biotransformation, through a series of reactions, of an organic compound that is not used to support microbial growth. The pesticides are transformed by microorganisms and enzymes into useful compounds for other biological, chemical, and physical transformations, and finally degraded thanks to this synergistic effect. **E.G:** *P. indica* CGMCC 6648 is the tested bacterium, capable of degrading imidacloprid (IMI) through the hydroxylation pathway, and forms two metabolites: one olefin and 5- hydroxy IMI. In the co-metabolic process, the involved enzymes can be hydrolytic enzymes (esterases, amidases, and nitrilases), transferases (glutathione S-transferase and glucosyl transferases), oxidases (cytochrome P-450s and peroxidase) and reductases (nitroreductases and reductive dehalogenases).

Conclusion

The acceleration of biodegradation necessitates identifying and developing efficient organisms, achieved through bioprospection and targeted modifications. Specific strategies to enhance process efficiency and throughput include optimizing biomass production, strategic inoculation in diverse environments, and employing bioreactor systems for processing heavily contaminated waters or soils. Omics-based technologies and databases have opened-up new vistas in all areas of biotechnology for pesticides-bioremediation. Nanotechnology and immobolization technology have also shown remarkable potential in this field.

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Growing Wealth Under Cover: A Farmer's Success with Poly house Coloured Capsicum Cultivation From Traditional Farming to Modern Horticulture



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Shri Madesha S. was previously engaged in traditional farming, cultivating millet crops and vegetable under open field cultivation that generated low yields and limited income. Seeking better opportunities and sustainable profitability, he explored various government-supported horticulture schemes. Upon learning about the benefits of the National Horticulture Board (NHB) schemes, he decided to venture into protected cultivation of coloured capsicum under polyhouse conditions.

With a clear vision to produce high-quality vegetables and improve farm income, he established a hi-tech polyhouse project covering 4,000 square metres as per NHB specifications and standards. The project was implemented with the guidance of the National Horticulture Board and financial support from Bank of India, Byranahalli Branch, Nelamangala Taluk.

Building a Foundation for Success

The success of the project is rooted in its modern infrastructure. One poly house unit covering a total area of 4,000 square metres were established to provide a controlled environment for crop production. The polyhouses are equipped with advanced drip irrigation and fertigation systems, enabling precise application of water and nutrients to approximately 14,000 coloured capsicum plants.

Water management was given special attention. A borewell drilled to a depth of 950 feet, fitted with a 7.5 HP motor, ensures a reliable water supply throughout the year. To enhance water conservation a scientifically designed rainwater harvesting tank measuring 18 M × 19 M × 5 M and lined with a 500-micron polyfilm sheet was constructed.

The farm is also equipped with essential horticultural machinery and equipment, including power sprayers and other modern tools. A labour room measuring 6.80 M × 6.00 M was constructed to support efficient farm operations from permanent labours.



NHB Assisted Project

NHB Assistance: Turning Vision into Reality

The total project cost was Rs 57.21 lakh. Of this, Rs 42.91 lakh was availed as a term loan from Bank of India, Byranahalli Branch, while the remaining Rs 14.30 lakh was invested by the farmer from his own resources.



Coloured Capsicum under Poly house

A major boost to the project came through the National Horticulture Board's capital investment back end subsidy. Under the NHB scheme, Shri Madesha S. received timely subsidy assistance of Rs 21.83 lakh, which significantly reduced the financial burden and encouraged the adoption of advanced horticultural technologies.

Harvesting Prosperity Through Protected Cultivation

The results have been highly encouraging. By following scientific cultivation practices and adopting organic and sustainable crop management methods, Shri Madesha S. has achieved impressive productivity levels.

From the 4000 square metre polyhouse, the farmer harvested an impressive 56 MT of premium-quality coloured capsicum during 2024-25 and 42 MT during 2025-26 comprising green, red and yellow varieties. The produce known for its superior quality and market appeal consistently fetched remunerative prices, ensuring strong financial returns. Over the two year period the he generated an average net profit of approximately Rs 21.70 lakh per acre per annum.

According to Shri Madesha S., the timely financial assistance and technical support provided by the National Horticulture Board played a pivotal role in the success of the project. The adoption of protected cultivation technology has enabled him to overcome climatic uncertainties, improve productivity and secure a stable income.



Coloured Capsicum

A Role Model for Progressive Farmers

The success of Shri Madesha S. serves as an inspiring example of how modern horticulture technologies can transform the lives of farmers. His journey demonstrates that with proper planning, scientific cultivation methods, institutional support and access to finance, farmers can significantly enhance their productivity and profitability.

Today, his poly house farm stands as a model for aspiring entrepreneurs and progressive farmers across Karnataka, encouraging them to embrace protected cultivation and diversify into high-value horticultural crops.



Cultivating a Brighter Future

The story of Shri Madesha S. is not merely about cultivating coloured capsicum; it is about cultivating prosperity through innovation. His remarkable journey highlights the transformative impact of NHB-supported projects in promoting modern horticulture and improving farmers' livelihoods.

As Indian agriculture moves towards technology-driven and climate-resilient farming systems, success stories like that of Shri Madesha S. will continue to inspire a new generation of farmers to adopt scientific practices and build a more prosperous future.



Fish Value Addition: A Business Approach for Women's Empowerment



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Abstract

The fisheries sector plays a crucial role in food security, nutrition, and livelihood generation across coastal and inland regions. However, a significant proportion of fish is marketed in fresh form, where low prices, spoilage, and post-harvest losses often reduce economic returns. Fish value addition offers an effective solution by transforming raw fish into convenient, nutritious, and marketable products with higher consumer appeal and longer shelf life. For women, especially those engaged in fish vending and small-scale fisheries activities, value addition provides an excellent opportunity for entrepreneurship, income generation, and economic empowerment. Through processing, packaging, branding, and marketing of value-added fish products, women can establish profitable micro-enterprises while contributing to food security and sustainable fisheries development. This article highlights the scope, opportunities, challenges, and business potential of fish value addition as a pathway for women's empowerment and rural development.

Keywords: Fish value addition, women entrepreneurship, fisheries, value-added products, coastal women, livelihood, fish processing.

Introduction

Fish is recognized globally as one of the most nutritious and healthy foods. It is an excellent source of high-quality protein, essential amino acids, omega-3 fatty acids, vitamins, and minerals. The global demand for fish and fishery products has increased steadily due to growing awareness of their health benefits and the rising preference for nutritious foods. According to the State of World Fisheries and Aquaculture (SOFIA, 2024), global fisheries and aquaculture production reached record levels, reflecting the increasing importance of aquatic foods in ensuring food and nutritional security.

Despite this growth, fish remains one of the most perishable food commodities. Fresh fish deteriorates rapidly if not handled and preserved properly, leading to substantial post-harvest losses. In many coastal communities, fisherwomen and fish vendors are often compelled to sell fish immediately after landing, frequently at low prices, due to the absence of adequate storage and preservation facilities. As a result, a considerable portion of the potential economic value of fish remains unrealized (Ninan, 2018).

Value addition has emerged as a practical and profitable solution to these challenges. Value addition refers to any activity along the supply chain that increases the usability, convenience, nutritional value, culinary appeal, or economic worth of fish and fishery products (Ninan, 2018; Datta, 2015). Through simple processing operations such as cleaning, filleting, drying, smoking, pickling, freezing, packaging, and preparation of ready-to-cook or ready-to-eat products, fish can be transformed into products that command higher prices and attract wider consumer acceptance.

In recent years, changing consumer lifestyles have significantly increased the demand for convenience foods. Urbanization, increasing incomes, nuclear family structures, and greater participation of women in the workforce have encouraged consumers to seek foods that are easy to prepare, hygienically packaged, and nutritionally rich (Datta, 2015). These trends have created immense opportunities for value-added seafood products in both domestic and export markets.

Women occupy a vital position within the fisheries value chain. Although they are often underrepresented in fishing activities, women play key roles in fish processing, preservation, marketing, and retailing. Studies indicate that women contribute substantially to fisheries-based livelihoods, particularly in post-harvest operations

(Magesa et al., 2024). However, their participation is frequently limited to low-income activities such as fish vending. Fish value addition provides an opportunity to shift women from subsistence-level operations to profitable entrepreneurial ventures.

Understanding Fish Value Addition

Fish value addition goes beyond traditional preservation techniques. It involves improving a product's quality, appearance, convenience, shelf life, nutritional value, and marketability. A simple example is the conversion of raw fish into fish cutlets, fish fingers, fish sausages, fish curry, fish pickle, fish noodles, fish powder, or ready-to-cook marinated products.

Value addition can occur at different stages of the supply chain:

- Primary Value Addition
- Washing and cleaning
- Grading and sorting
- Filleting and dressing
- Chilling and freezing
- Secondary Value Addition
- Drying and smoking
- Pickling
- Fish powder preparation
- Fish mince production
- Fish sausage manufacturing
- Tertiary Value Addition
- Ready-to-eat products
- Ready-to-cook products
- Retort-pouched seafood meals
- Fish-based snacks
- Nutraceutical and functional seafood products

These processes increase product value while reducing waste and enhancing consumer convenience (Ninan, 2018).

Why Fish Value Addition is Important

The importance of fish value addition extends beyond profitability. It contributes significantly to food security, employment generation, resource utilization, and sustainable fisheries development.

1. Reduction of Post-Harvest Losses

A significant quantity of fish is lost annually due to spoilage and poor handling practices. Processing and preservation techniques increase shelf life and reduce wastage, ensuring greater utilization of available fish resources (Datta, 2015).

2. Better Utilization of Low-Value Fish

Many fish species and by-catch remain underutilized because of their small size, unattractive appearance, or low market demand. Value addition converts these resources into acceptable and nutritious products such as fish mince, fish sausages, surimi products, fish cutlets, and fish powder (eGyanKosh, 2017).

3. Increased Income

Value-added products often generate substantially higher profits than fresh fish sales. Processed products can be sold throughout the year and transported to distant markets, providing better returns to producers and entrepreneurs.

4. Enhanced Consumer Convenience

Modern consumers prefer foods that require minimal preparation time. Ready-to-cook and ready-to-eat fish products satisfy this demand while retaining nutritional quality (Datta, 2015).

5. Employment Generation

Fish value addition creates employment opportunities in processing, packaging, labeling, transportation, marketing, and retailing. These activities are particularly suitable for women-led enterprises and self-help groups.

Women and Fisheries Entrepreneurship

Women have traditionally contributed to fisheries through fish handling, processing, vending, and household management. However, their economic contribution often remains undervalued. Studies indicate that women

represent a substantial portion of the post-harvest fisheries workforce and play a crucial role in fish marketing and processing activities (Magesa et al., 2024).

Value addition creates opportunities for women to move beyond fish vending and become entrepreneurs. Through processing activities such as drying, frying, packaging, smoking, and preparation of ready-to-eat products, women can capture a larger share of the value chain and significantly improve their incomes.

Research conducted among women fish vendors revealed that fish processing was the most common value addition activity, followed by grading, cleaning, and packaging. The study further demonstrated that value-added fish products contribute to improved income generation, expanded market opportunities, reduced waste, and enhanced food security (Magesa et al., 2024).

Business Opportunities for Women in Fish Value Addition

Several value-added fish products can be produced using simple technologies and modest investments.

1. Fish Pickle

Fish pickle is one of the most popular value-added seafood products. It combines fish with spices, vinegar, and oil, resulting in a product with extended shelf life and strong consumer acceptance.

2. Ready-to-Eat Fish Curry

Retort-processed fish curry offers convenience, long shelf life, and high nutritional value. It is particularly attractive to urban consumers and working professionals.

3. Fish Noodles and Pasta

Incorporation of fish powder or fish mince into noodles and pasta enhances protein content and nutritional quality while creating innovative seafood-based products.

4. Fish Cutlets and Fish Fingers

These products are highly popular among children and urban consumers due to their convenience and appealing taste.

5. Fish Powder

Fish powder can be incorporated into soups, snacks, complementary foods, and nutritional supplements. It represents an excellent option for utilizing low-value fish resources.

6. Dried and Smoked Fish Products

Improved drying and smoking technologies can produce hygienic products with longer shelf life and improved market value.

Karthickumar et al. (2020) demonstrated that women trained in the preparation of fish pickle, fish curry, fish noodles, and fish pasta earned significantly higher profits compared to conventional fish vending activities.

Marketing Strategies for Women Entrepreneurs

The success of a fish value-addition enterprise depends not only on product quality but also on effective marketing.

1. Brand Development

Creating a unique brand identity helps differentiate products from competitors and build customer loyalty.

2. Attractive Packaging

Proper packaging improves product appearance, preserves quality, and enhances consumer confidence.

3. Digital Marketing

Social media platforms, WhatsApp Business, Facebook, and Instagram provide cost-effective marketing channels for small-scale entrepreneurs.

4. Participation in Exhibitions

Food fairs, fisheries expos, and local exhibitions provide opportunities to showcase products and establish customer networks.

5. Direct Marketing

Selling directly to consumers, restaurants, hotels, and institutional buyers helps maximize profit margins.

Challenges Faced by Women Entrepreneurs

Despite significant opportunities, women engaged in fish value addition face several constraints:

- Limited access to finance and credit.

- Inadequate cold storage and processing facilities.
- Limited technical knowledge and entrepreneurial skills.
- Poor market linkages.
- Lack of branding and packaging expertise.
- Social and cultural barriers restricting business participation.

Addressing these challenges requires coordinated efforts from government agencies, fisheries institutions, financial organizations, and extension services.

Government Support and Institutional Assistance

Several initiatives support women entrepreneurs in fisheries:

- Pradhan Mantri Matsya Sampada Yojana (PMMSY)
- National Fisheries Development Board (NFDB)
- Self-Help Group (SHG) programmes
- Fisheries Cooperative Societies
- Fisheries Colleges and Universities
- Krishi Vigyan Kendras (KVKs)
- Food Processing Incubation Centres

These programmes provide technical training, financial assistance, infrastructure support, and market development opportunities.

Future Prospects

The future of fish value addition is highly promising. Rising consumer awareness regarding health and nutrition, growing demand for convenience foods, increasing urbanization, and advances in food processing technologies are expected to drive continued growth in the value-added seafood sector.

Emerging areas include:

- Functional seafood products
- Nutraceuticals from fish by-products
- Protein-enriched seafood snacks
- Retort pouch seafood meals
- Fish-based instant foods
- Sustainable packaging solutions

Women entrepreneurs can play a central role in these emerging sectors by adopting innovative processing technologies and market-oriented business models.

Conclusion

Fish value addition represents a powerful strategy for transforming fisheries into a more profitable, sustainable, and inclusive sector. By converting fresh fish into convenient, nutritious, and marketable products, women can substantially increase their income while reducing post-harvest losses and improving food security. The development of women-led fish processing enterprises not only strengthens household livelihoods but also contributes to rural development, employment generation, and sustainable utilization of aquatic resources. With appropriate training, access to finance, modern processing technologies, and effective marketing support, fish value addition can become a cornerstone of women's entrepreneurship in the fisheries sector. As consumer demand for innovative seafood products continues to grow, the future offers immense opportunities for women to emerge as successful leaders in the value-added fish business.

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Microgreens: Emerging Functional Foods for Healthy Nutrition and Sustainable Urban Agriculture



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Abstract

Microgreens are young edible seedlings of vegetables, herbs and grains harvested at an early stage, typically between 7 and 21 days after germination. They have gained significant attention in recent years due to their high nutritional value, rich flavour and adaptability to urban farming systems. These miniature greens are packed with vitamins, minerals, antioxidants and bioactive compounds, making them a powerful functional food. Their rapid growth cycle, low input requirement and ability to be cultivated in small spaces make them an ideal solution for sustainable agriculture and urban food security. This article provides a comprehensive overview of microgreens, including their history, nutritional importance, cultivation practices, economic potential and challenges.

Introduction

The increasing global population, rapid urbanization and rising awareness about healthy diets have created a strong demand for nutrient-rich and sustainable food sources. In this context, microgreens have emerged as a promising alternative to conventional vegetables. These young seedlings represent a stage between sprouts and baby greens and are harvested when the cotyledons and the first true leaves develop.

Microgreens differ from sprouts in both cultivation and consumption. While sprouts are grown in water and consumed whole, including roots and seeds, microgreens are cultivated in soil or other growing media and harvested by cutting above the root zone. Their growth period is short, usually ranging from 7 to 21 days, which allows for rapid production cycles.

The concept of microgreens originated in the United States during the 1980s, where they were initially used by chefs as garnishing elements in high-end restaurants. Over time, their popularity expanded beyond culinary aesthetics due to their exceptional nutritional properties. Today, microgreens are recognized as functional foods that provide health benefits beyond basic nutrition.

Nutritional Importance of Microgreens

One of the most remarkable features of microgreens is their high concentration of nutrients. Studies have shown that microgreens often contain higher levels of vitamins and antioxidants compared to their mature counterparts. They are particularly rich in:

- **Vitamins** such as Vitamin C, E, and K
- **Carotenoids** like beta-carotene and lutein
- **Phenolic compounds** that act as antioxidants
- **Essential minerals** including iron, calcium, potassium and zinc

Due to their early growth stage, microgreens have an active metabolism, leading to the accumulation of these beneficial compounds. Their high antioxidant content helps in reducing oxidative stress and lowering the risk of chronic diseases such as heart disease, diabetes and cancer.

Microgreens also serve as a natural dietary supplement, providing essential micronutrients in concentrated form. Their high bioavailability ensures efficient absorption in the human body.

Functional Food Value and Health Benefits

Microgreens are classified as functional foods because they offer health benefits beyond basic nutrition. Regular consumption can contribute to:

- Strengthening the immune system
- Improving digestion
- Reducing cholesterol levels
- Supporting heart health
- Preventing anaemia due to iron content
- Enhancing eye health through carotenoids
- Providing anti-aging benefits due to antioxidants

For example, broccoli microgreens are known for their immune-boosting properties, while fenugreek microgreens help prevent anaemia. Similarly, linseed microgreens are rich in omega-3 fatty acids, which support cardiovascular health.

Culinary Uses and Consumer Appeal

Microgreens are widely appreciated for their intense flavour, vibrant colour and delicate texture. They are used in a variety of culinary applications.

- Salads and sandwiches
- Soups and smoothies
- Garnishing of gourmet dishes
- Functional health foods

Different varieties offer unique Flavors ranging from sweet and mild to spicy and tangy. This diversity makes them highly attractive to chefs and consumers alike.

Production and Cultivation Practices

Microgreens are easy to cultivate and require minimal resources, making them suitable for both beginners and commercial growers.

Growing Conditions

Microgreens require optimal growing conditions, including a temperature of 18-24°C to support rapid metabolic activity, 12-16 hours of daily light to promote photosynthesis and prevent weak growth, relative humidity of 40-60% to maintain moisture balance while reducing fungal risk and good air circulation to ensure healthy development and minimize disease incidence.

Growing Media

Microgreens can be grown in various media such as:

- Soil
- Cocopeat
- Vermiculite
- Jute mats
- Rockwool

They can also be cultivated using hydroponic systems, which eliminate the need for soil and enhance water-use efficiency.

Sowing and Management

Seeds are uniformly spread on the growing medium and lightly covered. Proper watering using a fine mist ensures uniform germination. The crop is usually ready for harvest within 1-3 weeks.

Nutrient Management

Microgreens can grow using seed reserves, but additional nutrients improve yield and quality. Organic inputs such as:

- Compost and vermicompost
- Moringa leaf extract
- Seaweed extracts

are commonly used to enhance growth and nutritional value.

Urban and Commercial Significance

Microgreens are particularly well-suited for urban agriculture due to their small space requirement and short growth cycle. They can be grown in:

- Rooftop gardens
- Kitchen gardens
- Vertical farming systems
- Indoor controlled environments

Their high yield per unit area and quick turnaround time makes them economically attractive. With increasing demand for organic and health-focused foods, microgreens have strong market potential. Additionally, they contribute to food security by enabling local production of fresh vegetables in urban areas.

Post-Harvest Management

Microgreens are highly perishable and have a short shelf life of about 3–7 days. Proper post-harvest handling is essential to maintain quality.

- Storage at low temperatures (2.5-3.5°C)
- Use of clamshell containers for packaging
- Hygienic handling to prevent contamination

Advancements in packaging, including biodegradable materials, are improving their shelf life and sustainability.

Challenges in Microgreens Production

Despite their advantages, microgreens cultivation faces several challenges:

Production Challenges

- Requirement of high-quality, untreated seeds
- Sensitivity to temperature and light conditions
- Risk of fungal contamination and diseases

Management Issues

- Overwatering or underwatering affects growth
- High humidity can lead to mold and damping-off
- Weak seedlings due to insufficient light

Economic Constraints

- High initial investment for controlled environments
- Lack of standardized large-scale production techniques
- Short shelf-life affecting marketability

Addressing these challenges through improved technologies and management practices is essential for scaling up production.

Conclusion

Microgreens are an innovative and sustainable solution to modern nutritional and agricultural challenges. Their exceptional nutrient density, ease of cultivation and adaptability to urban environments make them highly valuable in today's food systems. They offer a practical way to produce fresh, healthy food with minimal resources and space. As consumer awareness continues to grow, microgreens are expected to play a significant role in improving human health, enhancing food security, and promoting sustainable agriculture. With advancements in production and post-harvest technologies, they hold immense potential for future commercial expansion.

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Building Online Farming Communities: The Emerging Role of Digital Peer Learning in Agriculture



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Abstract

The rapid expansion of digital technologies has transformed the way agricultural knowledge is created, shared and applied, giving rise to online farming communities that foster collaborative learning among farmers. This article explores the emerging role of digital peer learning, where farmers exchange real-time experiences, practical solutions and innovative farming practices through platforms such as WhatsApp, YouTube, Facebook, Telegram and specialized agricultural applications. Unlike traditional extension systems, digital peer learning promotes a two-way, participatory approach in which farmers become both knowledge seekers and knowledge providers. The article highlights how these online communities accelerate the adoption of climate-smart agriculture, precision farming, sustainable crop management and market intelligence while strengthening connections between farmers, researchers, extension professionals and agribusiness organizations. It also discusses the growing influence of Artificial Intelligence (AI), smartphones and digital advisory services in enhancing personalized agricultural support. Despite challenges such as misinformation, digital literacy gaps and unequal internet access, online farming communities have emerged as powerful platforms for innovation, resilience and inclusive rural development. By transforming individual experiences into collective knowledge, digital peer learning is redefining agricultural extension and building a more connected, informed and future-ready farming ecosystem. As agriculture continues to embrace digital transformation, these virtual communities are expected to play a pivotal role in ensuring sustainable food production, knowledge democratization and farmer empowerment in the twenty-first century.

Keywords: Artificial Intelligence, Digital Technologies, Digital Literacy and Empowerment

Introduction

Agriculture has always been a community-driven profession where farmers learn from one another through observation, discussion and shared experiences. Traditionally, this exchange occurred in village meetings, local markets, agricultural fairs and extension programs. However, the rapid growth of digital technology has transformed the way knowledge is exchanged. Today, farmers are increasingly connected through smartphones, social media platforms, messaging applications, online forums and digital advisory services. These platforms have given rise to online farming communities, where knowledge is shared instantly across villages, states and even countries.

Digital peer learning refers to the process in which farmers learn directly from fellow farmers using digital platforms. Unlike conventional top-down extension systems, peer learning is participatory, experience-based and highly interactive. It has become an important complement to agricultural extension services by enabling farmers to access practical solutions, discuss local challenges and adopt innovative technologies more rapidly.

Online Farming Communities

Online farming communities are digital networks where farmers, researchers, extension personnel, agribusiness companies and agricultural experts interact to exchange knowledge and experiences. These communities operate through various platforms, including:

- WhatsApp Farmer Groups
- Facebook Farming Communities
- Telegram Channels

- YouTube Agricultural Channels
- Farmer Discussion Forums
- Digital Advisory Platforms
- Community Radio Mobile Apps
- Farmer Producer Organization (FPO) Networks

These communities create an environment where every farmer becomes both a learner and a teacher.

The Concept of Digital Peer Learning

Digital peer learning is based on the principle that practical experiences shared by fellow farmers often encourage greater confidence than recommendations received solely from experts.

For example, if a farmer successfully controls Fall Armyworm using an integrated pest management strategy and shares photographs, videos, and field results through WhatsApp, other farmers facing similar problems can immediately adopt the practice. This real-time exchange reduces uncertainty and accelerates innovation.

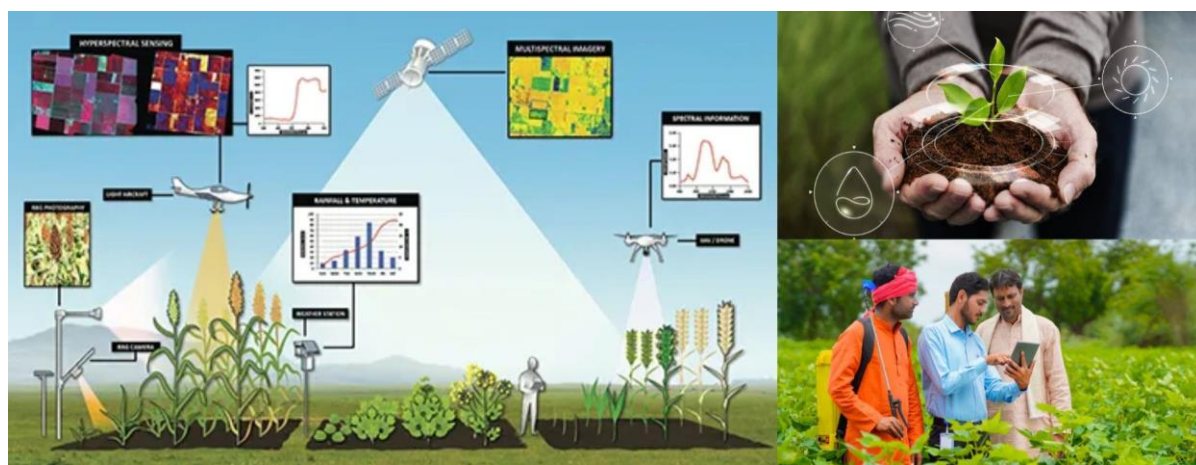


Fig. 1. Sowing Success: How Digital Platforms are Transforming Small-Scale Farming in India

Important Digital Peer Learning

Several factors have contributed to its rapid growth:

- Widespread availability of smartphones
- Affordable internet connectivity
- Expansion of rural digital infrastructure
- Increased use of social media among rural youth
- Government initiatives promoting Digital Agriculture
- Growing interest in precision farming and climate-smart agriculture

The COVID-19 pandemic further demonstrated the importance of digital communication when physical extension activities became difficult.

Major Benefits of Online Farming Communities

1. Faster Knowledge Sharing

Farmers receive immediate solutions for crop diseases, pest outbreaks, nutrient deficiencies and weather-related problems without waiting for field visits.

2. Learning from Real Experiences

Recommendations are supported by actual field experiences, photographs, videos and yield comparisons shared by fellow farmers.

3. Low-Cost Agricultural Extension

Digital communities reduce travel expenses and allow extension officers to reach thousands of farmers simultaneously.

4. Encouraging Innovation

Farmers actively share innovations such as:

- Organic pest management
- Precision irrigation
- Drone applications
- Biofertilizers
- Natural farming practices
- Climate-smart technologies

5. Strengthening Farmer-to-Farmer Extension

Experienced farmers become local digital mentors who guide beginners through practical demonstrations and discussions.

6. Better Market Information

Farmers exchange information about:

- Daily market prices
- Buyer contacts
- Export opportunities
- Input suppliers
- Storage facilities
- Transportation options

This helps farmers obtain better prices for their produce.

Role of Social Media Platforms

WhatsApp

- Instant crop advisory
- Disease diagnosis through images
- Group discussions
- Weather alerts

Facebook

- Live farming demonstrations
- Community discussions
- Agricultural events
- Farmer success stories

YouTube

- Step-by-step cultivation practices
- Machinery demonstrations
- Expert interviews
- Scientific farming techniques

Telegram

- Distribution of e-books
- Government scheme updates
- Agricultural notifications
- Research publications

Role of Artificial Intelligence in Digital Peer Learning

Artificial Intelligence (AI) is making online farming communities more efficient by providing:

- Personalized crop recommendations
- Pest and disease identification
- Voice-based advisory services
- Translation into regional languages
- Predictive weather alerts
- Automated chatbot support

AI can also identify frequently asked questions from farmer discussions and recommend appropriate scientific solutions.

Integration with Agricultural Extension

Modern extension workers no longer serve only as information providers. Instead, they function as:

- Digital facilitators
- Community moderators
- Knowledge curators
- Technology promoters
- Innovation connectors

Extension agencies increasingly combine physical demonstrations with online learning groups to create a hybrid extension model.

The New Heroes of Agriculture: Farmer Influencers

Across India, many progressive farmers have become digital educators. Without formal teaching qualifications, they inspire thousands by sharing:

- Daily field updates
- Honest successes and failures
- Machinery demonstrations
- Organic farming techniques
- Water-saving innovations
- Financial planning tips
- Entrepreneurship ideas

Their influence proves that practical experience is one of agriculture's greatest classrooms.

Women Farmers are Finding their Digital Voice

Online communities are giving women farmers unprecedented opportunities. Through digital platforms, women now:

- Lead Farmer Producer Organizations.
- Share kitchen garden innovations.
- Demonstrate value addition techniques.
- Market homemade food products.
- Teach mushroom cultivation.
- Promote seed conservation.

Digital agriculture is helping make farming knowledge more inclusive than ever before.

Challenges of Digital Peer Learning

Despite its advantages, several challenges remain:

- Spread of misinformation
- Fake agricultural advice
- Poor internet connectivity in remote villages
- Digital illiteracy among elderly farmers
- Language barriers
- Lack of scientific verification
- Privacy and cybersecurity concerns

Addressing these challenges requires collaboration among government agencies, universities, extension personnel and digital platform providers.

Future Opportunities

The future of online farming communities is highly promising. Emerging technologies are expected to transform peer learning through:

- AI-powered virtual agricultural assistants
- Drone image sharing for disease diagnosis

- Virtual Reality (VR)-based farmer training
- Blockchain-enabled farmer networks
- IoT-based field monitoring
- Digital Farmer Producer Organizations
- Smart village knowledge hubs
- Voice-based multilingual advisory systems

These innovations will make agricultural knowledge more accessible, personalized and reliable.

Conclusion

Online farming communities are redefining agricultural learning by transforming farmers into active creators and sharers of knowledge rather than passive recipients of information. Digital peer learning complements traditional agricultural extension by enabling faster communication, encouraging innovation, and promoting collaborative problem-solving. As digital infrastructure continues to improve and technologies such as Artificial Intelligence, drones, and IoT become more integrated into agriculture, these online communities will play an increasingly important role in building resilient, knowledgeable and sustainable farming systems. Empowering farmers through digital peer learning is not merely a technological advancement it is a pathway toward more inclusive, participatory and future-ready agriculture.

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Smart Horticulture: AI, IoT and Precision Technologies for Sustainable Fruit and Vegetable Production



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Introduction

Horticulture plays a vital role in Indian agriculture by providing nutritious fruits, vegetables, flowers, spices, plantation crops, and medicinal plants. Besides contributing to food and nutritional security, the horticulture sector generates employment, enhances farmers' income, and supports agricultural exports. India is one of the world's leading producers of horticultural crops, but the sector continues to face challenges such as climate change, irregular rainfall, water scarcity, pest and disease outbreaks, labour shortages, and significant post-harvest losses. These challenges affect both the quantity and quality of produce, highlighting the need for more efficient and sustainable production systems.

Precision horticulture has emerged as an innovative approach that applies advanced technologies to manage spatial and temporal variability within fields. By delivering the right input, at the right time, in the right amount, and at the right place, precision horticulture enhances crop productivity while minimizing environmental impacts (Praharaj *et al.*, 2023). The integration of digital tools and real time data analytics enables informed decision making and efficient resource management, making precision horticulture a cornerstone of modern sustainable agriculture.

The rapid advancement of digital technologies is opening new opportunities to address these challenges. Smart horticulture integrates Artificial Intelligence (AI), the Internet of Things (IoT), precision farming, drones, remote sensing, and automated decision-support systems to improve crop production and post-harvest management. These technologies enable real-time monitoring of crop and soil conditions, optimize the use of water, fertilizers, and pesticides, facilitate early detection of pests and diseases, and improve harvesting, storage, and transportation practices. As a result, farmers can achieve higher productivity, better-quality produce, lower production costs, and reduced environmental impact.

In India, the adoption of smart horticulture is gaining momentum through government initiatives, research institutions, agri-tech start-ups, and digital farming solutions. With increasing demand for safe, high-quality horticultural products and the need for climate-resilient agriculture, smart technologies are becoming an essential component of modern farming. This article highlights the concept, key technologies, applications, benefits, challenges, and future prospects of smart horticulture, demonstrating how innovation can make horticultural production more productive, profitable, and sustainable.

Why Smart Horticulture is Needed

The horticulture sector is expanding rapidly due to increasing consumer demand for fresh, nutritious, and high-quality fruits and vegetables. However, farmers face several challenges that limit productivity and profitability. Climate change has increased the frequency of droughts, heat waves, unseasonal rainfall, and extreme weather events, making horticultural production more uncertain. At the same time, shrinking landholdings, declining water availability, rising input costs, and labour shortages have made conventional farming practices less efficient and more expensive.

Another major concern is the high level of post-harvest losses. A significant proportion of fruits and vegetables is lost during harvesting, grading, storage, transportation, and marketing because of their perishable nature. These losses not only reduce farmers' income but also affect food availability and increase environmental waste.

Smart horticulture offers practical solutions to these challenges by integrating modern technologies with crop management practices. Sensors, drones, and satellite imagery can continuously monitor crop health, soil moisture, weather conditions, and nutrient status. Artificial Intelligence (AI) analyzes this information and

provides timely recommendations for irrigation, fertilizer application, pest and disease management, and harvesting. Similarly, Internet of Things (IoT)-based systems enable real-time monitoring of fields and greenhouses, allowing farmers to make quick and informed decisions.

In the context of climate change, resource conservation, and the growing demand for safe and quality food, smart horticulture has become a necessity rather than a choice. It empowers farmers with data-driven decision-making, enhances resource-use efficiency, improves profitability, and supports sustainable agricultural development. By embracing smart technologies, the horticulture sector can become more resilient, productive, and capable of meeting the future food and nutritional needs of a growing population.

Concept and Principles of Precision Horticulture

Precision horticulture is based on the recognition that variability exists within orchards, vegetable fields, and protected cultivation systems. This variability may arise from differences in soil properties, topography, microclimate, crop growth stages, and pest pressure. The core principles of precision horticulture include observation, measurement, analysis, and site-specific management. Key components involve the use of sensors to collect data on soil moisture, nutrient status, canopy characteristics, and environmental parameters (Onyango *et al.*, 2021).

Digital farming

Digital farming is the integration of precision farming and smart farming, and is achieved through the implementation of intelligent software and hardware. Precision farming is popularly defined as a technology-enabled approach to farming management that observes, measures, and analyses the need of individual fields and crops. Smart farming is more focused on the use of data acquired through various sources (historical, geographical and instrumental) in the effective management of the farm activities (Singh *et al.*, 2025).

IoT (Internet of Things)

This technology comprises the use of sensors, drones, robots, and digital cameras. Sensors, cameras, and robots are installed on the farms to record the data. Digital farming can be done through the installation of network-connected 'smart' devices as part of IoT (Internet of Things) or they can be software as a service (SaaS) based agtech. When hardware transfers data over a network they become 'smart devices' and become part of the IoT. Since IoT utilizes hardware, it requires solid technical knowledge for operating the equipment along with high maintenance and setup cost. The high capital input cost is what keeps IoT out of the reach of most farmers.



Fig.1: AI and IoTs in horticulture (Singh *et al.*, 2025)

Artificial intelligence

Artificial intelligence (AI) refers to systems that display intelligent behaviour by analyzing their environment and taking actions—with some degree of autonomy—to achieve specific goals. Looking at its modernity, it is being adopted in the large agricultural sector in India as well. Artificial intelligence is becoming an increasingly integrated and important part of agricultural applications. It is being used for its ability to process large amounts of data and make accurate predictions. Artificial intelligence is being used to improve crop yields, optimize irrigation and fertilizer practices, and reduce the impact of pests and diseases. One of the major areas where artificial intelligence is being applied in agriculture is the development of algorithms (Singh *et al.*, 2025). It can generate and interpret large datasets. An algorithm is being used to identify patterns and trends in agricultural data. It is used to develop agricultural practices. Another area where it is being applied in agriculture is the development of autonomous robots. Autonomous robots can perform tasks such as weed control and crop monitoring.

Sensor-Based Irrigation and Fertigation

Sensor-based irrigation and fertigation are key components of smart horticulture, enabling the precise application of water and nutrients according to crop requirements. Soil moisture, temperature, humidity, and electrical conductivity (EC) sensors continuously monitor field conditions and transmit real-time data to automated irrigation systems. Based on this information, irrigation is applied only when required, preventing over-irrigation and water wastage.

Similarly, sensor-based fertigation delivers the right amount of fertilizers through irrigation water at the appropriate growth stage, improving nutrient-use efficiency and reducing fertilizer losses. These systems enhance crop growth, fruit quality, and yield, while lowering labour costs, energy consumption, and environmental pollution. Farmers can also monitor and control irrigation remotely using mobile applications and IoT platforms, making water and nutrient management more accurate, efficient, and sustainable.



Fig. 2: Sensor-based irrigation and fertigation modules in tomato (Singh *et al.*, 2025)

Precision Pest and Disease Management

Precision horticulture promotes targeted pest and disease management through early detection and site-specific interventions. Sensor-based monitoring, remote sensing, and image analysis tools enable the identification of pest infestations and disease symptoms at early stages. Decision-support systems provide recommendations for optimal control measures based on pest threshold and environmental conditions. The integration of precision technologies with integrated pest management (IPM) strategies reduces pesticide use, minimizes resistance development, and protects beneficial organisms (Nicola *et al.*, 2020). Precision spraying systems apply pesticides only where needed, improving efficacy and environmental safety.

Challenges and Digital Solutions in Horticulture

Challenges	Digital Solution	Expected Outcome
Water scarcity	IoT-based smart irrigation	Water saving (20–40%)
Pest and disease attack	AI image recognition and sensors	Early detection and control
Labour shortage	Drones and automation	Reduced labour requirement
Climate variability	Weather forecasting and AI advisory	Better crop planning
High fertilizer use	Precision nutrient management	Reduced fertilizer consumption
Post-harvest losses	Cold chain monitoring and smart packaging	Longer shelf life
Poor market access	Digital marketplaces	Better prices for farmers

Future Prospects and Conclusion

The future of precision horticulture lies in the integration of AI, machine learning, big data analytics, and robotics to further enhance decision-making and automation. Advances in low-cost sensors and user-friendly platforms are expected to improve accessibility for smallholder farmers. Precision horticulture will play a pivotal role in sustainable intensification by enhancing productivity, resource-use efficiency, and environmental stewardship. It represents a transformative approach for modern fruit and vegetable production. By leveraging advanced technologies and data-driven management, precision horticulture contributes to resilient, efficient, and sustainable horticultural systems capable of meeting future food and nutritional demands (Lakshmi *et al.*, 2024). Despite challenges such as high initial costs and limited technical awareness, smart technologies offer sustainable solutions for modern horticulture. Smart horticulture is the future of climate-resilient, profitable, and sustainable fruit and vegetable production.

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Importance of Artificial Intelligence (AI) in Agricultural Education & Extension



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Introduction

In India, Artificial Intelligence (AI) has rapidly emerged as one of the most transformative technologies in Education sector. Most importantly, the Generative Artificial Intelligence (Generative AI) tools such as Gemini, Microsoft Copilot, ChatGPT, and Claude are solving the informative and academic needs of the students. Also, in the Agricultural Education and Extension perspectives; integration of AI significantly improves the knowledge and valuable insights into how AI tools influence the academic learning of agricultural students, extension systems, farmers, agricultural Entrepreneurs and other development stakeholders. The present academic environment in the agricultural university students and Extension system are connected with smartphones linked internet connectivity and digital learning platforms. It helps them to easily access of AI-powered applications for search of textbooks, scientific journals and other purposes such as assignments and seminar preparation, summarizing research articles, creating innovative project ideas, preparing for competitive examinations and solving analytical problems. It saves time, simplifies learning and acts as an intelligent academic assistant for the blended and personalized learning experiences with diverse information quickly and efficiently.

Teaching- Learning Environment of Agricultural Universities

The importance of balanced usage of AI integration along with other online tools enhances the effectiveness of teaching-learning environment in Agricultural education system. In India, Agriculture is a state subject and the decentralized system of agricultural higher education. There are lot of differences are there between the conventional teacher and the ICT enabled AI accessible smart teachers. The AI accessible teachers' actively supports to develop analytical thinking through discussions, debates and case studies. Also, India's future agriculture depends on innovation, entrepreneurship and technology-driven decision-making. In Agricultural production perspectives also, students graduating work in Agri-entrepreneurship, start-ups precision farming, climate-smart agriculture, agribusiness management and private led digital extension services. hence, the role of teachers in Agricultural Universities responsibilities increased to develop the students with technological competence, scientific reasoning, enhanced communication skills and creativity. Hence, the educational institutions should promote blended learning environments with AI complements classroom teaching, practical training, field demonstrations and experiential learning. Such an approach will help students become confident professionals capable of addressing real-world agricultural challenges.

Benefits of AI in Agricultural Education

Several educational advantages of AI-assisted learning SUCH AS better understanding of complex concepts through simplification of difficult concepts using examples, diagrams and easy-to-understand explanations. Supports creativity through innovative ideas generation for research proposals, business plans, extension programmes and startup related activities development purposes. It also supports to Problem-Solving Skills particularly in agriculture such as climate change impact issues, pest outbreaks, declining soil fertility and market uncertainty and it provides alternative solutions before making decisions. Time Efficiency and Personalized Learning are other important advantages through usage of AI in agriculture under the present globalized market environment to make education more inclusive and learner-centred manner.

Artificial Intelligence importance for Indian Agriculture

India is witnessing rapid digital transformation in agriculture through initiatives in past 20 years of period and the post liberalization era is highly supportive to connect Indian economy with global economy in multiple perspectives. Hence, the future agriculture is always in commercial perspectives through smart precision Agriculture and artificial Intelligence-based advisory systems. Also, agricultural professionals will increasingly work with satellite imagery, drones, IoT devices, big data analytics and AI-powered decision support systems.

Agriculture also matters for farmers' livelihoods, food security and environmental sustainability. Also, Field conditions differ across regions, and solutions often require local knowledge, practical experience and scientific judgment. So, extension professional and farmers' traditional wisdom along with the blended AI can assist in appropriate decision-making process. It added value to education and field experience.

The future of agricultural education lies in creating a healthy partnership between human intelligence and artificial intelligence. Students should learn to ask better questions, critically evaluate AI-generated information and apply scientific principles in practical situations. Artificial Intelligence impact depends entirely on how it is used. Responsible AI adoption can improve learning outcomes, increase productivity and prepare students for the digital future. However, excessive dependence may reduce independent thinking and scientific inquiry. Hence, Teachers should continue nurturing curiosity, innovation and ethical responsibility while embracing modern educational technologies. India's agricultural universities have a unique opportunity to lead this transformation by developing graduates who are technologically empowered, scientifically competent and socially responsible. AI should become a catalyst for better learning platform for the interface with human intelligence.

Conclusion

Artificial Intelligence is rapidly transforming agricultural education by making learning more accessible, interactive and personalized. The AI tools significantly improve students' efficiency, creativity and problem-solving abilities. For Indian agriculture to benefit from the AI revolution, educational institutions must encourage responsible and balanced use of AI technologies. Students should use AI to enhance their understanding while continuing to rely on scientific evidence, practical experience and independent reasoning. When combined with quality teaching and experiential learning, AI has the potential to produce a new generation of agricultural professionals capable of leading India's journey towards sustainable, climate-resilient and technology-driven agriculture. At the same time, excessive dependence on AI can affect critical thinking and independent learning. Hence, appropriate blend of Human Intelligence with Artificial Intelligence support to develop globally fit talented agricultural professionals to address the indicators of developed India 2047.

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Microplastics as an Emerging Soil Contaminant: Impacts on Soil Health and Sustainable Agriculture



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Abstract

Microplastics have emerged as one of the most concerning environmental pollutants due to their widespread occurrence, persistence, and potential impacts on ecosystems. Although research initially focused on marine environments, agricultural soils are now recognized as major sinks for microplastic accumulation. The extensive use of plastic materials in modern agriculture, including mulch films, greenhouse covers, irrigation pipes, fertilizer bags, and packaging materials, has significantly increased the amount of plastic residues entering soil. In addition, sewage sludge, compost, wastewater irrigation, atmospheric deposition, and improper disposal of plastic waste contribute to the continuous input of microplastics into agricultural lands. Once present in the soil, these particles persist for long periods because they degrade very slowly under natural conditions. Microplastics alter soil physical, chemical, and biological properties by affecting soil aggregation, water movement, nutrient cycling, microbial diversity, and enzyme activities. They also adsorb heavy metals, pesticides, and other contaminants, increasing their mobility and ecological risks. Furthermore, the presence of microplastics may influence plant growth, reduce crop productivity, and pose potential threats to food safety through the transfer of plastic particles into the food chain. As sustainable agriculture depends on healthy soils, understanding the behavior and impacts of microplastics is essential for protecting soil resources and ensuring long-term agricultural productivity. This review discusses the sources of microplastics in agricultural soils, their effects on soil health, implications for sustainable agriculture, current management strategies, and future research priorities aimed at minimizing soil contamination and promoting environmentally sustainable farming systems.

Keywords: Microplastics; Soil health; Sustainable agriculture; Soil pollution

Introduction

Soil is one of the most important natural resources supporting life on Earth. It provides the foundation for agricultural production, supplies essential nutrients and water to plants, regulates biogeochemical cycles, stores carbon, filters pollutants, and supports a diverse range of microorganisms and soil fauna. Healthy soil is fundamental to sustainable agriculture because it maintains crop productivity, conserves biodiversity, and contributes to environmental sustainability. However, rapid industrialization, urbanization, population growth, and intensive agricultural practices have placed increasing pressure on soil resources, resulting in the accumulation of various contaminants that threaten soil quality and ecosystem functioning.

Traditionally, soil pollution studies have focused on contaminants such as heavy metals, pesticides, industrial chemicals, excessive fertilizers, and petroleum hydrocarbons. In recent years, microplastics have emerged as a new class of environmental contaminants receiving considerable scientific attention. Unlike conventional pollutants that may degrade or become immobilized over time, microplastics are highly persistent because they are resistant to biological and chemical degradation. Their widespread occurrence in agricultural soils has raised concerns regarding their effects on soil health, crop production, ecosystem services, and food security.

Microplastics are plastic particles measuring less than 5 mm in diameter. They originate either as **primary microplastics**, intentionally manufactured in microscopic sizes for industrial and commercial applications, or as **secondary microplastics**, formed through the fragmentation of larger plastic products exposed to sunlight, mechanical abrasion, temperature fluctuations, and weathering processes. Secondary microplastics constitute the majority of plastic particles found in agricultural soils because modern farming extensively relies on plastic materials.

Over the past few decades, the use of plastics in agriculture has increased dramatically. Plastic mulch films, greenhouse coverings, irrigation pipes, seedling trays, silage wraps, protective nets, fertilizer bags, and packaging materials have become indispensable components of modern crop production systems. These materials improve agricultural efficiency by conserving soil moisture, regulating soil temperature, suppressing weed growth, reducing evaporation losses, and increasing crop yields. However, prolonged exposure to environmental conditions causes these plastics to degrade into progressively smaller particles that remain in the soil long after the visible plastic has disappeared.

Agricultural plastics are not the only source of soil microplastics. Sewage sludge produced during wastewater treatment contains enormous quantities of microplastic particles removed from domestic wastewater. Because treated sludge is widely applied to farmland as an organic fertilizer, large numbers of microplastics are unintentionally introduced into agricultural soils. Similarly, compost produced from municipal solid waste may contain plastic fragments if waste segregation is inadequate. Irrigation using treated wastewater, atmospheric deposition of airborne fibers, tyre wear particles, and improper disposal of agricultural plastic waste further contribute to soil contamination.

Unlike aquatic ecosystems where plastics may be transported by rivers and ocean currents, agricultural soils act as long-term sinks for microplastics. Their persistence allows continuous accumulation over many years, increasing the likelihood of interactions with soil minerals, organic matter, microorganisms, plant roots, and soil fauna. The behavior of microplastics in soil depends on several factors, including particle size, shape, density, polymer composition, surface characteristics, and environmental conditions. Common polymers detected in agricultural soils include polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), polyethylene terephthalate (PET), and polystyrene (PS).

As scientific understanding of soil microplastics continues to evolve, comprehensive reviews are essential for integrating current knowledge and identifying research priorities. This review examines the major sources of microplastics in agricultural soils, their impacts on soil physical, chemical, and biological health, their implications for sustainable agriculture, and the management strategies required to minimize future contamination. Understanding these interactions will support the development of sustainable farming systems capable of maintaining soil productivity while protecting environmental quality.

Microplastics as Emerging Soil Contaminants

Microplastics have become one of the fastest-growing environmental concerns because of their widespread occurrence, persistence, and ability to interact with various components of terrestrial ecosystems. While oceans were initially considered the primary destination of plastic waste, recent studies have shown that agricultural soils receive equal or even greater quantities of microplastics each year. Unlike aquatic environments where plastics may be transported over long distances, soils act as long-term reservoirs in which microplastics accumulate gradually through repeated agricultural activities.

Microplastics are generally classified into **primary** and **secondary** microplastics. Primary microplastics are intentionally manufactured in microscopic sizes for industrial applications, cosmetic products, cleaning agents, and plastic manufacturing processes. Secondary microplastics are generated through the fragmentation of larger plastic materials after exposure to sunlight, heat, mechanical stress, and microbial activity. In agricultural soils, secondary microplastics dominate because they originate from degraded mulch films, irrigation systems, greenhouse covers, fertilizer bags, and other plastic products commonly used in farming.

The persistence of microplastics distinguishes them from many conventional soil contaminants. Unlike organic pollutants that may degrade through microbial activity, most plastics remain in soil for decades. Continuous weathering gradually breaks larger fragments into progressively smaller particles, eventually forming nanoplastics that are capable of interacting more closely with soil microorganisms and plant roots.

Microplastics occur in various shapes, including fibers, fragments, films, foams, pellets, and beads. Each type exhibits different transport behavior within soil. Fibers often become entangled with soil particles and plant roots, while spherical particles move more freely through soil pores. Film-shaped microplastics, primarily originating from agricultural mulch, frequently accumulate near the soil surface before being mixed into deeper layers through tillage and biological activity.

Another important characteristic of microplastics is their large surface area relative to their size. This property enables them to adsorb heavy metals, pesticides, antibiotics, and persistent organic pollutants from the surrounding environment. Consequently, microplastics function not only as contaminants themselves but also as carriers that transport other pollutants throughout the soil ecosystem. Their surfaces also provide habitats for microbial communities, collectively known as the **plastisphere**, which may contain beneficial microorganisms as well as plant pathogens and antibiotic-resistant bacteria.

The growing recognition of microplastics as emerging soil contaminants highlights the need for comprehensive research into their environmental behavior, ecological impacts, and long-term implications for soil health and sustainable agriculture.

Sources of Microplastics in Agricultural Soils

Agricultural soils receive microplastics from multiple sources, many of which are directly linked to modern farming practices and waste management systems. The widespread use of plastic materials in agriculture has significantly improved crop production and resource-use efficiency. However, these benefits have also resulted in the continuous accumulation of plastic residues in soils. Unlike many organic pollutants, microplastics persist in the environment because they degrade very slowly, allowing them to accumulate over several years. Understanding the major sources of microplastics is essential for developing effective strategies to reduce soil contamination.

- **Agricultural Plastic Mulching**

Plastic mulch films are one of the most important sources of microplastic contamination in agricultural soils. Polyethylene mulch is extensively used in vegetable production, fruit orchards, and horticultural systems because it helps conserve soil moisture, regulate soil temperature, suppress weed growth, and improve crop yield. Although mulch films are usually removed after harvest, complete recovery is rarely achieved. Small fragments remain in the soil and gradually break down into microplastics due to exposure to sunlight, ultraviolet (UV) radiation, rainfall, temperature fluctuations, and mechanical disturbance during tillage.

Repeated application of plastic mulch over many growing seasons leads to the progressive accumulation of plastic particles. In regions where plastic mulching has been practiced intensively for several decades, agricultural soils often contain considerably higher concentrations of microplastics than non-mulched fields. This continuous input has made mulch film degradation one of the dominant contributors to soil microplastic pollution worldwide.

- **Sewage Sludge Application**

The application of sewage sludge as an organic fertilizer has become another major pathway for microplastics entering agricultural soils. Wastewater treatment plants remove a large proportion of microplastics from domestic and industrial wastewater. Instead of being destroyed, these particles become concentrated in the sewage sludge generated during the treatment process.

Because sewage sludge is rich in organic matter, nitrogen, phosphorus, and micronutrients, it is widely applied to farmland to improve soil fertility. However, together with these beneficial nutrients, millions of microplastic particles are introduced into agricultural fields. Synthetic fibres released during the washing of polyester, nylon, and acrylic textiles are particularly abundant in sewage sludge. Long-term application of sludge can therefore result in a substantial increase in soil microplastic concentrations.

- **Compost and Organic Amendments**

Organic compost derived from municipal solid waste can also introduce microplastics into agricultural soils. Improper segregation of biodegradable and non-biodegradable waste allows plastic materials such as food packaging, disposable containers, and plastic bags to enter composting facilities. During composting, organic matter decomposes, whereas plastics remain intact and gradually fragment into smaller particles.

The application of contaminated compost to agricultural fields unintentionally transfers microplastics into the soil. Although compost improves soil fertility and organic matter content, poor waste management practices reduce its environmental sustainability. Improving waste segregation and compost quality is therefore essential to minimize plastic contamination.

- **Wastewater Irrigation**

Increasing water scarcity has encouraged many countries to reuse treated wastewater for irrigation. Wastewater irrigation conserves freshwater resources and provides nutrients that support crop growth. However, treated wastewater frequently contains microplastics that are not completely removed during wastewater treatment.

These particles originate from household wastewater, synthetic textile fibres, industrial discharges, personal care products, and urban runoff. Continuous irrigation with treated wastewater gradually increases the concentration of microplastics in agricultural soils. This problem is particularly important in arid and semi-arid regions where wastewater reuse is becoming increasingly common.

- **Atmospheric Deposition**

Microplastics are also transported through the atmosphere. Tiny plastic fibres and fragments generated from synthetic clothing, vehicle tyre wear, industrial emissions, construction activities, and urban dust can become airborne and travel long distances before settling on agricultural land.

Atmospheric deposition is now recognized as an important source of microplastics even in remote agricultural areas where direct plastic use is limited. Wind, rainfall, and dust storms redistribute these particles across landscapes, contributing to widespread soil contamination.

- **Agricultural Activities and Plastic Waste**

Several routine agricultural operations also contribute to microplastic generation. Greenhouse covers, irrigation pipes, seedling trays, fertilizer bags, silage wraps, plastic ropes, and packaging materials gradually deteriorate through weathering and repeated use. Mechanical cultivation, harvesting, and transportation accelerate fragmentation, producing large numbers of secondary microplastics.

Improper disposal of agricultural plastic waste further increases contamination. Burning, burying, or abandoning plastics in fields allows weathering processes to continue, resulting in the slow release of microplastics into surrounding soils.

Impacts of Microplastics on Soil Physical Health

The physical properties of soil determine its ability to support plant growth, regulate water movement, and resist erosion. Microplastics alter these properties by changing soil structure, pore distribution, and aggregate stability.

- **Soil Structure and Aggregate Stability**

Soil aggregates are groups of mineral particles held together by organic matter, microbial secretions, and fungal hyphae. Stable aggregates improve aeration, infiltration, and resistance to erosion. The introduction of microplastics disrupts these natural binding mechanisms.

Film-shaped and fibre-shaped microplastics interfere with aggregate formation by separating mineral particles and reducing cohesion. As a result, aggregate stability decreases, making soils more susceptible to erosion by wind and water. Poor aggregate stability also reduces the capacity of soil to store water and nutrients.

- **Bulk Density and Porosity**

Microplastics generally possess lower density than mineral soil particles. Their accumulation therefore influences soil bulk density and pore distribution. In some cases, fibrous microplastics increase soil porosity by creating additional pore spaces. While increased porosity may improve aeration, excessive pore formation can reduce soil strength and impair root anchorage. Conversely, certain plastic fragments may clog soil pores, restricting water infiltration and gas exchange.

The overall impact depends on the concentration, shape, and polymer type of the microplastics as well as soil texture.

- **Water Retention and Infiltration**

Efficient water movement is essential for maintaining soil moisture and supporting crop growth. Microplastics alter water retention and hydraulic conductivity by modifying pore structure. Fibres may enhance water-holding capacity by increasing the number of small pores that retain moisture. However, film fragments often reduce infiltration by creating physical barriers within the soil. Poor infiltration increases runoff and decreases the efficiency of rainfall and irrigation. These changes become particularly important under drought conditions, where water availability directly influences crop productivity.

- **Soil Erosion**

Reduced aggregate stability and altered soil structure increase the susceptibility of soils to erosion. Rainfall easily detaches weakly aggregated soil particles, transporting them into rivers, lakes, and reservoirs. Wind erosion may also increase in dry regions where plastic-contaminated soils become more vulnerable to particle detachment. Loss of fertile topsoil reduces agricultural productivity while simultaneously spreading microplastics into surrounding ecosystems.

Impacts of Microplastics on Soil Chemical Health

Microplastics influence numerous chemical processes that regulate soil fertility and environmental quality. One of their most important characteristics is the ability to adsorb contaminants. Their large surface area enables them to bind heavy metals such as cadmium (Cd), chromium (Cr), lead (Pb), nickel (Ni), copper (Cu), and zinc (Zn), as well as pesticides, antibiotics, petroleum hydrocarbons, and persistent organic pollutants. Consequently, microplastics act as carriers that transport these contaminants throughout the soil profile, potentially increasing their mobility and bioavailability.

In addition to adsorbing pollutants, plastics themselves contain chemical additives used during manufacturing. Plasticizers, stabilizers, pigments, antioxidants, and flame retardants gradually leach into the surrounding soil during weathering. Some of these substances are toxic and may negatively affect microorganisms, plants, and soil fauna.

Microplastics may also influence soil pH, nutrient availability, and cation exchange processes. Changes in microbial activity caused by plastic contamination can alter nitrogen mineralization, phosphorus cycling, and organic matter decomposition, reducing nutrient availability for crops.

Interactions between microplastics and soil organic matter are particularly important. Organic matter may increase the retention of plastic particles through adsorption or facilitate their movement depending on environmental conditions. Since soil organic matter is fundamental for nutrient storage, carbon sequestration, and aggregate stability, disturbances caused by microplastics may have long-term consequences for soil fertility. Overall, the chemical effects of microplastics extend beyond the plastic particles themselves because they modify the behavior, transport, and persistence of numerous other environmental contaminants.

Impacts of Microplastics on Soil Biological Health

Soil is a living ecosystem that supports a diverse community of microorganisms and soil fauna essential for maintaining fertility and ecosystem stability. Bacteria, fungi, archaea, earthworms, nematodes, insects, and other organisms regulate nutrient cycling, decompose organic matter, improve soil structure, and enhance plant growth. The accumulation of microplastics in agricultural soils can disturb these biological processes and reduce overall soil health.

One of the primary biological effects of microplastics is the alteration of **soil microbial diversity**. Numerous studies have reported that the presence of plastic particles changes the abundance and composition of bacterial and fungal communities. Some microorganisms capable of colonizing plastic surfaces become more dominant, while others decline because of changes in soil conditions. This shift in microbial communities may reduce ecosystem resilience and affect the natural balance of soil microorganisms.

Microplastics also influence **soil enzyme activities**, which are indicators of soil biological functioning. Enzymes such as urease, phosphatase, dehydrogenase, catalase, and β -glucosidase regulate nutrient mineralization and organic matter decomposition. Research has shown that microplastic contamination may reduce the activity of these enzymes by altering microbial metabolism or creating unfavorable environmental conditions. Reduced enzyme activity slows nutrient cycling, decreases nutrient availability, and ultimately lowers soil fertility.

The surfaces of microplastic particles provide suitable habitats for microbial colonization, forming specialized communities known as the **plastisphere**. The plastisphere differs from the surrounding soil microbiome and may harbor both beneficial microorganisms and harmful pathogens. Some studies have also identified antibiotic-resistant bacteria on plastic surfaces, suggesting that microplastics may facilitate the spread of antimicrobial resistance in terrestrial ecosystems.

Soil fauna are equally affected by microplastic pollution. Earthworms, often referred to as ecosystem engineers, ingest plastic particles while feeding on soil organic matter. Ingested microplastics may cause intestinal blockage, reduce feeding efficiency, impair reproduction, and alter burrowing behavior. Since earthworms contribute to soil aeration, aggregation, and nutrient cycling, any reduction in their activity negatively affects soil quality.

Microplastics may also interfere with beneficial plant-microbe interactions. Symbiotic microorganisms such as mycorrhizal fungi and nitrogen-fixing bacteria improve nutrient uptake and support plant growth. Disturbances in these relationships reduce nutrient-use efficiency and increase plant susceptibility to environmental stresses, including drought and nutrient deficiency.

Effects on Crop Growth and Sustainable Agriculture

Healthy soils are the foundation of sustainable agriculture. Since microplastics influence soil structure, nutrient cycling, water availability, and biological activity, they can directly and indirectly affect crop growth and agricultural productivity.

Seed germination is one of the earliest stages influenced by soil contamination. High concentrations of microplastics may reduce water availability around seeds, delay germination, and decrease germination percentage. Poor seed establishment results in uneven crop stands and lower productivity.

Root development is particularly sensitive because roots remain in continuous contact with contaminated soil. Microplastic particles may physically obstruct root elongation, modify root architecture, and reduce the absorption of water and nutrients. Restricted root systems limit plant growth and reduce tolerance to drought and other environmental stresses.

Several greenhouse and laboratory studies have reported reductions in plant height, root biomass, shoot biomass, chlorophyll content, and photosynthetic efficiency following exposure to microplastics. However, the magnitude of these effects varies depending on plant species, soil type, polymer characteristics, and microplastic concentration. Some studies have observed negligible or even positive responses at very low concentrations, indicating that further field-based research is required to fully understand plant responses under natural agricultural conditions.

Another important concern is the uptake of nanoplastics and extremely small microplastic particles by plant roots. Experimental studies have demonstrated that these particles can enter root tissues through microscopic openings and move to stems, leaves, and edible plant parts under controlled conditions. Although the extent of this process in agricultural fields remains under investigation, it raises important questions regarding food safety and the potential transfer of plastics through the food chain.

Microplastics also reduce the long-term sustainability of farming systems by lowering soil quality, decreasing biodiversity, and increasing dependence on external inputs such as irrigation and fertilizers. Sustainable agriculture aims to maintain soil productivity while minimizing environmental degradation. Continued accumulation of persistent plastic contaminants is therefore inconsistent with the principles of sustainable land management.

Environmental and Human Health Implications

The impacts of microplastic pollution extend beyond agricultural fields and influence broader environmental and public health systems. One major concern is the ability of microplastics to transport contaminants. Their large surface area allows them to adsorb heavy metals, pesticides, antibiotics, and persistent organic pollutants from the surrounding environment. These contaminants may later be released under changing environmental conditions, increasing their mobility and bioavailability. As a result, microplastics function as vectors that facilitate the movement of multiple pollutants through soil, water, and food systems. Rainfall and irrigation runoff transport microplastics from agricultural fields into rivers, lakes, reservoirs, and groundwater. These water bodies may subsequently become sources of irrigation water, creating a continuous cycle of contamination.

Microplastics also influence greenhouse gas emissions by altering microbial processes involved in carbon and nitrogen cycling. Changes in microbial respiration may affect the production of carbon dioxide, methane, and nitrous oxide, although the magnitude of these effects varies among different soils and environmental conditions.

Human exposure may occur through several pathways, including the consumption of contaminated crops, drinking water, livestock products, and inhalation of airborne plastic particles. While research on the health effects of dietary microplastics is still evolving, laboratory studies suggest that prolonged exposure may induce oxidative stress, inflammation, and cellular damage. Continued investigation is therefore necessary to evaluate the potential risks associated with chronic human exposure. The widespread occurrence of microplastics demonstrates that plastic pollution is no longer confined to oceans but has become an important terrestrial environmental issue requiring immediate attention.

Management and Mitigation Strategies

Reducing microplastic pollution in agricultural soils requires integrated management approaches involving farmers, industries, researchers, and policymakers. The first priority is to **reduce unnecessary plastic use** in agriculture. Improving the durability and reusability of agricultural plastics can decrease the generation of plastic residues. Where appropriate, biodegradable mulch films may provide an alternative to conventional polyethylene films, although their long-term environmental performance should continue to be evaluated.

Proper collection, recycling, and disposal of agricultural plastic waste are equally important. Farmers should be encouraged to remove plastic residues completely after harvesting and avoid burning or burying plastic waste within agricultural fields.

Improving wastewater treatment technologies can significantly reduce the amount of microplastics entering agricultural soils through reclaimed water and sewage sludge. Advanced filtration systems, membrane technologies, and tertiary treatment processes are increasingly effective at removing fine plastic particles before wastewater reuse.

Better waste segregation during compost production is essential for preventing plastic contamination of organic amendments. Compost quality standards should include limits for plastic impurities before agricultural application.

Regular monitoring of agricultural soils using modern analytical techniques such as Fourier Transform Infrared Spectroscopy (FTIR), Raman spectroscopy, Scanning Electron Microscopy (SEM), and Pyrolysis–Gas Chromatography–Mass Spectrometry (Py-GC-MS) will improve contamination assessment and support evidence-based management decisions.

Government policies also play an important role. Regulations promoting plastic recycling, extended producer responsibility, environmentally friendly packaging, and sustainable agricultural practices can significantly reduce future plastic pollution.

Conclusion

Microplastics have emerged as an important contaminant of agricultural soils due to their widespread use, environmental persistence, and increasing accumulation through modern farming practices. Plastic mulching, sewage sludge application, compost, wastewater irrigation, atmospheric deposition, and improper waste disposal represent the major pathways through which microplastics enter agricultural ecosystems.

Once present in soil, microplastics alter physical, chemical, and biological properties by affecting aggregate stability, water movement, nutrient cycling, microbial diversity, enzyme activity, and soil fauna. Their ability to adsorb heavy metals and organic pollutants further increases environmental risks, while emerging evidence suggests potential transfer into plants and the food chain.

The continued accumulation of microplastics threatens soil health, agricultural productivity, biodiversity, and long-term sustainability. Since healthy soils are essential for global food security, reducing microplastic pollution should become a priority in sustainable agricultural management.

Effective solutions require a combination of improved waste management, reduced plastic consumption, biodegradable alternatives, enhanced wastewater treatment, standardized monitoring techniques, and stronger environmental regulations. Continued scientific research, technological innovation, and international cooperation will be essential for protecting soil resources and ensuring resilient agricultural systems for future generations.

Malnutrition Causes, Effects and Strategies for Prevention



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Abstract

Malnutrition is a major public health problem that affects millions of people, especially children, women and vulnerable groups in developing countries. It occurs when the body does not receive the right amount of energy protein, and essential nutrients. In children malnutrition commonly appears as stunting wasting underweight and micronutrient deficiencies which can negatively affect growth learning ability immunity and overall health. The main causes of malnutrition include poverty food insecurity poor dietary habits inadequate sanitation frequent infections limited healthcare access and lack of nutrition awareness. Severe forms of malnutrition such as marasmus and kwashiorkor are still found in many developing regions. Malnutrition not only affects individual health but also reduces educational performance work productivity and economic development. Preventive measures such as balanced diets breastfeeding promotion food fortification nutrition education, and community-based nutrition programs can help improve nutritional status. Addressing malnutrition requires combined efforts from governments healthcare workers and communities to ensure better health and quality of life for all.

Introduction

Malnutrition is a serious public health issue that affects millions of children worldwide, especially in developing countries. It refers to a condition that occurs when a child's diet does not provide adequate nutrients such as proteins, energy, vitamins, and minerals required for proper growth and development. Malnutrition includes both undernutrition (wasting, stunting, and underweight) and overnutrition, but undernutrition is more common among children.

Children are particularly vulnerable to malnutrition because their bodies are in a rapid stage of growth and development. When they do not receive proper nutrition, it directly affects their physical, mental, and emotional well-being. One of the major effects of malnutrition is stunted growth, where children become shorter than their age due to long-term nutritional deficiency. Another common effect is wasting, which refers to low weight for height and indicates acute malnutrition. Malnourished children often have weak immunity, making them more prone to infections such as diarrhea, pneumonia, and other diseases. In severe cases, malnutrition can even lead to death.

Malnutrition also affects the cognitive development of children. Poor nutrition in early childhood can result in reduced learning ability, poor school performance, and lower productivity in adulthood. This creates a cycle of poverty and poor health that can continue across generations. Children suffering from malnutrition may also experience fatigue, (weakness), and lack of concentration, which affects their daily activities and quality of life.

There are several causes of malnutrition among children. The primary cause is inadequate dietary intake, where children do not get sufficient or balanced food. Poverty is one of the biggest contributing factors, as families may not have enough resources to provide nutritious meals. Lack of maternal education also plays an important role, as mothers may not be aware of proper feeding practices, breastfeeding, and child care. Poor sanitation and unsafe drinking water can lead to infections, which further reduce nutrient absorption in the body.

Other causes include large family size, low birth weight, poor healthcare access, and inadequate breastfeeding practices. Social and cultural factors, such as food taboos and gender discrimination, can also affect a child's nutritional status. In many cases, these factors are interrelated and together contribute to the problem of malnutrition.

In conclusion, malnutrition is a complex issue with multiple causes and serious effects on children's growth and development. Addressing this problem requires a combined effort, including improving nutrition, increasing awareness, ensuring proper healthcare, and reducing poverty

Overview and Definitions

Marasmus and kwashiorkor are two forms of protein-energy malnutrition that primarily affect children in developing countries. They have some overlapping symptoms but also differ in important ways regarding physical symptoms, causes, time frame, risk factors, diagnosis, treatment, and prevention.

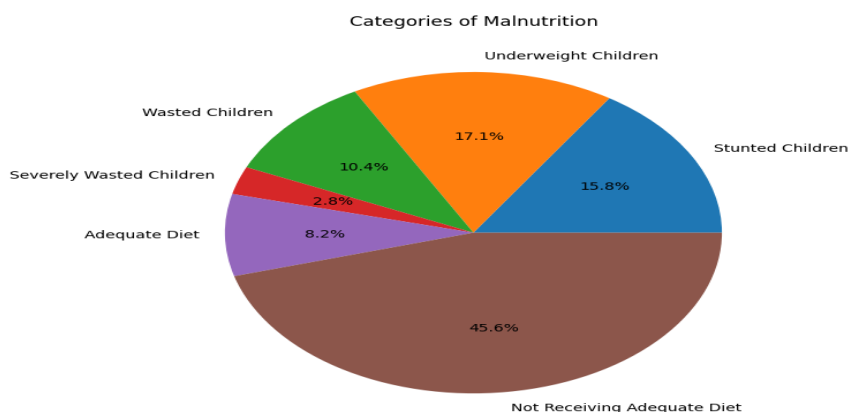
Marasmus and kwashiorkor are both considered severe forms of malnutrition. Malnutrition refers to getting too little or too many nutrients which leads to health problems. Marasmus and kwashiorkor specifically refer to not getting enough protein and calories which stunts growth and causes other issues. Marasmus is defined as a form of malnutrition characterized by energy deficiency usually due to a severe lack of protein and calories. It presents with the classic signs of starvation including extreme weight loss and muscle wasting. The word marasmus is derived from a Greek term that roughly translates to "wasting away".



Types of Malnutrition

Malnutrition can be classified into different types based on nutrient deficiency

Feature	Kwashiorkor	Marasmus
Aetiology	Due to protein deficiency	Due to protein and calorie deficiency
Weaning	Late weaning	Early and abruptly stopped weaning
Associated factors	Acute illness, trauma, infections or sepsis; repeated infection	Prolonged periods of starvation
Occurrence	Young children (6 months–5 years); mostly in developed countries, cities and towns	Infants are most affected; mostly in developing countries and rural areas
Appetite	High / feeder	Poor
Oedema	Present in extremities	Absent
Abdomen	Bulging, protruding stomach	Shrunk stomach
Ribs	Not very prominent	Prominent
Skin	Flaky skin	Dry skin
Weight loss	Mild or nil weight loss	Severe weight loss
Muscle wasting	Mild or nil	Severe
Subcutaneous fat	Present	Absent
Prognosis	Poor	Good
Treatment	High-protein diet	Diet rich in proteins, carbohydrates, fats and other nutrients



2. Micronutrient Deficiency (Hidden Hunger)

Micronutrient deficiency refers to the lack of essential vitamins and minerals required in small amounts for proper body functioning. It is often called “hidden hunger” because its effects are not always immediately visible. Common deficiencies include

- **Iron deficiency:** Leads to anemia, fatigue, and weakness
- **Iodine deficiency:** Causes goiter and thyroid-related problems
- **Vitamin A deficiency:** Can result in vision problems and even blindness
- **Vitamin D deficiency:** Leads to weak bones and rickets in children
- **Zinc deficiency:** Weakens the immune system and increases infection risk

Causes of Malnutrition

Malnutrition is caused by several interconnected factors that affect food intake and nutrient absorption.

1. Poverty and Food Insecurity

Poverty is one of the main causes of malnutrition. People with low income cannot afford nutritious food, leading to inadequate dietary intake and poor health.

2. Poor Dietary Practices

Unbalanced diets that lack essential nutrients such as proteins, vitamins, and minerals contribute significantly to malnutrition.

3. Diseases and Infections

Diseases such as HIV/AIDS, cancer, and frequent infections like diarrhea reduce appetite and interfere with nutrient absorption, worsening nutritional status.

4. Poor Sanitation and Hygiene

Unhygienic living conditions increase the risk of infections, which in turn reduce the body's ability to absorb nutrients.

5. Lack of Awareness

Many people are not aware of proper nutrition, balanced diets, and healthy food practices, leading to poor dietary choices.

6. Food Loss and Agricultural Constraints

Post-harvest losses, improper storage, and limited food production reduce food availability, contributing to malnutrition.

Effects of Malnutrition

Malnutrition has serious consequences on individuals and society as a whole.

• Physical Effects

Malnutrition leads to stunted growth, underweight, and wasting. It also causes muscle weakness and poor physical development.

• Health Effects

A weak immune system is one of the major effects, making individuals more prone to infections and diseases. Severe malnutrition can increase mortality rates, especially among children.

- **Cognitive Effects**

Malnutrition affects brain development, leading to poor memory, reduced learning ability, and lower academic performance.

- **Economic Effects**

Malnutrition reduces productivity and increases healthcare expenses, ultimately affecting the economic growth of a country.

Strategies to Combat Malnutrition

Several effective strategies can help reduce malnutrition:

1. Biofortification

Biofortification involves increasing the nutrient content of crops through breeding techniques. Examples include iron-rich rice, zinc wheat, and vitamin A-rich sweet potatoes. This approach helps improve nutrition in a sustainable way.

2. Food Fortification

Food fortification is the addition of essential nutrients to commonly consumed foods such as iodized salt, fortified milk, and cereals. It is a cost-effective method to address nutrient deficiencies at a large scale.

3. Therapeutic Diets

Special therapeutic foods are used to treat severe malnutrition:

F-75 and F-100 formulas

Ready-to-Use Therapeutic Food (RUTF)

These help in rapid recovery of malnourished children.

4. Pro-biotic Foods

Pro-biotic or fermented foods improve gut health, enhance digestion, and increase nutrient absorption.

5. Food Processing Techniques

Improved food processing and storage methods help reduce food loss, preserve nutrients, and ensure better food availability.

Conclusion

Malnutrition remains a major public health and development challenge that affects millions of people worldwide particularly children women and vulnerable populations. It has serious consequences on physical growth cognitive development immunity educational achievement and economic productivity. The problem is driven by multiple factors including poverty food insecurity inadequate dietary intake poor sanitation limited healthcare services and lack of nutrition awareness. Therefore addressing malnutrition requires a comprehensive and integrated approach involving nutrition health agriculture education and social protection sectors. Effective interventions such as food fortification biofortification therapeutic feeding programs promotion of breastfeeding appropriate complementary feeding and community based nutrition education can significantly improve nutritional outcomes. Strengthening food systems enhancing access to healthcare and ensuring the availability of safe and nutritious foods are essential for long term success. Collective efforts by governments international organizations researchers healthcare professionals and communities are necessary to reduce the burden of malnutrition and promote healthier populations. Investing in nutrition not only improves individual wellbeing but also contributes to sustainable development economic growth and a healthier future for generations to come.

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Climate Change and Nematodes: Emerging Challenges for Agriculture



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Abstract

Climate change is one of the most significant threats to global agriculture in the 21st century. Rising temperatures, altered rainfall patterns, increased frequency of droughts and floods, and elevated atmospheric carbon dioxide levels are influencing the distribution and activity of agricultural pests and pathogens. Among these, plant-parasitic nematodes represent a hidden but serious challenge. These microscopic roundworms attack plant roots, reduce nutrient uptake, weaken crop growth, and cause substantial yield losses worldwide. Climate change is expected to alter nematode populations, geographical distribution, survival, reproduction, and interactions with host plants. Warmer temperatures may enable several nematode species to expand into new regions, while environmental stress can make crops more susceptible to nematode damage. Understanding the relationship between climate change and nematodes is essential for developing sustainable pest management strategies and ensuring future food security.

Keywords: Agriculture, climate change, food security, global warming, plant-parasitic nematodes, sustainable management

1. Introduction

Agriculture is highly dependent on favourable climatic conditions. Temperature, rainfall, soil moisture, atmospheric composition, and seasonal weather patterns determine where crops can be grown and how successfully they can produce food. In recent decades, climate change has begun to alter these fundamental conditions. Increasing temperatures, irregular rainfall, prolonged drought, flooding, and extreme weather events are creating new challenges for agricultural production throughout the world. Climate change not only affects crop plants directly but also influences the pests and pathogens associated with them. Insects, fungi, bacteria, viruses, and plant-parasitic nematodes respond differently to changes in temperature and moisture. As environmental conditions change, some pests may become more damaging, expand into new geographical areas, or complete their life cycles more rapidly.

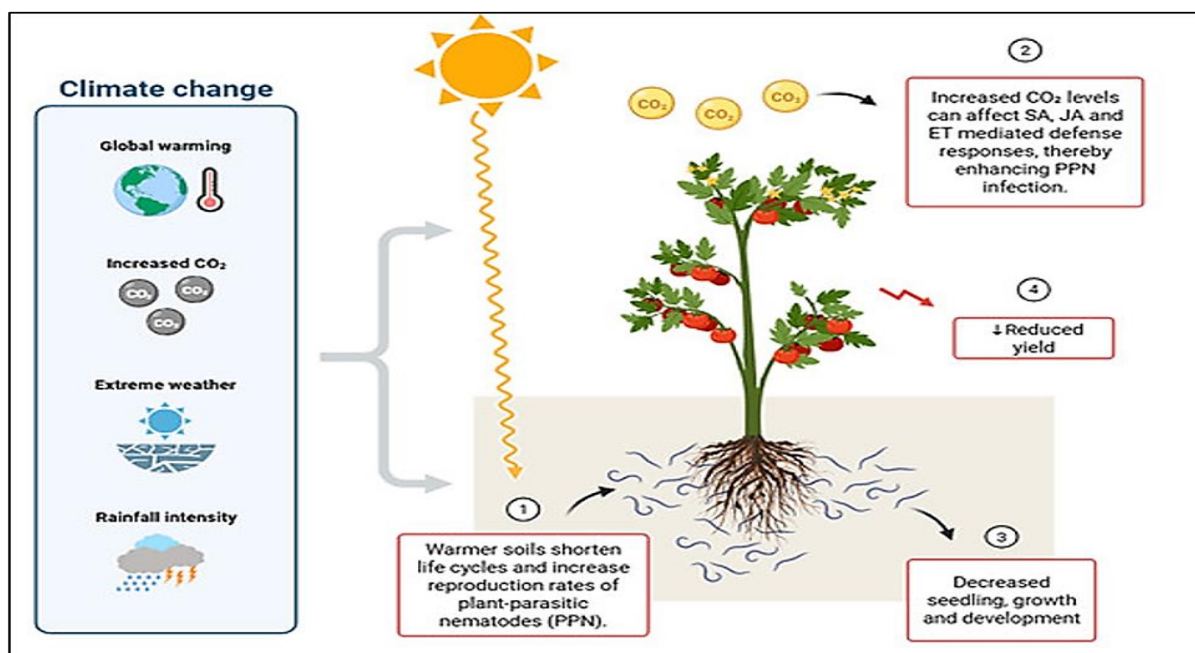
Plant-parasitic nematodes are particularly important because they live mainly in soil and plant tissues, where environmental factors strongly influence their biological activities. These microscopic worms attack the roots and other plant parts, interfering with water and nutrient uptake and ultimately reducing plant growth and productivity. Because nematode damage often remains unnoticed until significant crop loss has occurred, the possible effects of climate change on nematode problems require more attention.

2. Understanding climate change

Climate change refers to long-term changes in global or regional temperature and weather patterns, largely driven by human activities such as the burning of fossil fuels, deforestation, and industrial emissions, which increase the concentration of greenhouse gases in the atmosphere. The major features of climate change include:

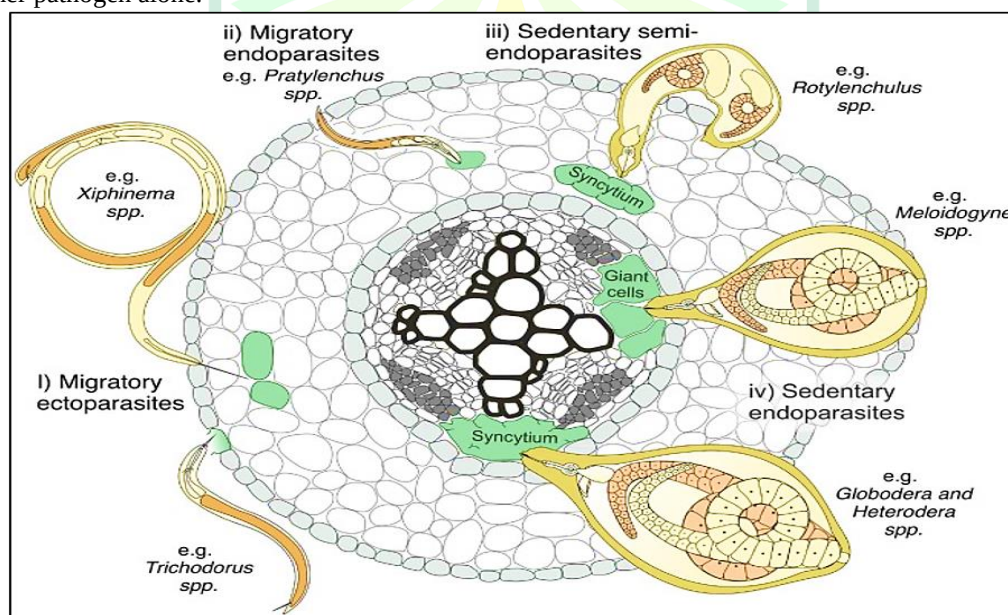
- Rising global temperatures
- Increased atmospheric carbon dioxide (CO₂) concentration
- Changes in rainfall patterns and distribution
- More frequent and severe droughts and floods
- Increased occurrence of extreme weather events

These environmental changes affect agricultural ecosystems by influencing crop growth, soil properties, and the diversity, survival, distribution, and activity of soil organisms, including both beneficial and plant-parasitic nematodes.



3. Plant-parasitic nematodes: hidden enemies of crops

Plant-parasitic nematodes are microscopic roundworms that obtain nutrients from living plant cells using a specialized feeding structure called a stylet. More than a hundred species are considered economically important in agriculture causing over \$100 billion in global crop losses annually. Among them, root-knot nematodes (*Meloidogyne* spp.), cyst nematodes (*Heterodera* and *Globodera* spp.), lesion nematodes (*Pratylenchus* spp.), reniform nematode (*Rotylenchulus reniformis*), burrowing nematode (*Radopholus similis*), and stem and bulb nematodes (*Ditylenchus* spp.) are responsible for substantial crop losses. Nematode-infected plants commonly exhibit stunting, yellowing, poor growth, wilting, nutrient-deficiency-like symptoms, and reduced yield. Below-ground symptoms may include root galling, lesions, necrosis, root pruning, and poorly developed root systems. Some nematodes also interact with fungi and bacteria, resulting in disease complexes that cause greater damage than either pathogen alone.



Different group of plant parasitic nematodes with their seeding sites in plant root

4. Influence of rising temperature on nematodes

Temperature is one of the most important factors regulating nematode biology. Most plant-parasitic nematodes thrive within specific temperature ranges.

4.1. Increased reproduction and development:

Warmer temperatures generally accelerate nematode metabolism, development, and reproduction. Root-knot nematodes, for example, complete their life cycle more rapidly under higher temperatures, leading to more generations within a growing season. As a result: Population densities increase rapidly. Crop damage becomes more severe. Management becomes more difficult.

4.2. Expansion into new areas:

Many nematode species previously restricted to tropical and subtropical regions may spread into temperate areas due to global warming. This geographical expansion increases the risk of introducing new nematode problems into regions that historically experienced little nematode damage.

4.3. Enhanced survival during winter:

Milder winters reduce nematode mortality. Species that normally decline during cold seasons may survive in greater numbers, resulting in larger initial populations at the start of the next cropping season.

4.4. Effects of altered rainfall patterns:

Climate change is altering precipitation patterns worldwide. Some regions are experiencing prolonged droughts, while others face excessive rainfall and flooding.

4.5. Drought conditions:

Water stress weakens plants and reduces their ability to tolerate nematode attack. Under drought conditions:

- Root systems become less vigorous.
- Plant defences decline.
- Nematode damage becomes more pronounced.

Studies have shown that drought-stressed crops often suffer greater yield losses when infected by root-knot and lesion nematodes.

4.6. Excessive rainfall and flooding:

Heavy rainfall can influence nematode movement and dispersal. In some cases, flooding may reduce populations of certain nematodes due to oxygen depletion in soil. However, excessive moisture may also facilitate the spread of nematodes to new fields through runoff and irrigation channels.

4.7. Changes in plant growth:

Higher CO₂ levels often stimulate plant growth and increase root biomass. Since many nematodes feed on roots, larger root systems may provide more feeding sites and support larger nematode populations.

4.8. Altered plant physiology:

Elevated CO₂ can change:

- Root exudate composition
- Nutrient content
- Plant defence mechanisms

These changes may influence nematode behaviour, reproduction, and host preference. In some situations, increased plant growth may partially compensate for nematode damage, while in others, nematode populations may increase substantially.

5. Climate change and nematode disease complexes

Plant-parasitic nematodes often interact synergistically with soil-borne fungi and bacteria, resulting in disease complexes that are more damaging than infections caused by either pathogen alone. Nematode feeding creates wounds in the root tissues that serve as entry points for fungal and bacterial pathogens. In addition, nematode infection disrupts water and nutrient uptake, weakens plant defence mechanisms, and alters root exudates, making plants more susceptible to secondary infections. Climate change is expected to intensify these interactions by influencing the growth, survival, and activity of both nematodes and soil-borne pathogens. Rising temperatures, elevated atmospheric CO₂, and changes in soil moisture can favour the simultaneous development of nematodes and pathogenic microorganisms, increasing the incidence and severity of disease complexes. Under warmer and

more humid conditions, both pathogen groups may complete their life cycles more rapidly, leading to greater disease pressure.

Some of the important examples illustrate these interactions. Root-knot nematodes (*Meloidogyne* spp.) are known to interact with *Fusarium oxysporum*, causing severe Fusarium wilt in cotton, tomato, and several vegetable crops. Similarly, root-knot nematodes predispose chilli, brinjal, and cucumber to infections by *Rhizoctonia solani*, *Pythium* spp., and *Phytophthora* spp., resulting in severe root rot and damping-off. Lesion nematodes (*Pratylenchus* spp.) enhance infections by *Verticillium dahliae* in potato and other crops, leading to greater wilt severity and yield losses. Likewise, the burrowing nematode (*Radopholus similis*) predisposes banana roots to infection by *Fusarium oxysporum* f. sp. *cubense*, the causal agent of Panama wilt, thereby accelerating root deterioration, plant decline, and yield loss.

As climate change creates environmental conditions favourable for both nematodes and microbial pathogens, the frequency and severity of these disease complexes are likely to increase, posing a greater threat to crop productivity. Therefore, future disease management strategies should adopt an integrated approach that considers the combined effects of nematodes, fungi, bacteria, and changing climatic conditions rather than managing each pathogen independently.

6. Emerging challenges for nematode management

Climate change creates considerable uncertainty for existing nematode management programmes because many control strategies are based on historical information about nematode distribution, seasonal activity, and population development. As temperature and rainfall patterns change, the timing of nematode emergence, reproduction, and crop infection may also shift. Changes in planting dates, cropping seasons, irrigation schedules, and the geographical distribution of crops may bring susceptible plants into contact with nematode populations that were previously absent or of minor importance.

Another major concern is that some currently effective management practices may become less reliable under future climatic conditions. Biological control agents such as *Trichoderma* spp., *Purpureocillium lilacinum*, and *Pseudomonas fluorescens* are influenced by soil temperature, moisture, pH, and microbial competition. Therefore, a bioagent that performs well under present conditions may show reduced survival, establishment, or nematode-suppressive activity under excessively warm, dry, or waterlogged soils.

The effectiveness of resistant crop varieties may also decline under increased nematode pressure. Warmer temperatures can shorten the nematode life cycle and allow more generations to develop within a single cropping season, resulting in rapid population build-up. Continuous exposure to high nematode populations may increase selection pressure on resistance genes and favour nematode populations capable of overcoming host resistance. In addition, the introduction or emergence of new, more virulent, or heat-adapted nematode populations may further complicate resistance breeding and varietal deployment.

Therefore, future nematode management must be flexible and climate-responsive. Regular surveillance, updated distribution maps, climate-based forecasting, repeated evaluation of resistant varieties, and testing of biological control agents under different temperature and moisture conditions will be necessary to maintain effective and sustainable nematode management.

7. Climate-smart nematode management

Dependence on a single management strategy is unlikely to provide sustainable protection against plant-parasitic nematodes under rapidly changing climatic conditions. Instead, integrated nematode management (INM) should combine resistant or tolerant varieties, crop rotation, cover crops, organic amendments, biological control agents, botanicals, soil solarization, sanitation, and the need-based use of safer nematicides. Improving soil organic matter and microbial diversity can enhance soil resilience while promoting naturally occurring antagonistic microorganisms that suppress nematode populations. Biological control agents such as *Trichoderma* spp., *Purpureocillium lilacinum*, *Pochonia chlamydosporia*, and *Pseudomonas fluorescens*, together with plant-derived products and organic amendments, offer environmentally friendly alternatives that reduce reliance on conventional chemical nematicides. These approaches, particularly the integration of botanicals, organic amendments, biological control agents, crop rotation, resistant varieties, and soil solarization, are widely recognized as key components of sustainable nematode management. Furthermore, precision agriculture and

advanced diagnostic technologies, including remote sensing, molecular diagnostics, geographic information systems (GIS), and predictive modelling, are expected to play an increasingly important role in identifying nematode hotspots, improving surveillance, and forecasting nematode risks under changing climatic conditions.

8. Future research priorities

Future research should focus on understanding how climate change influences economically important plant-parasitic nematodes through long-term studies involving multiple climatic factors such as temperature, moisture, and elevated CO₂. Developing predictive models, strengthening nematode surveillance and distribution mapping, and breeding climate-resilient crop varieties with durable resistance will be essential for future management. Greater attention should also be given to the role of beneficial soil microorganisms under changing climatic conditions, while improving farmer awareness and rapid diagnostic facilities will help ensure early detection and effective management of emerging nematode threats.

9. Conclusion

Climate change is expected to significantly affect plant-parasitic nematodes by altering their survival, reproduction, distribution, and interactions with host plants. Warmer temperatures and changing rainfall patterns may increase nematode populations, expand their geographical range, and intensify crop damage, while climate-stressed plants may become more susceptible to infection. These changes highlight the need for climate-resilient nematode management through regular surveillance, resistant varieties, biological control, organic amendments, and integrated pest management strategies to safeguard crop productivity and food security. Understanding and anticipating the changing behaviour of plant-parasitic nematodes under future climatic conditions will be crucial for protecting crop productivity, ensuring food security, and building resilient and sustainable agricultural systems.

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WORLD RURAL DEVELOPMENT DAY: JULY 06



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The United Nations as a global body has been spearheading various global celebrations through various important days with the ultimate aim of furthering the cause of humanity and all other forms of life on this planet. An important event of this global body is World Rural Development Day celebrated every year on July 06. Proclaimed by the UN General Assembly, the day highlights the challenges faced by rural communities and emphasizes global action to end rural poverty, build climate resilience, and achieve the UN's Sustainable Development Goals (SDGs). July 6th was deliberately chosen to mark the founding anniversary of the Centre on Integrated Rural Development for Asia and the Pacific (CIRDAP), which was established in 1979 in Dhaka, Bangladesh. The day champions the cause of rural communities who are still the disadvantaged ones suffering from so many issues of equity, equality, social exclusion, literacy, health, financial exclusion and many more. Let me clear it by an example. In 2024, 83% of urban residents used the internet versus <50 % in rural areas ([ITU 2024](#)).

The day promotes sustainable agriculture, digital and financial inclusion, infrastructure development, and the vital roles that women, youth, and Indigenous populations play in global food security. Rural areas are home to 80% of world's poorest peoples and they stand at the frontline of food insecurity, climatic shocks and mitigation pressures. This is despite the fact that rural communities are the 'first mile' of food systems: the places where food is grown, livelihoods are sustained and resilience begins. At the same time, they also hold immense potential to strengthen food security, create economic opportunity and support long-term stability. Investment in rural communities means investing in the foundations of more resilient societies. When rural areas have the resources they need, communities are better able to withstand shocks, young people have greater reason to build their futures at home, and producers can contribute more fully to local, national and global markets. Evidence indicates that increased investment in rural areas equivalent to 1% of a country's gross domestic product can reduce international out-migration by nearly one percentage point (IFAD, 2026).

India has been predominantly a rural country with two thirds of its population still residing in rural areas. India's 70% workforce belongs to rural areas. It is said that true India lives in her villages. The rural growth and development drive the overall growth and development of India as the rural economy of India constitutes around 50% in national income of India, thus, the rural economy of India is backbone of the Indian economy. Agriculture is a sector which is the source of livelihood for about 50% of the country's population living in rural settings. In some families all the members are engaged in this noble profession. Agricultural development is crucial to the development of country as well as for rural development. With a focus on the agriculture sector and ensuring that the relevant technologies, Programmes and policies reach out to the farmers well in time, rural development can be more inclusive as well as more effective. KVKs are playing a very important role in transfer of relevant technologies to farming communities.

At the district level, the Krishi Vigyan Kendras are front level extension institutions catering to the diverse needs of a district, some of which have different agro-climatic zones, different farming situations, and consequently different requirements of different stakeholders. Although, the initial idea of setting up of these KVKs was to provide vocational training to rural youths in agriculture and other allied sectors; but with the passage of time the roles and responsibilities of these KVKs changed. Today KVKs provide a platform for interface between farmers, researchers and extension functionaries to address the problems of agriculture and allied sectors. These institutions are engaged in on farm testing to assess the location specific needs of the farm sector, front line demonstrations to establish production potential of technologies on farmers' fields; conducting training and skill development programmes for farmer, youths, farm women, promoting agri-preneurship and acting as a resource and knowledge centre of agricultural technologies. Since the establishment of first KVK in 1974 at Puducherry under Tamilnadu Agriculture University, these have been proactively contributing to the

development of farms and farming community accelerating rural development. Most of the flagship programmes of the government are now reach out to potential beneficiaries through these district level institutes. A third party evaluation of KVKs was carried out by National Institute of Labour Economics Research and Development (NILERD), an autonomous institute under NITI Aayog in 2018 came out with findings which reveal that the KVKs all across the country are doing a tremendous job accomplishing and achieving many milestones. The evaluation found that KVKs are playing a proactive role in transferring new technology at field level with beneficial impacts and that these institutes have an edge over other service providers by virtue of having better technical expertise and demonstration abilities. The technologies demonstrated by KVKs were immediately adopted by 40 percent of the farmers and 25 percent adopted them by the next agricultural season. On an average a KVK covers 43 villages and 4300 farmers every year and 80% of villages covered are 10 kilometers away from KVK. The evaluation further said that 96 percent of the farming queries were attended by the KVKs and 42% technologies adopted by farmers resulted in higher productivity and 20 percent resulted in drudgery reduction. About 25% of the persons trained by KVKs started their own self employment ventures.

A meta-analysis study by Bhuvana and his associates in 2019 also revealed that the farmers who are beneficiaries of KVK activities like 'on farm testing', 'front line demonstration', 'training' and other KVK activities are 2.62 times, 3.40 times, 1.37 times and 2.01 times more probable to fall in high socio-economic status, knowledge level, the extent of adoption and farmer's income score category, compared to non-beneficiary farmers and the KVK's activities have a positive impact on farmers of India to have higher socio-economic status with improved knowledge level, the extent of adoption of scientific technologies and farmer's income. Another study by Rathore and Sadana (2023) concluded that Krishi Vigyan Kendra is contributing a lot to rural development through its multidisciplinary teamwork in a participative mode with different farming communities and provides training and proper guidance to improve the skills of rural people.

Overall KVKs drive rural development by Transfer of Technology. KVKs conduct On-Farm Testing (OFT) and Frontline Demonstrations (FLD) which prove the viability of modern technologies and practices directly to rural farmers. The Skill Development & Entrepreneurship programmes of the Kendras providing training to farmers, rural youth, and women, focusing on allied agricultural sectors like dairy, poultry, bee-keeping, and food processing to establish various ventures thereby enabling youths to become job providers instead of job seekers. As a Resource Centers, they operate as district knowledge hubs and provide real-time agro-advisories (e.g., weather updates, soil testing, pest control), ensuring rural communities have the data needed to protect their harvests and increase productivity. KVKs also help in empowerment of farming communities by Promoting Collectivization through Self Help Groups (SHGs), Farmer Producer Companies (FPCs) and Farmer Producer Organizations (FPOs) allowing small-scale rural farmers to access better markets and negotiate prices. Key digital programmes of KVKs like Kisan Sarthi, m Kisan & Digital Outreach platforms help them to send millions of advisories annually to registered farmers, offering timely, localized solutions. Through initiatives like 'Attracting and Retaining Youth in Agriculture (ARYA)' KVKs are equipping rural youth to start independent agri-enterprises and creation of assets, curbing rural-to-urban migration. To tackle climate change, KVKs are also spearheading the establishment of 'Climate Smart Villages' promoting resource-saving farm practices like zero-tillage, integrated farming systems (IFS), and recycling of organic wastes.

It can thus be concluded that as engines of growth, the KVKs are propelling rural development through agricultural development. These institutions have on every occasion lived up to the expectations of farming community as well as of the government and its various agencies. As front line extension institutions, they have no substitute and thus have to be strengthened. At the same time it is also necessary that the human resources working there should not feel discriminated and a victim of apathy and neglect.

The Indigenous Bull That Still Feeds India: Why Bull-Based Farming is the Backbone of Natural Agriculture



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"When the bull walks through the field, the soil breathes, the farmer smiles, and nature prospers."

The sight of a pair of indigenous bulls slowly ploughing a flooded paddy field is becoming increasingly rare. Modern tractors have replaced bullocks in many parts of the country, promising speed and efficiency. However, as agriculture faces rising fuel costs, declining soil fertility, climate change, and shrinking farm profitability, many farmers are rediscovering the unmatched value of bull-based farming, especially under natural farming systems.

Figure 1. A traditional farmer guiding a pair of indigenous bulls through a muddy paddy field, illustrating the enduring harmony between humans, livestock, and nature. Bull-powered cultivation is an integral component of natural farming, promoting sustainable land preparation, conserving indigenous cattle, minimizing dependence on fossil fuels, and maintaining soil health through environmentally friendly agricultural practices

More Than Just Draft Animals

For centuries, indigenous bulls have been the engine of Indian agriculture. They ploughed fields, transported farm produce, powered traditional irrigation systems, and contributed immensely to sustainable farming without consuming a single drop of diesel.

Unlike tractors, bulls work with nature rather than against it. Their gentle movement causes minimal soil compaction, allowing better water infiltration, improved root growth, and enhanced soil microbial activity. Healthy soil ultimately leads to healthy crops.

Bull-Based Farming and Natural Farming: A Perfect Combination

Natural farming depends heavily on indigenous cattle. While cows provide dung and urine for preparing Jeevamrit, Beejamrit, Ghan Jeevamrit, and Panchagavya, bulls perform the physical operations required in farming.

Bull-based farming supports natural agriculture through:

- Eco-friendly land preparation without fossil fuels.
- Minimal soil disturbance and improved soil structure.
- Lower greenhouse gas emissions.
- Conservation of indigenous cattle breeds.
- Reduced dependence on costly machinery.
- Greater self-reliance for small and marginal farmers.

Every hectare cultivated using bull power represents a step toward climate-resilient agriculture.

The Hidden Economics

Although tractors save time, their ownership and operation involve substantial expenses, including fuel, maintenance, repairs, and depreciation. Small farmers often spend a significant portion of their income hiring tractors during peak seasons.

Bullocks, on the other hand, require feed that can largely be sourced from crop residues, natural grazing, and locally available fodder. Their maintenance generates multiple returns:

- Farmyard manure
- Cow urine
- Draft power
- Organic inputs
- Calves for future generations

Thus, the same animal contributes to crop production, soil fertility, and farm sustainability.

The Living Fertility Factory

Indigenous cattle are central to natural farming because every component they provide is useful.

Fresh dung is used for preparing:

- Jeevamrit
- Ghan Jeevamrit
- Vermicompost
- Farmyard manure
- Biogas slurry

Cow urine forms an essential ingredient in:

- Beejamrit
- Jeevamrit
- Panchagavya
- Botanical pesticides

The bull therefore indirectly contributes to the production of nutrient-rich organic inputs simply by being part of the indigenous cattle production system.

Conserving Indigenous Breeds

Mechanization has significantly reduced the demand for bullocks, resulting in declining populations of indigenous cattle in many regions. As farmers prefer crossbred dairy cattle, valuable native breeds adapted to local climatic conditions are gradually disappearing.

Promoting bull-based farming creates an economic reason to conserve indigenous breeds, ensuring their survival for future generations.

These native animals possess remarkable qualities:

- Heat tolerance
- Disease resistance
- Ability to survive on low-quality fodder
- Longer productive lifespan
- Adaptability to local environments

These characteristics are becoming increasingly important under changing climatic conditions.

Environmental Benefits

Bull-powered agriculture contributes significantly to environmental conservation.

Unlike diesel-powered tractors, bulls:

- Produce virtually no fossil fuel emissions.
- Reduce dependence on imported petroleum.
- Improve soil organic carbon through manure.
- Support biodiversity.
- Enhance nutrient recycling within the farm.

Their manure also feeds biogas plants, producing clean cooking fuel while the digested slurry serves as an excellent organic fertilizer.

Bullocks in Paddy Cultivation

Paddy cultivation particularly benefits from bullock power. Traditional puddling with bullocks allows better mixing of soil and water while maintaining the natural structure of the field.

The slow pace of bullock ploughing helps farmers:

- Prepare uniform seedbeds.
- Reduce weed growth.
- Improve water retention.
- Minimize fuel expenditure.
- Maintain soil biological activity.

The photograph above perfectly illustrates this time-tested practice, where the farmer and his bulls work together in flooded paddy fields.

Reviving a Sustainable Tradition

Across India, several natural farming movements are once again promoting indigenous cattle and bullock farming. Farmers practicing Zero Budget Natural Farming and other ecological farming systems recognize that sustainability cannot rely solely on chemical-free inputs; it also requires energy sources that are renewable and locally available.

Bullocks represent renewable biological energy.

They convert locally available biomass into useful work while enriching the farm ecosystem instead of polluting it.

The Way Forward

To encourage bull-based natural farming, greater institutional support is needed through:

- Conservation of indigenous cattle breeds.
- Financial incentives for maintaining working bullocks.
- Community bullock banks for small farmers.
- Promotion of bullock-drawn improved implements.
- Integration of bullocks with biogas technology.
- Farmer training on natural farming practices.
- Research on efficient animal-powered farm implements.

Conclusion

In an age dominated by machines, the humble bull continues to demonstrate that true agricultural sustainability lies in working with nature rather than replacing it.

Bull-based farming is not a symbol of backwardness—it is a practical, environmentally friendly, and economically viable approach for millions of smallholder farmers. Combined with indigenous cattle, organic inputs, and natural farming practices, bull-powered agriculture can reduce production costs, restore soil health, conserve biodiversity, and strengthen rural livelihoods.

As India moves toward climate-smart and sustainable agriculture, the rhythmic footsteps of indigenous bulls in the field may once again become the heartbeat of resilient farming systems.

"The future of natural farming may well depend on preserving the strength of the bull, the wisdom of traditional farmers, and the richness of our indigenous cattle heritage."

Advances in Dairy Cattle Reproduction: From Natural Breeding to Embryo Transfer



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Abstract

Reproductive technologies have significantly transformed dairy cattle breeding and herd improvement programs worldwide. Traditional natural breeding, though effective, has gradually been replaced by advanced assisted reproductive technologies aimed at improving genetic gain, reproductive efficiency and productivity. Artificial insemination (AI) revolutionized dairy reproduction by enabling widespread use of superior sires, reducing transmission of venereal diseases, and accelerating genetic progress. Recent decades have witnessed remarkable progress in embryo-based technologies, like multiple ovulation and embryo transfer (MOET) and in vitro embryo production (IVEP). These technologies allow rapid multiplication of elite females, improved dissemination of superior genetics, and conservation of valuable germplasm. This article reviews the progress of reproductive technologies in dairy cattle from natural breeding to modern embryo transfer techniques, highlighting their principles, applications, advantages, limitations, and role in sustainable dairy development. The continued advancement and adoption of these technologies are expected to play a crucial role in meeting the growing global demand for milk and improving the economic efficiency of dairy farming.

Introduction

Reproductive health directly influences milk production and the economic status of farmers. Traditional natural breeding methods, once the only means of animal reproduction, have gradually been supplemented and replaced by advanced assisted reproductive technologies (ARTs) such as artificial insemination (AI) and embryo transfer (ET). The evolution from natural breeding to sophisticated embryo technologies represents one of the greatest achievements in veterinary reproductive science. These technologies have revolutionized animal breeding by enabling rapid genetic improvement, better disease control, and enhanced reproductive management. While AI maximized the reproductive impact of genetically superior males, ET opened the door to amplifying the reproductive potential of elite females. These developments, along with adjunct technologies like cryopreservation, semen sexing, and estrous synchronization, form the basis of the modern-day animal production.

Natural breeding: Natural breeding refers to mating between a male and female animal without human mediated reproductive intervention. Before the development of reproductive biotechnology, natural service was the only method available for cattle breeding.

Types of Natural Breeding

Free Mating: Bulls and cows are allowed to mix freely in grazing areas or farms. The bull detects estrus and mates naturally. It has advantages like simple, inexpensive, minimal labour requirement and suitable for extensive farming systems but it has disadvantages in the long run like poor breeding records, increased disease transmission, uncontrolled breeding and risk of inbreeding.

Hand Mating: Cows identified in estrus were presented to selected bulls under supervision. It has advantages like controlled mating, better breeding records and reduced injury risk but with disadvantage being labour intensive.

Pen Mating: A bull is maintained with a selected group of cows. It is better than free mating but possibility of disease spread.

Limitations of Natural Breeding in Cattle

- **Biosecurity and venereal diseases:** Natural mating serves as a direct vector for the horizontal transmission of venereal pathogens. In cattle, diseases like trichomoniasis (*Trichomonas foetus*), campylobacteriosis (*Campylobacter fetus*) and brucellosis (*Brucella bovis*) cause widespread infertility, early embryonic death, endometritis, and abortion storms within herds.
- **Geographic and numerical restraints:** A superior sire could only service females within its immediate physical vicinity.
- **Physical injury risk:** Natural mating poses inherent physical dangers. Large, heavy mature bulls risk fracturing the limbs or injuring the spines of smaller heifers. Conversely, aggressive or uncooperative cows can cause severe musculoskeletal trauma or penile deviation in the sire.
- **High maintenance cost:** Maintaining breeding bulls requires feeding, housing, health care and handling facilities

Artificial insemination (AI): It is the process in which semen collected from a bull is processed and deposited artificially into the reproductive tract of a cow at the appropriate stage of estrus. AI allowed a single high-indexing bull to father thousands of calves annually, accelerating genetic gain at an unprecedented rate. In dairy cattle, AI drove an exponential increase in milk yields and enabled the rigorous implementation of progeny-testing schemes.

Advantages of Artificial Insemination in Cows

- **Rapid genetic improvement:** AI allows semen from genetically superior bulls to be used in thousands of cows with the benefits of increased milk production, better growth rate and improved fertility traits.
- **Control of venereal diseases:** AI reduces direct contact between bulls and cows, minimizing transmission of diseases such as brucellosis, trichomoniasis and campylobacteriosis
- **Economical for farmers:** Farmers do not need to maintain breeding bulls.
- **Better use of superior bulls:** A single ejaculate can be diluted into many semen straws, allowing maximum utilization of elite bulls.
- **Safe and convenient:** AI reduces risks associated with aggressive or heavy bulls. It prevents injuries to cows, handlers and accidents during mating.
- **Semen storage and transportation:** Frozen semen can be stored for years in liquid nitrogen at -196°C leading to international semen transport and use of semen even after bull death.
- **Crossbreeding programs:** AI facilitates introduction of exotic or superior breeds into local cattle populations.
- **Accurate breeding records:** AI programs maintain proper records of bull identity, insemination date, pregnancy status and calving records. This improves herd management and genetic evaluation.

Disadvantages of Artificial Insemination in Cows

- **Requirement of skilled technicians:** Successful AI depends on properly trained personnel. Poor technique can lead to low conception rates, injury to reproductive tract and infection.
- **Dependence on accurate heat detection:** Incorrect estrus detection is one of the major causes of AI failure.
- **Difficult in small or unorganized farms:** In villages with poor veterinary access, timely AI services may not be available.

Artificial insemination is one of the most important reproductive technologies in cattle production. It has revolutionized dairy industry by enabling rapid genetic improvement, disease control and economical

breeding management. When properly implemented, the advantages of AI greatly outweigh its limitations and contribute significantly to improved cattle productivity and profitability

Estrus synchronization in cattle: Hormonal protocols synchronize estrus and ovulation in groups of cows. The commonly used hormones for synchronization are prostaglandin, Gonadotropins and progesterone.

Estrus synchronization enables:

- Timed AI
- Improved reproductive management
- Better labour efficiency

Use of sex sorted semen

Sex-sorted semen is an advanced reproductive biotechnology used in bovines to increase the probability of producing calves of the desired sex. In dairy cattle, female calves are generally preferred because they become milk-producing cows and dairy farms benefit greatly because female calves are economically more valuable. Sex-sorted semen technology separates X chromosome-bearing sperm and Y chromosome-bearing sperm before artificial insemination. X-bearing sperm produce female calves and Y-bearing sperm produce male calves. Sexed semen generally provides 85–95% accuracy for desired sex

Advantages of sex sorted semen

- Increased replacement heifers
- Faster herd expansion
- Increased milk production potential
- Rapid genetic improvement
- Reduction of unwanted male calves

Disadvantages of Sex-Sorted Semen

- Lower conception rate
- Lower sperm numbers per straw
- Sperm damage during sorting
- High Cost

Sex-sorted semen enables production of calves of the desired sex, improves herd management, accelerates genetic progress, and increases profitability in dairy production systems. Although conception rates may be slightly lower and costs higher than conventional semen, the economic and genetic advantages make sexed semen a valuable tool in modern bovine reproduction programs

Embryo Transfer Technology (ETT)

While AI maximized the genetic contribution of the bull, the cow remained a biological bottleneck, limited by her natural 9-month gestation period to producing just one calf per year. Embryo Transfer (ET) bypassed this barrier, allowing the genetic impact of elite females to match that of their male counterparts. ETT is of two types one is Multiple ovulation embryo transfer (MOET) and other is in vitro embryo production (IVEP)

Multiple Ovulation Embryo Transfer (MOET)

MOET is an advanced reproductive biotechnology used in cattle and other livestock species to accelerate genetic improvement by producing multiple offspring from genetically superior females within a short period. Under natural conditions, a cow usually produces one calf per year because only one ovum is normally ovulated during each estrous cycle. MOET overcomes this limitation by inducing multiple ovulations through hormonal treatment, followed by artificial insemination, collection of embryos and transfer into recipient females. Through superovulation, artificial insemination, embryo recovery, and embryo transfer, one elite donor cow can produce many offspring annually. MOET has contributed significantly to genetic improvement, disease control, germplasm conservation, and international cattle breeding programs.

Advantages of MOET

- Rapid genetic improvement

- Increased selection intensity
- Reduced generation interval
- Conservation of valuable genetics

Disadvantages of MOET

- High cost
- Variable superovulatory response
- Lower embryo recovery in some cases
- Skilled expertise

In vitro embryo production (IVEP)

IVEP is an advanced assisted reproductive technology in cattle in which embryos are produced outside the animal under laboratory conditions. It involves collection of oocytes from donor cows, maturation and fertilization in the laboratory, followed by embryo culture and transfer into recipient females. IVEP has become an important tool in modern dairy cattle breeding programs for rapid genetic improvement, multiplication of elite animals, conservation of valuable germplasm, and production of embryos from infertile or high-genetic-merit females.

Advantages of IVEP

- Large numbers of embryos can be produced from elite females.
- Use of pregnant or infertile donors.
- IVEP can produce more embryos than conventional MOET programs.
- Allows production of embryos of desired sex.
- Used in research as IVEP supports cloning, transgenesis and stem cell research.

Disadvantages of IVEP

- High cost
- Lower embryo quality in some cases
- Variable success rates
- IVEP requires highly trained embryologists and veterinarians.

In vitro embryo production (IVEP) is a highly advanced reproductive biotechnology that has transformed bovine reproduction and genetic improvement. Through in vitro maturation, fertilization, and embryo culture, large numbers of embryos can be produced from genetically superior cattle. Despite challenges such as high cost and technical complexity, IVEP continues to expand globally and remains a cornerstone of modern bovine reproductive management.

Impact of modern reproductive technologies

- Increasing milk yield
- Accelerating genetic progress
- Reducing disease transmission
- Enhancing reproductive efficiency
- Increasing farm profitability

Challenges in use of modern reproductive technologies

- Lack of trained personnel
- Inadequate infrastructure
- Poor cold chain management
- Limited farmer awareness
- High operational costs

Conclusion

The evolution from natural breeding to artificial insemination and embryo transfer marks a revolutionary advancement in cattle reproduction. Natural breeding, though simple, has limitations in genetic

improvement and disease control. Artificial insemination transformed cattle breeding by enabling widespread use of superior bulls and improving reproductive efficiency. Embryo transfer technology further accelerated genetic progress by multiplying elite female genetics rapidly. Today, reproductive biotechnology is reshaping modern cattle production. Continued research, skilled veterinary services and improved infrastructure will ensure that these technologies contribute significantly to sustainable livestock production, food security, and genetic conservation in the future.



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Reviving Kashmir's Forests: The Battle Against Deforestation and Climate Vulnerability



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Drive along the Srinagar Pahalgam highway on a clean morning and the Himalayas still take your breath away snow-capped ridge, waterfalls threading down grey cliffs the Lidder River catching the light below. But if you know where to look, something is missing. The dense canopy of deodar and fir that older residents describe with quiet nostalgia has thinned considerably. Hillsides that once held centuries -old stands of *Cedrus deodara* now expose bare patches of red soil, raw as a wound. Kashmir is losing its forests and with them, an entire web of life, livelihood and ecological stability that took millennia to weave.



Deforestation (Source: AI generated image)

The numbers confirm what the eye suspects. According to data from the US- based Global Forest Watch (GFW), Jammu and Kashmir lost approximately 4,190 hectares of tree cover between 2001 and 2023 a 0.39 % decline since 2000. That may sound modest in absolute terms. It is not. The Forest Survey of India 2023 report recorded a loss of 40.61km² of forest cover between 2021 and 2023 alone, driven by infrastructure development and a rising incidence of forests fires. In 2023 specifically, 112 hectares of natural forests disappeared and with it, an estimated 68,800 metric tonnes of carbon dioxide equivalent emissions entered the atmosphere.

The Many Faces of Destruction

The causes are not hard to identify though they resist easy solutions. Infrastructure expansion roads, tunnels, hydropower projects and a construction boom in tourism have claimed a disproportionate share. According to a Kashmir Vision analysis between 60 -70 percent of cleared forest land in recent years was removed for construction purpose. Tourist hotspots have been hit hardest. Pahalgam, Gulmarg and Sonamarg the valley celebrated hill stations have seen significant tree felling, often for hotels and resorts built with the blessing of politically connected interests. Between September and October 2019 alone, 727 hectares of forest land were diverted for infrastructure and military use.

Forest fires compound the picture

GFW data shows that between 2001-2003, fires accounted for 952 hectares of tree cover loss, while other deforestation drivers claimed 3,230 hectares. Between March 2021-2025, Jammu and Kashmir recorded 3,905 fire alerts through the VIIRS satellite system. The highest annual fire toll in recent history came in 2016 with 167 high-confidence alerts a threshold the region edges to words in every day springs.

The five worst-affected district are Rajouri, Kathua, Reasi, Doda and Udhampur together account for 53 percent of total tree cover loss in the region. Rajouri stands out with 526 hectares lost nearly three times the regional average of 199 hectares lost, nearly three times the regional average of 199 hectares. This is not problem confined to any single agency, community or policy failure or it is systemic.

When Forests Fall, Everything Follows

Kashmir's forests are not ornamental they regulate the water cycle across three major river basin the Jhelum, the Chenab, and the Indus tributaries. The anchor the topsoil of steep Himalayan slopes against a monsoon that arrives every year with force. They sequester carbon at scale GFW estimates that the cumulative tree cover loss between 2001-2003 generated roughly 19.8 lakh metric tonnes of CO₂ equivalent emissions a dept to the atmosphere that compounds interest will make Worse.

Soil erosion is the immediate visible consequence. Once tree roots no longer hold the hillside, rain carries topsoil into rivers, raising their beds, increasing flood risk downstream and degrading agricultural land. Villages in the foothills of Rajouri and Reasi have reported worsening flash floods over the past decades and farmers in lower valleys note that the Jhelum now runs browner and shallower than their parents' generations knew. Scientists studying the region warn that this cycle deforestations leading to erosion, erosion leading to floods, floods leading to further land degradation is already underway and will be difficult to reverse once fully entrenched.

The Hangul: A Species on the Edge

No single creature embodies Kashmir's ecological crisis more poignantly than the hangul (*Cervus hanglu hanglu*), the Kashmir stag. It is the only species of red deer in the Indian subcontinent, endemic to this valley, listed in Schedule I of the Wildlife Protection Act, and classified as Critically Endangered by the IUCN. The hangul is also the state animal of Jammu and Kashmir a symbol the state is slowly losing.

In the early twentieth century, between 3,000 and 5,000 hangul grazed freely across the forests of the Kashmir valley and parts of Himachal Pradesh's Chamba district. Poaching, habitat loss, and the disruptions of partition and conflict reduced that population to an estimated 150 individuals by 1970. Conservation efforts in the following decade pushed numbers back above 340 by 1980, but the gains stalled. A 2019 census found only 237 hangul remaining in the wild, confined almost entirely to the 141 square kilometres of Dachigam National Park on the outskirts of Srinagar.

A research paper published in 2023 did not mince words with fewer than 200 reproductive individuals, the hangul may be in a terminal phase of decline and could become extinct if effective interventions are not implemented. A more optimistic genetic study published in the journal Oryx in December 2023 using faecal DNA analysis rather than direct sightings identified 293 individuals in Dachigam, suggesting the population may be as high as 394 when statistical modelling is applied. Experts welcomed the finding but cautioned against complacency: population viability analyses still indicate further decline is probable without systematic habitat restoration.

The hangul's crisis is inseparable from the forests. Its preferred habitat dense riverine woodland, alpine meadows, and high-valley forest have contracted sharply. Livestock grazing within and around Dachigam competes for the same browse. Male-to-female ratios have deteriorated dramatically: where historical records show 25–30 stags per hundred hinds, recent surveys found as few as 15. Even as experts argue over the exact count, the trajectory is unmistakable.

Carbon, Climate, and a Warming Valley

Kashmir has long been described as unusually vulnerable to climate change for a region that contributes so little to global emissions. Average temperatures in the valley have risen measurably since the 1980s. Snowfall patterns

the source of meltwater that sustains rivers through summer have become erratic. Glaciers that feed the Indus system are retreating. In this context, forests are not a luxury; they are infrastructure.

Each hectare of healthy Himalayan Forest sequesters between five and twelve tonnes of carbon annually, depending on species composition and stand age. Deodar, the dominant commercial species, is particularly effective slow-growing, dense-wooded, and long-lived. When a deodar forest is felled, its stored carbon is released, not just from the felled trees but from the degraded soil beneath, which loses its capacity to hold organic carbon over years of subsequent erosion. Replanting does not restore this balance quickly: a newly planted sapling sequesters a fraction of what a century-old tree store.

The valley's forests also regulate local temperature and rainfall. Satellite studies suggest that areas with intact forest cover in the Himalayas experience measurably lower surface temperatures and support higher soil moisture retention. As forest patches contract, the microclimate they sustain breaks down, leading to hotter, drier conditions that make surviving vegetation more susceptible to fire a feedback loop that climate scientists call forest dieback, and which has been observed in analogous mountain systems worldwide.

What Is Being Done

Against this backdrop, the response from authorities has been real, if uneven. The Compensatory Afforestation Fund Management and Planning Authority (CAMPA) has been the principal instrument. Since its inception in 2010–11, CAMPA has treated more than 1.06 lakh hectares of degraded forest land across Jammu and Kashmir through afforestation, assisted natural regeneration, and ecological restoration. Nearly 7.46 crore saplings have been planted across different forest divisions during the same period. In 2021–22, over 5,000 hectares of degraded forest were rehabilitated and approximately 27 lakh plants established in monsoon and autumn planting seasons. During 2025–26 alone, nearly 2,952 hectares were treated under different CAMPA components.

The Social Forestry Department has established 4,289 Village Panchayat Plantation Committees, giving local bodies a formal role in planning and implementing tree planting on non-forest land, including village woodlots and avenue plantations. The government's Har Gaon Haryali (Green Village) drive has sought to extend this outreach to the panchayat level. Officials have also flagged specific degraded stretches such as Peer ki Gali and Tanghdar for immediate ecological intervention. Senior officials speaking at review meetings have been unambiguous afforestation is a core priority, not a peripheral one.

These are not trivial achievements. But they need to be weighed carefully. Planting saplings is not the same as restoring a forest. Survival rates for planted saplings in degraded Himalayan terrain are notoriously variable. Grazing by livestock the single most important driver of forest degradation in Kashmir, according to researchers continues largely unchecked. Studies tracking restored and non-restored plots over eight years found that the critical variable was not the planting itself but the exclusion of grazing: where livestock were kept out, natural regeneration followed; where they were not, even replanted trees struggled.

Forest diversion for non-forestry purposes has reportedly declined sharply after 2020, and the area covered under afforestation and restoration has nearly doubled in recent years. These are genuine improvements. Whether they can outpace the compounding effects of climate change, tourism pressure, and infrastructure demand remains an open question.

The Wisdom Beneath the Trees

What official schemes have sometimes missed and what researchers are increasingly highlighting is the depth of indigenous ecological knowledge embedded in Kashmiri communities. The fifteenth-century Sufi saint Sheikh-ul-Alam, revered as Nund Rishi, is remembered for the verse: ‘**Ann Poshhi Teli Yeli Wan Poshhi**’ food will last as long as forests last. This was not poetry in the ornamental sense; it was a statement of ecology compressed into a couplet, passed down for six centuries and quoted today by forest officials, researchers, and villagers with equal conviction. It is also a reminder that the connection between Kashmir's people and its forests was once encoded in culture, not merely in policy documents. The Gujjar and Bakarwal communities' semi-nomadic pastoralists who migrate between the plains and high-altitude meadows with the seasons have long been cast as the villains of forest degradation, blamed for the overgrazing that prevents forest regeneration. Researchers challenge this framing. They are indigenous communities. They have the right to use forest resources. Similarly, their livestock also has the right to graze inside the forests, says Bilal Muzaffar, a forest ecologist who has studied the valley's

restoration dynamics. He argues that if these communities were actively included in forest management given formal stakes and responsibilities under the Forest Rights Act, 2006 they would have both the incentive and the knowledge to act as effective forest stewards rather than as encroachers.

Local ecological knowledge about which native species regenerate best on which slope aspect, which plants signal healthy soil, how grazing pressure varies across the seasons this information lives in communities, not in government files. A 2020-22 ethnobotanical survey in the Kashmir Himalaya documented 110 medicinal plant species across 49 families known to local communities, a pharmacopoeia accumulated over generations of intimate contact with the forest. The same communities who know these plants are also the communities who notice first when they begin to disappear.

The Road Ahead

Reviving Kashmir's forests will require a convergence that India's conservation establishment has struggled to achieve: coordinated action across agencies, genuine community participation, long-term funding with accountability built in, and the political will to say no to infrastructure expansion in ecologically sensitive zones. The tools exist. CAMPA provides funding. The Forest Rights Act provides a framework for community involvement. Climate finance mechanisms including REDD+ (Reducing Emissions from Deforestation and forest Degradation) could generate resources if the UT's forest department develops the technical capacity to access them. A research paper mapping Kashmir's forests using Landsat data from 1980 to 2009 found that the study area had undergone 126 square kilometres of deforestation and 139 square kilometres of forest degradation both categories that could, in principle, be claimed under REDD+ frameworks if properly documented and verified.

What the science, the data, and the long memory of Kashmir's people suggest, in the end, is not a complicated lesson. The valley's beauty and its biological wealth are not separate from its ecological health. The hangul grazing in Dachigam, the deodar holding the hillside in Pahalgam, the Jhelum running clear through Srinagar these are connected. When the forest goes, they all, eventually, go with it. Sheikh-ul-Alam said this six hundred years ago. It would be a particular kind of tragedy if the generation alive today required satellite data to believe him.

References

Data sources: Global Forest Watch (GFW), Forest Survey of India (FSI) 2023, IUCN Red List, CAMPA J&K, and peer-reviewed studies published in Oryx, Mongabay-India, and PMC.

Role of Soil Microorganisms in Enhancing Soil health



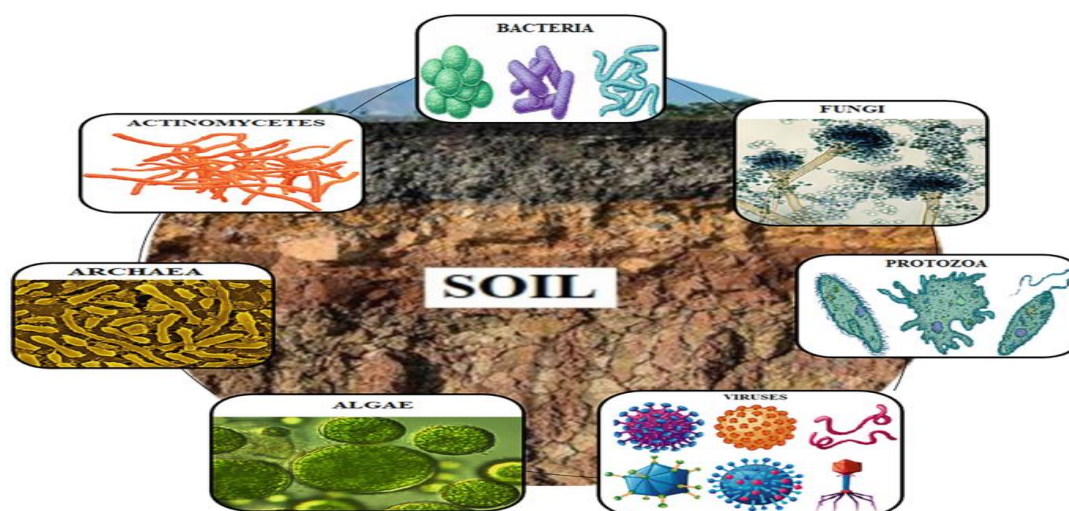
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Introduction

Soil microorganisms are tiny living organisms such as bacteria, fungi, algae, actinomycetes, and protozoa that live in the soil. Although they are microscopic, they play a crucial role in maintaining soil fertility and increasing agricultural productivity. These beneficial organisms support plant growth by improving nutrient availability, enhancing soil structure, and protecting crops from diseases. Therefore, they are considered an essential component of sustainable agriculture.

Microbial diversity is not just about numbers; it's about maintaining soil health and fertility. A diverse microbial community ensures a resilient soil structure capable of withstanding diseases and pests. It also promotes better water retention, ensuring plants have consistent access to the moisture they need. Furthermore, a rich microbial environment can suppress harmful pathogens, reducing the need for chemical interventions. While this importance has to be emphasized, Soil health innovations offer solutions like comprehensive soil testing services to assess and enhance these microbial communities. The soil microorganism promotes soil fertility, plant productivity and ecosystem services. Recent molecular research suggests that the soil microorganism has been significantly underestimated. Soil microbes are nature's recyclers. They break down organic matter, converting it into nutrients that plants can absorb.

Role of Soil Microorganisms in Agriculture

1. Nutrient Cycling

Soil microorganisms decompose dead plants, animals, and organic matter into simpler substances. This process releases essential nutrients such as nitrogen, phosphorus, sulfur, and potassium, making them available for plant growth.

2. Nitrogen Fixation

Certain bacteria, such as *Rhizobium* and *Azotobacter*, convert atmospheric nitrogen into forms that plants can absorb. This natural process reduces the need for chemical nitrogen fertilizers and improves soil fertility.

3. Phosphorus Solubilization

Many soil bacteria and fungi convert insoluble phosphorus into soluble forms that plants can easily absorb. This improves root development, flowering, and crop yield.

4. Improvement of Soil Structure

Microorganisms produce sticky substances that bind soil particles together, forming stable soil aggregates. This improves soil aeration, water infiltration, drainage, and moisture retention, creating a healthier environment for plant roots.

5. Plant Growth Promotion

Some beneficial microorganisms produce plant growth hormones such as auxins, gibberellins, and cytokinins. These hormones stimulate seed germination, root growth, and overall plant development, resulting in healthier crops.

6. Biological Control of Plant Diseases

Beneficial microorganisms protect plants by competing with harmful pathogens and producing natural antibiotics. They help reduce diseases caused by fungi, bacteria, and other harmful organisms, minimizing the use of chemical pesticides.

7. Decomposition and Humus Formation

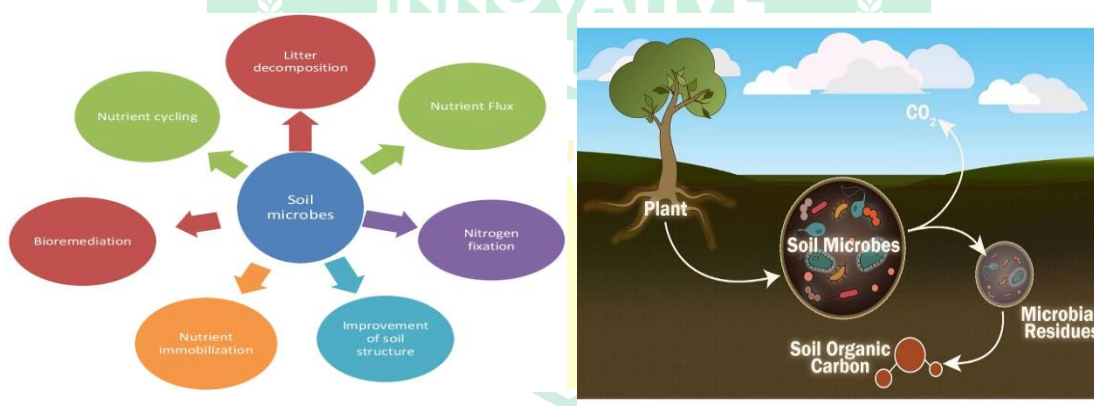
Microorganisms decompose crop residues and organic wastes into humus. Humus improves soil fertility, increases water-holding capacity, and enhances the availability of nutrients for plants.

8. Mycorrhizal Association

Mycorrhizal fungi form a beneficial relationship with plant roots. They increase the absorption of water and nutrients, especially phosphorus, helping plants grow better under drought and nutrient-deficient conditions.

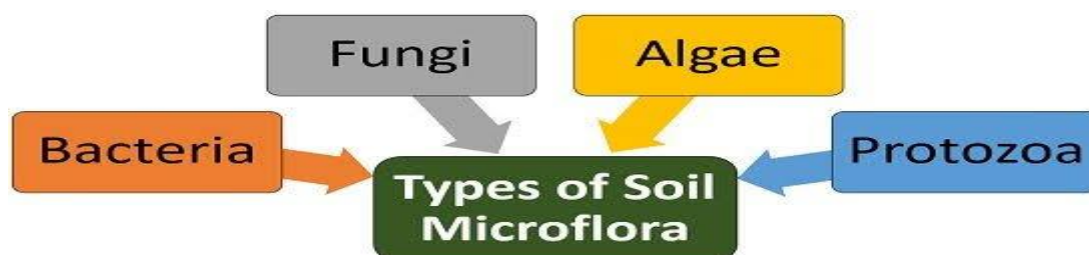
9. Environmental Protection

Soil microorganisms break down harmful chemicals, pesticides, and pollutants, reducing soil contamination. They also contribute to carbon cycling and help maintain ecological balance.



The Power of Microorganisms

Healthy soils are teeming with a diverse community of microorganisms that break down organic and mineral matter, facilitate nutrient uptake, and protect plants from pathogens. The primary microbial groups found in soils include bacteria, fungi, actinomycetes, protozoa, nematodes, and algae. Each plays a unique and crucial role:



Bacteria

Often called the “workforce” of the soil, bacteria are vital for nutrient cycling. Nitrogen-fixing bacteria such as *Rhizobium* form symbiotic relationships with legumes (like soybeans and beans), converting atmospheric nitrogen into forms plants can absorb—greatly reducing the need for synthetic fertilizers. Other free-living nitrogen-fixing bacteria, such as *Azotobacter*, *Azospirillum*, *Bacillus*, and *Clostridium*, support cereals and other crops. Some bacteria like *Bacillus* and *Pseudomonas* also help solubilize phosphate, while *Aspergillus* and *Bacillus* assist in mobilizing potassium—unlocking these nutrients from their insoluble forms in the soil.

Fungi

Fungi are primary decomposers, particularly of tougher organic material. Mycorrhizal fungi, especially Arbuscular Mycorrhizal Fungi (AMF), form symbiotic networks with plant roots, dramatically expanding the root system’s absorption area and enhancing uptake of water, phosphorus, and micronutrients.

Plant Growth-Promoting Rhizobacteria (PGPR)

Certain PGPR, such as *Pseudomonas*, not only aid in nutrient solubilization but also produce growth hormones and suppress diseases, acting as natural biocontrol agents.

Trichoderma

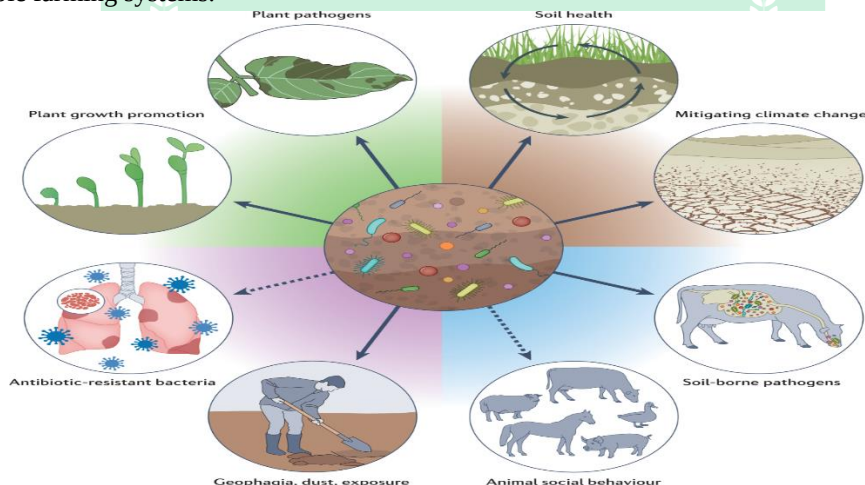
This genus of fungi is widely used for biological control of soilborne pathogens. It also enhances plant growth by improving nutrient absorption and stress tolerance.

The Benefits Are Real—and Measurable

The application of microbial inoculants has shown significant potential in increasing crop productivity while enhancing environmental sustainability. Research suggests that such inoculants can boost yields and reduce the need for chemical fertilizers by 20–50% without sacrificing performance.

Importance in Sustainable Agriculture

The use of beneficial soil microorganisms reduces dependence on chemical fertilizers and pesticides, lowers production costs, improves soil health, and increases crop productivity. They are a key component of eco-friendly and sustainable farming systems.



Conclusion

Soil microorganisms are indispensable for enhancing agricultural production. They improve nutrient availability, promote plant growth, maintain soil fertility, protect crops from diseases, and support environmental sustainability. Encouraging the use of beneficial microorganisms through biofertilizers and organic farming practices can ensure higher agricultural productivity while preserving soil health for future generation.

Production of Quality Vegetable Seedlings through Pro-Tray Technology: A Scientific Approach for Healthy Nursery Raising



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Abstract

Healthy and vigorous seedlings are the foundation of successful vegetable production. Pro-tray nursery technology has emerged as one of the most efficient and scientific methods for producing uniform, disease-free, and high-quality seedlings of tomato, chilli, brinjal, cauliflower, cabbage, broccoli, and several other vegetable crops. Individual cell sowing ensures better root development, minimizes transplanting shock, and enhances seedling survival after transplanting. The adoption of cocopeat-based growing media, protected nursery structures, balanced nutrition, and appropriate hardening practices significantly improves germination, seedling vigour, and crop productivity. This article presents the scientific principles and recommended management practices for successful vegetable nursery production using pro-tray technology.

Keywords: Pro-tray technology, Vegetable nursery, Cocopeat, Low tunnel, Shade-net, Protected cultivation, Seedling production, Nursery management.

Introduction

Quality seedlings play a vital role in obtaining higher yields and superior quality vegetable crops. Conventional nursery raising methods often result in uneven germination, poor root development, soil-borne diseases, and heavy seedling mortality after transplanting. Pro-tray nursery technology effectively overcomes these limitations by providing each seed with an independent growing cell filled with sterile growing media. This enables the development of a healthy root system, reduces disease incidence, and ensures uniform growth. Consequently, seedlings establish rapidly after transplanting, resulting in increased productivity and profitability. Due to these advantages, pro-tray technology has become an essential component of modern vegetable cultivation.

1. Selection of Pro-Trays and Growing Medium

For vegetable nursery production, 98-cell or 104-cell pro-trays are generally recommended as they provide adequate space for healthy root development.

Recommended Growing Medium

The ideal growing medium consists of:

S.No.	Component	Proportion
1.	Cocopeat	70%
2.	Vermiculite	20%
3.	Perlite	10%

This mixture is lightweight, porous, sterile, and possesses excellent water-holding capacity and aeration, resulting in 90–95% germination and vigorous seedling growth.

Alternative Growing Media

Where vermiculite and perlite are unavailable, farmers may use:

- 80% Cocopeat + 20% well-sieved Vermicompost, or
- 70% Cocopeat + 20% Vermicompost + 10% washed fine river sand

If only cocopeat is available, it can also be used successfully. However, seedlings should receive regular applications of water-soluble fertilizers to meet their nutritional requirements.

Important Precaution: Never use ordinary field soil or undecomposed farmyard manure in pro-trays, as they increase the incidence of damping-off and other soil-borne fungal diseases.

2. Seed Sowing Technique

Sow one seed per cell at a depth of 0.5–1.0 cm. Cover the seed lightly with cocopeat and irrigate gently using a mist sprayer or rose can. Place the trays inside a shade-net house or polyhouse to maintain favourable temperature and humidity conditions.

3. Protection of Nursery During the Rainy Season

Continuous rainfall and high humidity during the rainy season favour the development of damping-off, root rot, and other fungal diseases. Therefore, pro-trays should be protected under low tunnels or 50% shade-net structures. Low tunnels can be constructed using GI wire or bamboo hoops covered with 200-micron UV-stabilized transparent polyethylene sheets. Both ends should remain open to facilitate proper ventilation. During heavy rainfall, the tunnel ends may be temporarily closed to protect seedlings.

Where waterlogging is expected, pro-trays should be placed on 15–20 cm high stands or bricks instead of directly on the ground to ensure proper drainage.

4. Irrigation, Nutrition and Disease Management

- The growing medium should remain moist but never waterlogged. During the rainy season, irrigation should be applied only, when necessary, through a mist sprayer.
- Beginning 8–10 days after germination, apply 19:19:19 water-soluble fertilizer at 3–4 g per litre of water once every week.
- For organic nursery production, application of *Trichoderma* spp. is recommended to suppress fungal pathogens.
- Yellow and blue sticky traps should be installed for monitoring and controlling sucking insect pests. Whenever required, suitable fungicides and insecticides should be applied according to the recommendations of agricultural experts.

5. Hardening Before Transplanting

- Hardening is an essential practice for improving transplant survival.
- Reduce irrigation 2–3 days before transplanting and expose seedlings gradually to external environmental conditions by removing the polyethylene cover or shade for a few hours daily. This process strengthens seedlings and minimizes transplant shock.
- During transplanting, carefully remove seedlings along with the intact root ball, ensuring minimal disturbance to the root system.

6. Major Advantages of Pro-Tray Technology

- Achieves 90–95% seed germination.
- Saves 10–20% seed compared with conventional nursery methods.
- Produces healthy, vigorous, and uniform seedlings.
- Prevents root damage during transplanting.

- Ensures higher seedling survival after transplanting.
- Reduces the incidence of soil-borne diseases and insect pests.
- Improves crop establishment, productivity, and produce quality.
- Enables successful nursery production even during adverse rainy-season conditions.
- Facilitates easy transportation and handling of seedlings.
- Reduces labour requirements and nursery management costs.

7. Common Mistakes to Avoid

- Using ordinary field soil in pro-trays.
- Overwatering, leading to damping-off disease.
- Poor drainage around nursery structures.
- Sowing more than one seed per cell.
- Excessive fertilizer application at early seedling stages.
- Transplanting without proper hardening.
- Keeping pro-trays directly on the ground during the rainy season.

8. Special Advisory for Farmers

Farmers are advised to raise vegetable seedlings in pro-trays using cocopeat-based growing media and protect them inside low tunnels or 50% shade-net structures covered with 200-micron UV-stabilized transparent polyethylene during the rainy season. Irrigation should be provided only when required through a mist sprayer, and balanced nutrition should be supplied using water-soluble fertilizers. Adoption of these scientific nursery management practices enables farmers to produce healthy, disease-free, and vigorous seedlings at a lower cost, resulting in better crop establishment, higher productivity, improved produce quality, and enhanced farm income.

Conclusion

Krishi Vigyan Kendras act as the key link between agricultural research and farmers by demonstrating, training, and popularizing scientific nursery technologies. Their continuous technical support has significantly accelerated the adoption of pro-tray technology, contributing to sustainable vegetable production, improved livelihoods, and enhanced nutritional security.

The monsoon season, while essential for agricultural production, also poses serious challenges to the safe storage and preservation of food. Excess moisture and high humidity can lead to significant post-harvest losses if appropriate scientific measures are not adopted. Simple yet effective practices such as proper drying, hygienic handling, airtight storage, timely inspection of stored commodities, and the use of improved hermetic storage technologies like Super Bags and Poly-lined Bags can substantially reduce spoilage, insect infestation, and fungal contamination.

Beyond preventing losses, scientific food storage contributes to improved food safety, better nutritional quality, and enhanced market value of agricultural produce. It also enables farm families to preserve surplus produce through value addition, creating additional income and employment opportunities, particularly for rural women and self-help groups.

As climate variability continues to influence agricultural production and storage conditions, strengthening post-harvest management has become more important than ever. Farmers should view scientific storage not merely as a protective measure but as an investment that safeguards both their harvest and their livelihood. Through continuous awareness, capacity building, and the adoption of modern food preservation technologies, farming communities can reduce waste, improve household food security, and build resilient agricultural systems. Krishi Vigyan Kendras have a pivotal role in this transformation by promoting scientific storage practices, demonstrating innovative technologies, and empowering farmers with practical knowledge. Collective adoption of these technologies will not only reduce post-harvest losses but also contribute significantly to sustainable agriculture, nutritional security, and the long-term prosperity of rural communities.

Fruits and Vegetables: A Pathway to Sustainable Food and Nutrition



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Abstract

Fruits and vegetables are the cornerstone of healthy diets and sustainable food systems. They are rich sources of vitamins, minerals, dietary fibre, antioxidants, and bioactive compounds that are essential for maintaining good health and preventing malnutrition. Sustainable production, processing, and consumption of fruits and vegetables not only improve nutritional security but also enhance environmental sustainability, rural livelihoods, and climate resilience. Despite their immense importance, challenges such as post-harvest losses, inadequate processing facilities, and changing climatic conditions continue to limit their potential. Food Science and Technology, together with effective agricultural extension through Krishi Vigyan Kendras (KVKs), plays a vital role in overcoming these challenges by promoting scientific cultivation, value addition, food safety, and nutrition awareness. This review highlights the role of fruits and vegetables in building sustainable food and nutrition pathways while emphasizing the contribution of KVKs in strengthening resilient and nutrition-sensitive food systems.

Keywords: Fruits, Vegetables, Sustainable Food Systems, Nutrition Security, Food Science and Technology, Krishi Vigyan Kendra, Value Addition, Climate Resilience.

Introduction

Food and nutrition security are among the most pressing global challenges due to rapid population growth, climate change, shrinking natural resources, and changing dietary patterns. Sustainable food systems aim to provide safe, nutritious, affordable, and environmentally responsible food while protecting resources for future generations.

Fruits and vegetables are indispensable components of these systems because they improve dietary quality, prevent micronutrient deficiencies, support ecological sustainability, and generate higher economic returns for farmers. Promoting their production and consumption is essential for achieving sustainable development and improving public health.

Nutritional Importance of Fruits and Vegetables

Fruits and vegetables provide:

- Vitamins (A, C, E, K and Folate)
- Essential minerals such as iron, calcium, potassium and magnesium

- Dietary fibre
- Natural antioxidants
- Phytochemicals and bioactive compounds

Regular consumption helps to:

- Prevent hidden hunger and micronutrient deficiencies.
- Improve immunity and digestive health.
- Reduce obesity and lifestyle diseases.
- Lower the risk of cardiovascular diseases, diabetes, hypertension and certain cancers.
- Promote healthy growth and cognitive development.

Fruits and Vegetables for Sustainable Food Systems

Sustainable Production

Climate-smart agriculture, integrated nutrient management, protected cultivation, water-efficient irrigation, organic farming, and integrated pest management enhance productivity while conserving natural resources.

Nutrition Security

Year-round production and availability of fruits and vegetables increase dietary diversity and improve household nutrition, especially among women and children.

Economic Benefits

Horticultural crops provide higher income opportunities through fresh marketing, processing, and value addition. Rural enterprises based on fruits and vegetables create employment and strengthen local economies.

Environmental Sustainability

Sustainable horticultural practices improve soil fertility, conserve biodiversity, reduce greenhouse gas emissions, and increase resilience to climate change.

Role of Food Science and Technology

Food Science and Technology plays a critical role in sustainable food systems by:

- Reducing post-harvest losses.
- Improving shelf life through scientific preservation.
- Developing value-added products.
- Ensuring food safety and quality.
- Promoting functional and fortified foods.
- Utilizing processing waste for compost, bioactive compounds, animal feed, and biodegradable products.
- Supporting rural entrepreneurship through food processing technologies.

These innovations improve food availability, increase farmers' income, and reduce food waste.

Role of Krishi Vigyan Kendras (KVKs)

Krishi Vigyan Kendras (KVKs) serve as the frontline extension system connecting agricultural research with farming communities. They play a significant role in promoting sustainable food and nutrition pathways through technology dissemination, capacity building, and nutrition education.

Major contributions include:

- Demonstration of improved fruit and vegetable production technologies.
- Promotion of Nutrition Kitchen Gardens for household nutrition security.
- Training farmers, farm women, rural youth, and Self-Help Groups on food processing and value addition.
- Establishment of demonstrations on post-harvest management and scientific storage.
- Promotion of entrepreneurship through production of pickles, jams, squashes, dehydrated vegetables, fruit powders, and other value-added products.
- Conducting Front Line Demonstrations (FLDs), On-Farm Trials (OFTs), field days, farmer fairs, and awareness campaigns.
- Disseminating digital advisories through mobile applications, WhatsApp groups, radio talks, and ICT-based extension.
- Creating awareness on food safety, balanced nutrition, and healthy dietary practices.

- Strengthening women empowerment through nutrition-sensitive agriculture and income-generating activities.

Through these interventions, KVKs contribute significantly to increasing farm income, reducing post-harvest losses, improving household nutrition, promoting climate-resilient agriculture, and supporting sustainable rural development.

Challenges

Major challenges include:

- High post-harvest losses.
- Inadequate cold storage and transportation.
- Climate variability.
- Limited processing infrastructure.
- Poor market linkages.
- Low consumer awareness regarding healthy diets.
- Food loss and waste across the supply chain.

Future Strategies

To strengthen sustainable food and nutrition pathways, emphasis should be given to:

- Climate-resilient horticulture.
- Expansion of Nutrition Kitchen Gardens.
- Strengthening cold chain and post-harvest infrastructure.
- Promotion of food processing and value addition.
- Digital agricultural extension.
- Capacity building of farmers and women entrepreneurs.
- Food waste reduction.
- Public awareness on healthy diets.
- Research and innovation in sustainable food technologies.
- Strong collaboration among research institutions, KVKs, government agencies, and farmers.

Contribution to Sustainable Development Goals (SDGs)

Promotion of fruits and vegetables directly supports:

- SDG 2: Zero Hunger
- SDG 3: Good Health and Well-being
- SDG 8: Decent Work and Economic Growth
- SDG 12: Responsible Consumption and Production
- SDG 13: Climate Action
- SDG 15: Life on Land

Conclusion

Fruits and vegetables are fundamental to sustainable food and nutrition systems because they simultaneously improve human health, environmental sustainability, and rural livelihoods. Their production, scientific post-harvest management, value addition, and safe consumption are essential for achieving nutrition security and sustainable development. Food Science and Technology provide innovative solutions for minimizing food losses, enhancing food quality, and developing nutritious products, while Krishi Vigyan Kendras play a pivotal role in transferring these technologies to farming communities through demonstrations, training, and extension services. A coordinated approach involving researchers, KVKs, policymakers, extension agencies, farmers, and consumers is essential to build resilient, nutrition-sensitive, and sustainable food systems for future generations.

Climate-Resilient Crop Breeding: Securing Agriculture Through Plant Breeding



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Introduction

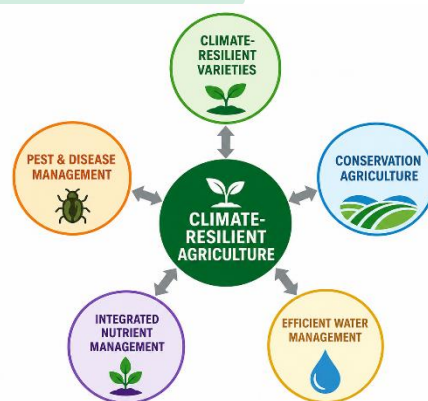
Climate change is a reality that is reshaping global agriculture. Rising temperatures, unpredictable rainfall, droughts, floods, soil salinity, and emerging pests and diseases are threatening agricultural productivity at an unprecedented scale. The Intergovernmental Panel on Climate Change (IPCC) reports that climate change has already affected food production systems worldwide, with negative impacts expected to intensify in the coming decades (IPCC, 2023). The Food and Agriculture Organisation (FAO) highlights that agriculture is both highly vulnerable to climate change and essential for global food security (FAO, 2022). India, with nearly half its population relies on agriculture. Droughts, floods, heat waves, and salinity intrusion are reducing crop yields and threatening farmers' livelihoods. These issues are intensified by shrinking arable land, declining water resources, and a global population expected to reach 10 billion by 2050. Meeting future food demands will require increases in agricultural production despite worsening climate conditions.

While improved agronomic practices, irrigation, and crop management aid climate adaptation, they are not sufficient for sustainable food production. Developing crop varieties that can inherently withstand climatic stresses is the most cost-effective and long-term solution. Plant breeding plays a vital role by combining desirable traits such as higher yield, improved quality, pest and disease resistance, and tolerance to environmental stresses. Since the Green Revolution, plant breeding has increased global crop productivity and prevented food shortages (Khush, 2001). Today, breeders must go beyond yield improvement to develop varieties that sustain stable productivity under drought, heat, floods, salinity, and evolving pest pressures, while using resources increasingly efficiently.

Climate-resilient crop breeding is the most ecologically sustainable and friendly strategies for addressing climate change. Through integrating conventional breeding with molecular biology, genomics, artificial intelligence, genome editing, and exact phenotyping, plant breeders are developing crops that can sustain food production under increasingly unpredictable conditions.

1. Genetic diversity: Nature's treasure for future agriculture

Genetic diversity is the foundation of all breeding program. The variation found in landraces, traditional cultivars, wild relatives, and germplasm collections provides valuable genes for drought tolerance, disease resistance, salinity tolerance, nutritional quality, and other adaptive traits.



Plant breeders systematically identify these useful genes and transfer them into high-yielding varieties through crossing and selection. The conservation of plant genetic resources in national and international gene banks has therefore acted as a cornerstone of climate-resilient agriculture. As Tanksley and McCouch (1997) emphasised, crop wild relatives and traditional varieties represent invaluable reservoirs of genes that may become essential for future crop improvement.

2. Developing heat-resilient crops

Heat stress, driven by global warming, is a major challenge for agriculture. High temperatures during flowering and grain filling reduce pollen viability, disrupt fertilisation, accelerate maturity, and lower grain quality. Wheat, rice, pulses, vegetables, and oilseeds are especially vulnerable. Plant breeders identify genetic sources capable of maintaining membrane stability, photosynthetic efficiency, pollen fertility, and reproductive performance under elevated temperatures. These desirable genes are incorporated. Plant breeders seek genetic sources that maintain membrane stability, photosynthetic efficiency, pollen fertility, and reproductive success under high temperatures. These genes are then incorporated into elite cultivars through systematic breeding.

3. Flood and submergence tolerance: A remarkable success story

Although some regions suffer drought, others experience severe floods. Waterlogging deprives roots of oxygen, reduces nutrient uptake, and can destroy crops within days. Breeding has focused on developing rice varieties carrying the Sub1 gene. Scientists discovered this gene in traditional rice germplasm and successfully introduced it into high-yielding varieties using marker-assisted breeding.

Rice varieties with the Sub1 gene can survive full submergence for nearly two weeks and recover quickly after floods recede (Xu *et al.*, 2006). Millions of farmers in South and Southeast Asia benefit from these varieties, demonstrating how a single gene can enhance agricultural resilience. Identification of genomic regions linked to salinity tolerance and incorporated them into high-yielding varieties. Rice varieties with the Saltol quantitative trait locus show strong tolerance to saline conditions, enabling productive cultivation in salt-affected soils (Thomson *et al.*, 2010). These efforts are expanding cultivable land and improving food security in vulnerable coastal areas.

4. Modern technologies are revolutionising plant breeding.

Plant breeding has advanced significantly in the past two decades. While conventional hybridisation remains important, it is now supported by advanced genomic methods that accelerate genetic improvement.

Marker-assisted selection (MAS) allows breeders to identify plants with desirable genes using DNA markers, eliminating the waiting period for field evaluation. This method greatly increases selection efficiency and shortens breeding time. Genome-based selection (GS) uses genome-wide molecular information to predict plant breeding value, allowing breeders to select superior individuals even before phenotypic evaluation (Varshney *et al.*, 2021). Genome editing technologies, especially CRISPR-Cas systems, enable precise modification of genes linked to stress tolerance, disease resistance, and yield improvement (Chen *et al.*, 2019). Technologies such as drones, remote sensing, thermal imaging, hyperspectral cameras, artificial intelligence, machine learning, and high-throughput phenotyping enable breeders to rapidly and accurately evaluate thousands of breeding lines (Crossa *et al.*, 2021). These technologies are transforming plant breeding from a slow, labour-intensive process into a precise, data-driven discipline that can respond quickly to climate change.

5. Success stories: When plant breeding changed the course of agriculture

Plant breeding's impact is clear in many success stories. The Green Revolution of the 1960s transformed food production with semi-dwarf, fertiliser-responsive wheat and rice varieties. India achieved food grain self-sufficiency largely through improved varieties and agronomic practices (Khush, 2001). The development of Sub1 rice, which can tolerate submergence, has benefited millions in flood-prone South and Southeast Asia (Xu *et al.*, 2006). Rice varieties with the Saltol locus have improved productivity in salt-affected coastal regions (Thomson *et al.*, 2010). Drought-tolerant maize and heat-tolerant wheat varieties have also increased yield stability and protected production against climate stresses (Reynolds *et al.*, 2021).

6. Challenges in breeding climate-resilient crops

Despite scientific advances, developing climate-resilient crop varieties remains challenging. Climate stresses often occur together, with crops facing drought, heat, nutrient deficiency, and pest attacks simultaneously.

Breeding for multiple stress tolerance is therefore highly complex. The challenge is the long breeding cycle. Even with advanced technologies, developing and releasing a new variety typically requires several years of evaluation throughout diverse environments to ensure stable performance. Climate change itself is dynamic, meaning breeders must continually respond to new environmental conditions. The erosion of plant genetic diversity also threatens future breeding. Traditional landraces and wild relatives are disappearing due to modernisation, urbanisation, and changing agricultural practices. Conserving these genetic resources in national and international gene banks is essential for future crop improvement (Tanksley and McCouch, 1997).

7. The future of climate-resilient crop breeding

The future of plant breeding depends on integrating conventional knowledge with advanced technologies. Genomics, genome editing, artificial intelligence, bioinformatics, speed breeding, and digital agriculture will complement and enhance traditional breeding methods. Towards predictive breeding, where genomic information, environmental data, and artificial intelligence are combined to predict superior plant performance even before field testing. Pangenomics is helping researchers discover hidden genes absent from reference genomes but present inside diverse crop populations, therefore expanding the available genetic diversity for breeding.

8. Plant breeding and the Sustainable Development Goals

Climate-resilient crops support several United Nations Sustainable Development Goals (SDGs). Improved varieties contribute to SDG 2 (Zero Hunger) by increasing productivity and ensuring stable harvests. Efficient resource use supports SDG 6 (Clean Water and Sanitation) and SDG 12 (Prudent Consumption and Production). Reduced pesticide use supports SDG 15 (Life on Land), and breeding for climate adaptation supports SDG 13 (Climate Action).

Conclusion

Plant breeding has transformed agriculture from Green Revolution to the development of modern climate-resilient varieties. By leveraging genetic diversity and advanced technologies like genomics, marker-assisted selection, genome editing, artificial intelligence, speed breeding, and exact phenotyping, breeders are accelerating the creation of crops ready for future climate challenges.

However, scientific innovation alone is not enough. Continuous funding for breeding research, conservation of genetic resources, strong national seed systems, supportive policies, and active farmer participation are needed to translate advances into real-world impact. As Norman E. Borlaug, the father of the Green Revolution, wisely observed, “Food is the moral right of all who are born into this world.” Guaranteeing that right under a changing climate depends largely on our ability to develop resilient crops capable of sustaining agriculture for future generations. Plant breeding is more than developing new varieties; it is the foundation of climate resilience, agricultural sustainability, and global food security. Each climate-resilient variety released today is a commitment to future harvest stability, stronger farming communities, and a safer planet for generations to come.

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Conventional and Conservation Agriculture Systems: Sustainability Concerns



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Abstract

Conventional agriculture, characterised by intensive tillage, synthetic agrochemical inputs, monoculture, and mechanisation, has driven substantial gains in crop productivity but has simultaneously raised concerns over soil degradation, biodiversity loss, and long-term environmental sustainability. In contrast, Conservation Agriculture (CA) has emerged as a resource-conserving alternative built on three interlinked principles: minimal mechanical soil disturbance, permanent organic soil cover, and diversified crop rotations. By working with, rather than against, natural biological processes, CA aims to improve water infiltration, soil structure, and organic matter content while reducing erosion and input costs over time. This review contrasts the two systems across agronomic, economic, and environmental dimensions, highlighting that while conventional farming offers short-term yield efficiency and lower initial costs, CA offers superior long-term soil health, water conservation, and climate resilience. However, CA adoption remains constrained by high initial equipment costs, competition for crop residues (particularly for livestock feed), knowledge gaps among farmers and extension workers, and the absence of a universally applicable blueprint given the site-specific nature of agro-ecosystems. Overcoming these socioeconomic and technical barriers through policy support, farmer training, and improved access to appropriate machinery is essential for the wider adoption of sustainable, conservation-based farming systems.

Keywords: Agro-ecosystems, Conservation Agriculture, Conventional Farming, Zero Tillage, Sustainable Agriculture

Definition:

Conventional farming (also known as traditional farming or industrial agriculture) often refers to high-input modern agricultural systems that include the frequent applications of synthetic chemical fertilizers, fungicides, insecticides, herbicides, high-yielding cultivars, monoculture, GMOs, heavy machinery, intensive tillage, and irrigation. This approach focuses on monoculture and large-scale operations, often increasing efficiency in food production but raising concerns about environmental sustainability and food security.

Advantages:

Conventional farming is the predominant form of agriculture, especially in India. Therefore, it is important to know its advantages.

1. **Higher Yields:** Conventional farming methods use synthetic pesticides, fertilizers, etc., which ensure greater crop productivity and control pests in farms.
2. **Less Expensive:** This type of farming incurs fewer costs because the synthetic inputs it uses are cheaper.
3. **Greater Accessibility:** Since conventional agriculture is more common, the products used in this type of farming are easily accessible.
4. **Efficient Land Use:** Conventional farmers have an added advantage because this type of farming allows them to grow more crops per acre of land.
5. **Sustainability:** Conventional farming methods use drip irrigation and other water-saving technologies, and they can be considered more sustainable, at least in this case.

Disadvantages:

Apart from the advantages of conventional farming, one also needs to focus on its disadvantages.

1. **High Consumption of Time:** Conventional agriculture takes more time to harvest crops.
2. **High Price:** Due to more time consumption, the crops are grown at a higher price.

3. **Risk of Soil Disease:** Crops are at risk of contracting soil disease.
4. **Poor Quality of Plants:** Since chemical fertilizers and other artificial chemical inputs such as pesticides are used, good-quality crops are not grown.
5. **Injurious to Small Farmers:** Small farmers will have limited room for expansion because the larger farming corporations will dominate the business, leaving other industries behind.
6. **Health and Environmental Threats:** Conventional cash crop farming pollutes the environment because artificial fertilizers and pesticides release byproducts.

What is Conservation Agriculture?

Conservation Agriculture (CA) is a concept for resource-saving crop production that strives to achieve respectable gains together with high and sustained product situations while simultaneously conserving the environment. CA is grounded on enhancing natural processes over and below the ground. Interventions analogous to mechanical soil tillage are reduced to an absolute minimum, and the use of external inputs analogous to agrochemicals and nutrients of mineral or organic origin is applied at an optimum level and in a way and volume that does not interfere with or disrupt the natural processes.

The CA is characterized by three principles that are linked to each other:

- a. Minimal mechanical soil disturbance.
- b. Endless organic soil cover.
- c. Diversified crop rotations in the case of periodic crops or plant associations in the case of perennial crops.

CONVENTIONAL (INDUSTRIAL) AGRICULTURE	VS	CONSERVATION AGRICULTURE (CA)
 Intensive tillage  Synthetic inputs  Monoculture	PRACTICES	 Minimal tillage  Organic cover  Crop rotation
 Soil degradation  Lower water infiltration  Lower long-term sustainability	OUTCOMES	 Soil health improvement  Better water infiltration  Higher long-term sustainability
 Lower initial cost  Lower short-term profit	ECONOMICS	 Higher initial cost  Higher long-term profit
 Higher emissions  Biodiversity loss	ENVIRONMENT	 Lower emissions  Biodiversity conservation

Definition

Conservation agriculture (CA) aims to conserve, ameliorate and make further effective use of natural resources through the intertwined operation of available soil, water, and biological resources combined with external inputs. It contributes to environmental conservation as well as to enhanced and sustained agricultural production. It can also be referred to as resource-effective agriculture.

According to FAO, CA is a set of practices that leave crop residues on the surface, which increases water infiltration and reduces erosion. It's a practice used in conventional agriculture to reduce the drastic effects of tillage on soil erosion. However, it still depends on tillage as the agricultural structure-forming elements in the

soil. Nonetheless, conservation tillage practices similar to zero tillage practices can be transition way towards conservation agriculture.

An appropriate definition of CA appears to be “a sustainable agriculture production system comprising a set of farming practices adapted to the requirements of crops and local conditions of each region, whose farming and soil operation ways cover the soil from erosion and declination, ameliorate its quality and biodiversity and contribute to the preservation of the natural resources, water, and air while optimizing yields”.

Principles of Conservation Agriculture:

Conservation agriculture is an approach to agricultural management based on three principles:

1. **Minimum soil disturbance-** Zero tillage is ideal, but the system may involve controlled tillage in which no more than 20 to 25% of the soil surface is disturbed.
2. **Retention of crop residues or other soil surface cover** - Many definitions of CA use 30% permanent organic soil cover as the minimum, but the ideal level of soil cover is site-specific.
3. **Use of crop rotations** - Crop rotation helps reduce build-up of weeds, pests and diseases. Where farmers do not have enough land to rotate crops, intercropping can be used. Legumes are recommended as rotational crops for their nitrogen-fixing functions.

By doing this, CA will:

1. **Give and maintain an optimum environment of the root zone to the maximum possible depth:** Roots are suitable to serve effectively and without restrictions to capture high quantities of nutrients and water.
2. **Assure that water enters the soil so that:**
 - a. Short no way or for the shortest time possible, suffer water stress that will limit the expression of their implicit growth.
 - b. Residual water passes down, not flowing over the surface as runoff.
3. **Favour salutary natural exertion in the soil to:**
 - a. Maintain and rebuild soil architecture.
 - b. Compete with implicit in-soil pathogens.
 - c. Contribute to soil organic matter and colourful grades of muck.
 - d. Contribute to capturing, retention, chelation, and slow release of nutrients.
4. **Avoid physical or chemical damage to roots that affects their effective functioning.**

Advantages of Conservation Agriculture

1. Economic benefits:

- a. Time-saving and therefore reduction in labour demand.
- b. Reduction of costs (energy, machinery operating costs, and conservation).
- c. Advanced effectiveness in the sense of less effort for a lower input.

2. Agronomic benefits:

- a. Organic matter increases.
- b. In-situ soil water conservation.
- c. Enhancement of soil structure and therefore reduces lodging.

3. Environmental benefits:

- a. Reduction in soil erosion.
- b. Improvement of water quality.
- c. Improvement of air quality.
- d. Biodiversity increases.
- e. Carbon sequestration.

Disadvantages of Conservation Agriculture

1. The most important limitation in all areas where conservation agriculture is practiced is the lack of initial knowledge.
2. High initial costs of specialized planting equipment.
3. A new dynamic farming system that requires new management skills and a learning process by the farmer.

4. As conservation agriculture partly relies on the use of herbicides, at least during the initial stage of adoption, some people are worried that adoption of conservation agriculture will increase herbicide use and that, in turn, will lead to increased impurity of water by herbicides.
5. Reduction in leaching of pesticides under conservation agriculture might be caused by greater microbial activity degrading pesticides faster or by greater organic matter adsorbing the pesticides.
6. There is no blueprint available for conservation agriculture, as all agro-ecosystems are different.

Constraints for Adopting Conservation Agriculture

An internal change of growers, technicians, extensionists, and experimenters away from soil-degrading tillage operations towards a sustainable production system like no-tillage is necessary to gain changes in the attitudes of growers; still, noted that presumably, the most important factor in the adoption of CA is overcoming the bias or mindset about tillage. The following are a few important constraints that impede broad-scale adoption of CA:

1. Lack of applicable seeders, especially for small and medium-scale growers:

These would include the development of a permanent bed and furrow planting system and harvest operations to manage crop residues.

2. Widespread use of crop residues for livestock feed and fuel:

- a. Especially under rainfed situations, farmers face a scarcity of crop residues due to less biomass production of different crops.
- b. There is competition between CA practice and animal feeding for crop residue. This is a major constraint for the creation of CA under rainfed situations.

3. Burning of crop residues:

- a. For timely sowing of the next crop and without machinery for sowing under the CA system, farmers prefer to sow the crop in time by burning the residue.
- b. This has become a common practice in the rice-wheat system in north India.
- c. This creates environmental problems for the region.

4. Lack of knowledge about the potential of CA among agricultural scientists, extension officers, and farmers.

5. Skilled and scientific manpower:

- a. Managing conservation agriculture systems will call for enhanced capacity of scientists to address problems from a system perspective and to be able to work in close partnerships with farmers and other stakeholders.
- b. Strengthened knowledge and information-sharing mechanisms are demanded.

Distinguishing features of conventional and conservation agricultural systems:

Conventional Agriculture	Conservation Agriculture
Cultivating the land, using science and technology to dominate nature	Least interference with natural processes
Excessive mechanical tillage and soil erosion	No-till or drastically reduced tillage (biological tillage)
High wind and soil erosion	Low wind and soil erosion
Residue burning or removal (bare surface)	Surface retention of residues (permanent cover)
Water infiltration rate is low	Water infiltration rate is high
Use of ex-situ materials	Use of in-situ materials
Kills established weeds, but stimulates more weed seeds to germinate	Weeds are a problem in the early stages of adoption but decrease with time
Productivity gains in the long run are in declining order	Productivity gains in the long run are in incremental order

Sustainability concerns:

Sustainability concerns of conservation agriculture (CA) include high initial costs for specialized machinery, limited availability of appropriate technology for small farmers, knowledge gaps regarding CA practices, potential for short-term yield reductions during the transition period, increased weed and pest pressure without proper management, and competition for crop residues between soil cover and livestock feed. Overcoming these

socioeconomic, technological, and knowledge-based barriers is crucial for the widespread and effective adoption of CA and to achieve its long-term benefits for soil health, water conservation, and climate resilience.

1. Economic Concerns

a. High Initial Costs:

Adopting CA often requires investing in new machinery like no-till seeders, which can be prohibitively expensive for small and marginal farmers.

b. Financial Risks:

The transition to CA can sometimes result in reduced yields in the initial years, creating financial strain and risk for farmers, especially if they cannot afford the upfront costs.

c. Limited Access to Technology:

A lack of affordable and appropriate seeders and other technologies can hinder the adoption of CA practices, particularly in developing regions.

2. Knowledge and Management Concerns

a. Knowledge Gaps:

Farmers may lack the necessary knowledge and technical expertise in soil science, crop rotation, and pest management to successfully implement CA practices.

b. Increased Weed and Pest Pressure:

Without the physical disturbance of tillage, weeds can become a greater challenge, requiring farmers to adopt new integrated weed management strategies.

c. Soil Nutrient Immobilization:

During the initial stages of CA, the decomposition of crop residues can lock up soil nitrogen, temporarily leading to lower nutrient availability for crops, requiring careful management of inputs.

3. Resource-Related Concerns

a. Crop Residue Competition:

While retaining crop residues provides permanent soil cover, this can lead to conflicts with livestock farmers who rely on these residues for animal feed.

b. Time Lag in Results:

Farmers may not see immediate yield benefits when starting CA, as it takes time for soil ecosystems and fertility to improve, potentially discouraging adoption.

4. Socioeconomic Barriers

a. Perceived Risks:

Farmers' hesitancy to switch from conventional practices due to concerns about yield reductions or lack of training can be a significant barrier to CA adoption.

b. Need for Policy Support:

Strong policy frameworks and targeted support are necessary to overcome these adoption barriers and promote CA more effectively, particularly in regions like South Asia.

Conclusion

In conclusion, conventional and conservation agriculture follow different pathways to achieve agricultural production and sustainability. Conventional agriculture has played an important role in increasing crop yields, but its continued dependence on intensive tillage and external inputs can negatively affect soil health and the wider environment. Conservation agriculture provides a more sustainable approach by reducing soil disturbance, maintaining soil cover and promoting crop diversification. Nevertheless, its adoption is not straightforward and depends on local conditions, farmer knowledge, machinery availability and economic support. Therefore, strengthening extension services, farmer training, policy support and access to suitable technologies will be essential for promoting conservation agriculture as a practical and sustainable farming system.

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Water Crisis in Indian Agriculture: Innovative Solutions That Actually Work



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India accounts for 17 percent of the world's population, 2.4 percent of the world's geographical area and 4 percent of the world's freshwater resources. Agriculture is the biggest user of water. It consumes 90% of the total water. Groundwater depletion rates are estimated to be around 100-200 km³/year, accounting for 15-25% of total groundwater withdrawals.

A stark picture of the crisis: Water-guzzling crops like paddy and wheat are being cultivated, leaving the Indo-Gangetic plains reeling under severe groundwater stress. Frequent droughts and abnormal monsoon patterns also affect Peninsular India, disrupting the traditional agricultural calendars. The crisis is our own doing. Which means it is fixable. Farmer-led, tech-backed solutions across India are proving that it is possible to grow more with significantly less water and need urgent scaling.

Why Indian Farms are Dry

Before we arrive at the solutions, there is a lot to grasp. First, why are Indian farms so thirsty? The Indo-Gangetic plains, India's breadbasket, are suffering under severe groundwater stress due to the cultivation of water-guzzling crops such as paddy and wheat. Peninsular India also suffers from frequent droughts and unusual monsoon patterns, which disrupt classical agricultural calendars and irrigation schemes. The agricultural landscape faces increasing stress from traditional irrigation practices compounded by climate change pressures. In India, the irrigation efficiency is 35-40%, and more than 60% of water is wasted. Subsidies for irrigation often lead to

overexploitation and depletion of the water table. Faulty irrigation procedures and free water are the reasons for poor irrigation efficiency in India. India's water availability has reduced dramatically from 3000 m³/capita/year in 1951 to 1458 m³/capita/year today. (Per Capita Water Availability, 2022) The Central Ground Water Board has said that 16 per cent of the country's groundwater blocks are "over-exploited". Impacts of climate change will include changes in the amount and quality of water resources. Spatial and temporal variations in water availability. The reliance on rain-fed agriculture that still supplies the majority of food worldwide is becoming an ever more dangerous gamble. MSP and procurement policy lock-in defies water logic, trapping farmers in water-guzzling behaviours.

Solutions Actually Working on the Ground

Micro-Irrigation 2.0

Micro-irrigation is one of the best strategies to break this tendency. Drip irrigation is an advanced low volume method that carefully applies irrigation water straight to plant roots at or near the soil surface. Research has shown that drip irrigation can save up to 60% of water compared to traditional flood irrigation, while increasing crop yields. Research has indicated that drip irrigation systems have the potential to save water compared to conventional flood irrigation methods, with savings up to 50% in cereals such as wheat, rice, maize and other crops. Gujarat has



0.80 Mha under drip irrigation, whereas Andhra Pradesh has 1.38 Mha under drip irrigation. Farmer cooperatives and water user associations are efficient in fostering participatory water management. These organisations help farmers to collectively manage water resources, decide on water distribution and use water-saving techniques.

DSR & AWD: Rewriting the Paddy Playbook

Beyond micro-irrigation, innovative rice farming practices are revolutionising water use in India's most water-thirsty crop. Direct-seeded rice (DSR) has tremendous water saving benefits over traditional approaches such as puddled transplanted rice. The total water saving obtained with DSR is an excellent reduction of 35-40% over conventional puddled transplanted rice farming. (Deb et al., 2024) This highlights the potential of DSR to contribute towards sustainable water management in rice agriculture, while preserving or even improving the yields. Alternate Wetting and Drying (AWD) is a major departure from continuous flooding. AWD reduces water usage by 25-40% while maintaining yields and producing less methane by releasing water to fields in intervals and then allowing them to dry. Rice AWD reduces methane emissions by 40-60%. In practice, the strategy is working, as evidenced by its adoption in the rice bowl of eastern India.

Solar as second crop

Farmers aren't just altering the way they cultivate food; they're also changing the way they power their farms—Dhundi, Gujarat – Farmers in the world's first solar co-operative sell surplus power to the grid. Solar irrigation systems are increasingly becoming popular in India as a sustainable and cost-effective irrigation alternative. These systems are powered by solar panels and water pumps, and do not require the usage of fuel or electric pumps. Schemes like KUSUM by the government aim to encourage solar energy in the agriculture sector. It aims to reduce the carbon footprint of the sector and enhance income of farmers. Solar pumping is a solution to the problem of access and reliability, particularly for systems where



gravity-fed water flow is no longer possible or during droughts. Solar technology can bring water to fields where gravity doesn't reach, replacing polluting diesel pumps or unreliable power systems with a sustainable, zero-carbon option. According to the Ministry of New and Renewable Energy, the country is installing solar pumps to help farmers cut electricity expenses and dependence on unreliable grid power.

Community Groundwater Management

Technology alone will not do it. The best solutions are made with communities, not for them. The community-based approach ensures that solutions are locally relevant and universally accepted. Participatory water management is key to farmer cooperatives and water user associations. These organisations allow farmers to collectively manage water resources, decide on water distribution and implement water-saving measures. The development of such organisations has been promoted under several Government schemes, resulting in a feeling of ownership and responsibility towards water resources across the farming community. Labour-saving technologies like the drip irrigation system are particularly helpful to a woman who is traditionally the manager of irrigation in a lot of societies. The success and sustainability of water management techniques depend on community-based water management initiatives with the participation of local communities.

Crop Diversification: Market Muscle

Farmers are increasingly employing computerised tools to monitor and control water use, in addition to selecting the correct crops. Important Adaptation Action: Selection of Drought-Resistant Varieties. The choice of different traditional types of millets, pulses and oilseeds selected by generations for their ability to withstand water scarcity still gives fairly stable yields even during water scarcity. These qualities have been further improved by later breeding procedures, leading to cultivars that still work with 30 to 40% of the water needed by traditional cultivars. In water-scarce areas, the traditional rice-wheat rotation is being diversified to include crops with lower water needs (maize, pulses and oilseeds). Legume-cereal intercropping systems are 15 to 25 percent more water efficient compared with monocropping systems, owing to complementarity in root systems and contributions of nitrogen fixation.

Cheap Tech and Digital Water

Sensors placed in fields can offer farmers real-time data on the moisture, temperature, and nutrient levels of the soil, allowing them to make informed decisions about irrigation and fertilisation. IoT technology can be used to remotely monitor and operate irrigation systems to ensure maximum water utilisation and minimum wastage. Automated drip irrigation systems have revolutionised conventional agricultural practices by providing accurate and efficient water management. These systems use technology to monitor soil moisture, climate and soil types to make field irrigation precise. Sensors, microcontrollers and wireless connectivity improve automation by analysing the data in real time for the optimised utilisation of water. Wireless Sensor Networks are an important tool for precision agriculture, providing real-time data for increasing productivity and efficiency and reducing the risks from climatic anomalies, water shortages, and pests.

The Policy Fixes That Shut Off the Tap

Many national and state programs encourage farmers to conserve water. Launched in 2015, the Pradhan Mantri Krishi Sinchayee Yojana (PMKSY) focuses on enhancing on-farm water usage efficiency and increasing irrigation coverage under the slogan "Har Khet Ko Pani" (water to every field). PMKSY encourages micro irrigation, rainwater harvesting and conjunctive use of surface and ground water in drought-prone areas. As of 2022, almost 12 million hectares have been brought under micro-irrigation, directly helping to build resilience to drought. Under the National Action Plan on Climate Change, the National Mission on Sustainable Agriculture (NMSA) aims at climate resilient agriculture, notably in sensitive agro-ecological zones. The mission supports technologies and practices including soil health management, water-use efficiency, agroforestry, and climate-resilient agricultural systems. There is an urgent need to mainstream drought risk reduction across sectors by converging schemes such as PMKSY (irrigation), PMFBY (insurance), NMSA (climate-resilient farming), and Jal Shakti Abhiyan (water conservation) into a convergent drought resilience framework. Providing free electricity does not encourage saving water. Direct Benefit Transfers for electricity can. The pilot states have shown promising results in reducing power consumption and groundwater extraction with implementation of Direct Benefit Transfer for electricity subsidies in agriculture, the Ministry of Power said on Friday. (Direct

Delivery of Power Subsidy to Manage Energy–ground Water–agriculture Nexus, 2015) Decentralised drought management cells at district and block levels can be set up for improved responsiveness.

Barriers to Scale – Why Islands of Hope Are Islands

Many water conservation technologies, like modern irrigation systems, are capital intensive, and this might act as a disincentive for small and marginal farmers who form the majority of the Indian farming community. The small farm holding sizes, fragmented nature of land holding and lack of access to credit may be the hurdles in the investment of high capital input technologies. Other impediments to uptake are the need for technical knowledge and maintenance, especially for smallholder farmers. In India, the management of drought is hampered by the fragmentation of responsibility and lack of cooperation between ministries and departments. But Farmer Producer Organisations (FPOs) build adaptive ability through economies of scale in input procurement, crop diversification and collective selling for stabilising farmers' income. FPOs also serve as channels for extension services and government initiatives, enabling speedier distribution of climate-smart practices.

Closing — From Crisis to Water Wisdom

To move from pilot projects to a larger scale, a more holistic approach is needed. The seamless integration of regenerative agriculture with local low-carbon energy offers a potent, practical roadmap for reaching the United Nations Sustainable Development Goals. This method takes development activities out of their silos and builds a systems-thinking framework that responds directly to the interconnected concerns of poverty, climate change and resource security. It calls for and nurtures a new kind of future leadership: leadership with long-term vision, teamwork and a thorough understanding of ecological and social systems. The tools are there. With political resolve and commercial imagination, such pilot miracles can become the new normal. The dry season can end, by choice and not by chance.

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Organic Farming in India: Opportunities, Growth and Challenges



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The Green Revolution has successfully met the increasing need for food and fiber but at tremendous environmental cost. Environmental degradation, depletion of groundwater, food contamination and loss of natural ecosystems have been the hallmarks of the Green Revolution. As the population grows, the nation is faced with the problem of supplying safe food. Organic farming is a comprehensive alternative to traditional food production. Organic farming is a production strategy which avoids or substantially excludes the use of synthetic compounded fertilizers, herbicides, growth regulators and livestock feed additives. Organic farming systems depend on crop rotation, crop residues, animal manures, legumes, green manures, off-farm organic wastes, mechanical cultivars, mineral bearing rocks and bio fertilizers to sustain soil productivity as well as tillage and as plant nutrients and biological means, to the maximum extent possible, to control insects, weeds and other pests. In recent years organic farming is increasing, quite fast. The Indian agriculture has a better scope to transform itself into organic agriculture as the use of chemical fertilizer per capita and per ha in the nation is significantly lower than the worldwide norms. Organic farming is a concept and a system of farming. The objects of environmental, social and economic sustainability are the core of organic farming.

Concept of Organic Farming

IFOAM says organic agriculture is a farming system that sustains the health of soils, ecosystems and people. It focuses on biological processes, biodiversity, and cycles adapted to local circumstances, instead of inputs having negative consequences. Organic farming uses science and creativity together with tradition for the benefit of the whole environment, the development of fair relationships and the improvement of the quality of life for everyone. Organic farming is a holistic production/management strategy which promotes and enhances agro-ecosystem health, including biodiversity, biological cycles and soil biological activity.

Rainfed Areas: The Untapped Potential for Organic Farming

Rainfed areas are reported to have relative advantage to go for organic farming primarily due to low level of external input use, shorter conversion period and smaller yield reductions compared to irrigated areas. At present, about 51% of the net sown area is rainfed contributing 41% of the total food production, supports 40% of human and 60% of livestock population. These areas contribute almost 100% of forest products, 84-87% of coarse grain cereals and pulses, 80% of horticulture, 77% of oilseeds, 60% of cotton, and 50% of fine cereals including rice, wheat, maize, and sorghum. Due to low input demand, rainfed areas are potential hotspots to produce organic products.

Indian Organic Farming Scenario and Government Initiatives

In 2019-20, India produced about 2.75 million MT of certified organic products which included all types of food products such as oil seeds, sugar cane, cereals and millets, cotton, pulses, aromatic and medicinal plants, tea, coffee, fruits, spices, dry fruits, vegetables and processed foods. Madhya Pradesh is the largest producer among the numerous states followed by Maharashtra, Karnataka, Uttar Pradesh and Rajasthan. Total exports in 2019-20 amounted to 6.389 lakh MT. The export of organic food amounted to roughly Rs 4,686 crore (689 million USD). Organic products are exported to the United States, the European Union, Canada, Switzerland, Australia, Japan, Israel, the United Arab Emirates, New Zealand and Vietnam. India intends to bring at least 4% of its net cultivated acreage under organic farming by March 2026. India has been able to establish and implement a number of projects for the promotion of organic farming which has resulted in a considerable increase in the area and exports

during the period. Farmer Producer Organizations shall undertake cultivation, processing and marketing of organic food in the country. Indeed, access to a sure market will be important for organic marketing.

Benefits of Organic Farming



The benefits of organic farming are: enhanced soil fertility, greater profitability, less use of external inputs, land reclamation, improved market access and improved capability and self-reliance of farmers. Organic farming techniques aim to be environmentally sustainable by reducing the use of chemicals and relying on organic ways of pest management and promoting biodiversity that promotes ecological balance and boosts resistance to pests and diseases. “Organic farming is more climate-friendly and better for the environment than conventional agriculture.” Ecological notions based on variety are appreciated in the management of organic farmers. Organic foods reveal higher concentrations of plant secondary metabolites, more micronutrients and more conjugated fatty acids, which are beneficial to human health and are associated with a reduced prevalence of non-communicable diseases. Research has found that organic foods have a greater dry matter content notably in the case of leafy vegetables and tubers. Organic cereals have lower protein content but the protein that is there is of a higher quality and has superior amino acid scores. Solid Organic Manures the Basis of Soil Fertility. In organic farming, apart from liquid organic formulations, solid organic manures are the most important source of bulk nutrients and organic matter. Farm Yard Manure (FYM) is a decomposed mixture of cow dung, urine, litter and left-over feed. It's applied in large quantities, usually 10-15 tones/hectare, to offer the essential plant nutrients and to improve the physical properties of the soil. Vermicompost is the end product of the decomposition of organic matter by earthworms. It is rich in humus, plant-available nutrients, compounds that encourage development and healthy soil micro-organisms. Panchagavya and Jeevamruth are utilized as growth promoters and immune boosters while FYM and vermicompost are applied to supply the needed fundamental soil organic carbon and progressive nutrient release for sustaining long term productivity of crops in organic systems.

Organic Inputs: Panchagavya, Jeevamruth and Beejamruth

Liquid organic formulations like Panchagavya, Beejamruth, Jeevamruth, and Amritpani, prepared with locally available materials, play a crucial role in supporting plant growth. Panchagavya is a bio stimulant consisting of a combination of five products obtained from cow, which includes cow dung, cow urine, cow milk, curd and ghee. The term Panchagavya represents Pancha- five, Gavya- produce from cow. It acts as an immunostimulant that promotes growth, increases the overall yield and also renders resistance to diseases and pests. The key feature of Panchagavya was its efficacy to

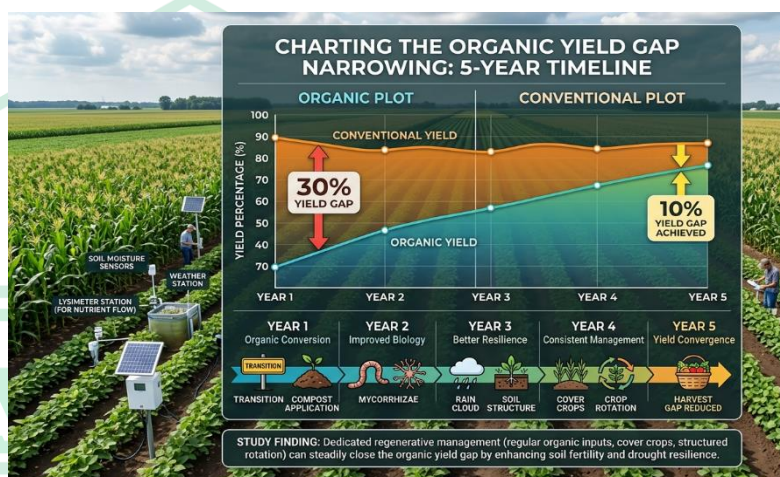


restore the yield level of all crops during the transitory period of switching over to organic farming from the very first year.

Jeevamruth is a bio stimulant consisting of a combination of five products, which includes cow dung, cow urine, pulse flour, jaggery, handful of garden soil and some amount of water. It acts as an immune-stimulant that promotes growth, increases the overall yield and also renders resistance to diseases and pests. Beejamruth is used for the seed treatment and the name represents Beej- seed, amruth- a valuable food. Beejamruth is very useful for seed pre-treatment as it increases the germination ability of the seeds.

The Reality Check: Organic vs Conventional Farming

Overall, the organic yield difference was 35%, implying that more land is needed to grow the same amount of crops. If you have a 35% yield gap you need 50% additional arable land. For all crops averaged, the yield differential between organic and conventional farming in Germany was on average about 40 per cent. ICAR research in Indian context have indicated various yield gaps depending upon crop and agro-ecological zone. The initial years of conversion to organic production show an organic yield gap of 10 to 20 percent for rainfed pulses and oilseeds and as high as 30 percent for irrigated rice and wheat. These gaps, however, tend to close over time as soil biological activity increases and nutrient cycling stabilizes. OF had an average yearly increase of 25mm in seepage volume compared with BMP in the long run. OF had a substantially larger yearly N load (median) than BMP (26.1 kg ha⁻¹ and 20.5 kg ha⁻¹, respectively). Conversely, the OF lysimeters exhibited a 35% drop in long-term dry matter production. The organic management employed here has to be adjusted to minimize long-term increases in N emissions. This implies that soil tillage must be limited, fallow periods during the vegetation-free season avoided and the plowing of legumes in the fall obviated, since this might be linked with large N mineralization losses.



Challenges in Organic Farming

Organic farming has tremendous benefits, but there are certain barriers to its adoption in Indian agriculture. These include limited infrastructure and lack of dependable internet access, which inhibits the usage of AI-driven equipment in remote regions. Financial stability is also a major hurdle to the broad acceptance of organic livestock farming in India. Farmers face severe financial stress throughout the transition phase from conventional to organic agriculture. Expansion of organic farming is constrained by several factors such as reduced yield in initial years of conversion, non-availability of organic manures on the farm to meet the nutrient requirements, discrepancy between crop need and soil supply due to slow release of nutrients from organic manures, difficulty in handling bulky manures and inadequate certification. The biggest problem for organic farmers is the lack of a constant and reliable supply of certified inputs and a financially viable market for organic farm goods. There is no formal definition or oversight for terms such as 'cage-free,' 'free-range' or 'all natural' in India, making consumers particularly vulnerable to marketing gimmicks. Although India has NPOP for export certification and PGS-India for domestic markets, technical assistance and proper certification support is still lacking, with many farmers relying on non-governmental organizations as opposed to institutional extension services for guidance.

Conclusion

India has the capacity to generate all sorts of organic goods due to its diverse agro-climatic conditions and traditional expertise. Organic farming can potentially substantially improve the livelihoods of small farmers through greater revenues and lower risk. Export potential is expanding and overcoming difficulties in rainfed areas, creating cost efficient production techniques and proper scientific research can assist India to emerge as

good exporter of organic goods and enhance farm net profits. Organic farming is a regenerative approach that restores food and agriculture systems, which means increased ecological benefits. It therefore provides a credible option to grow clean, sustainable food with minimal environmental damage. Small and marginal farmers need to adopt organic methods of agriculture, especially from the point of view of their long-term food security and reduction of risk. The “towards organic” approach for intensive agricultural areas and “certified organic farming” with a combination of tradition, innovation and science in the de-facto organic areas and rainfed regions will contribute to safe food security in future in addition to raising the income of farm households and enhancing climate resilience.

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Medicinal Potential of Ash Gourd (*Benincasa hispida*): A Mini Review



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Ash gourd (*Benincasa hispida* (Thunb.) Cogn.) belongs to the family Cucurbitaceae and is cultivated throughout tropical and subtropical Asia. Besides being an important vegetable crop, it has been recognized as a medicinal plant for centuries in Ayurveda and Traditional Chinese Medicine (Kirtikar and Basu, 2006). The fruit is traditionally recommended for the treatment of gastric ulcers, constipation, fever, urinary disorders, epilepsy, and mental fatigue (Nadkarni, 2011). Modern pharmacological studies have validated many of these traditional claims by demonstrating its antioxidant, anti-inflammatory, hepatoprotective, and antidiabetic activities (Al-Snafi, 2013).

Bioactive Constituents

Ash gourd contains numerous phytochemicals responsible for its therapeutic activities. Major constituents include flavonoids, phenolic compounds, triterpenoids, sterols, polysaccharides, dietary fibre, vitamin C, and minerals (Harborne, 1998; Choudhary *et al.*, 2018). These phytochemicals exhibit strong antioxidant activity by scavenging reactive oxygen species and protecting cellular components from oxidative damage (Al-Snafi, 2013).

Major bioactive compounds of ash gourd

Bioactive compound	Biological activity
Flavonoids	Antioxidant, anti-inflammatory
Phenolics	Free radical scavenging
Triterpenoids	Hepatoprotective
Sterols	Hypocholesterolaemia
Polysaccharides	Immunomodulatory
Vitamin C	Antioxidant
Dietary fibre	Digestive health

Pharmacological Activities

Antioxidant activity: Ash gourd exhibits significant antioxidant activity due to its high concentration of phenolic compounds and flavonoids. These compounds neutralize reactive oxygen species, thereby reducing oxidative stress associated with chronic diseases such as diabetes, cardiovascular diseases, and cancer (Al-Snafi, 2013; Choudhary *et al.*, 2018).

- **Anti-inflammatory Activity:** Experimental studies have shown that extracts of *B. hispida* suppress inflammatory mediators and reduce tissue inflammation (Al-Snafi, 2013). Traditional Ayurvedic medicine also recommends the fruit for inflammatory conditions (Nadkarni, 2011).
- **Gastroprotective and Anti-ulcer Activity:** One of the best-documented medicinal properties of ash gourd is its anti-ulcer activity. Fruit extracts protect the gastric mucosa, reduce gastric acidity, and promote ulcer healing (Grover *et al.*, 2002; Al-Snafi, 2013).
- **Antidiabetic Activity :** Several experimental investigations have demonstrated that ash gourd improves glucose metabolism and lowers blood glucose levels in diabetic animal models (Grover *et al.*, 2002). The hypoglycaemic activity is attributed to antioxidant phytochemicals and polysaccharides.
- **Hepatoprotective Activity:** Studies have shown that ash gourd extracts protect liver tissues against chemically induced oxidative damage and improve liver enzyme profiles (Al-Snafi, 2013).

- **Cardioprotective Activity:** The high potassium content, low sodium content, and antioxidant compounds help reduce oxidative stress and improve cardiovascular health (Choudhary *et al.*, 2018). Regular consumption may contribute to maintaining healthy blood pressure and lipid profiles.
- **Neuroprotective Activity:** Traditional medicine recommends ash gourd for improving memory and treating neurological disorders (Nadkarni, 2011). Experimental studies suggest that antioxidant compounds reduce oxidative stress in neurons and improve cognitive function (Al-Snafi, 2013).
- **Antimicrobial Activity:** Extracts of *B. hispida* have demonstrated inhibitory activity against several bacterial and fungal pathogens, indicating its potential as a natural antimicrobial agent (Al-Snafi, 2013).

Nutraceutical Importance

Ash gourd is regarded as an excellent functional food because it contains approximately 96–97 % moisture and only 13–15 kcal per 100 g edible portion (Ranganna, 2010). It is rich in potassium, vitamin C, dietary fibre, and antioxidants while being naturally low in fat and sodium, making it particularly suitable for individuals suffering from obesity, hypertension, diabetes, and digestive disorders (FAO, 2023).

Therapeutic Applications

Medicinal applications of ash gourd

Disease/Condition	Therapeutic effect	Supporting references
Gastric ulcer	Protects gastric mucosa	Grover <i>et al.</i> (2002); Al-Snafi (2013)
Hyperacidity	Reduces acidity	Nadkarni (2011)
Diabetes	Lowers blood glucose	Grover <i>et al.</i> (2002)
Liver disorders	Hepatoprotective	Al-Snafi (2013)
Obesity	Low calorie functional	Ranganna (2010)
Hypertension	Rich source of potassium	FAO (2023)
Urinary disorders	Mild diuretic	Kirtikar and Basu (2006)
General weakness	Nutritive tonic	Nadkarni (2011)

Conclusion

Ash gourd (*Benincasa hispida*) is an important medicinal vegetable possessing significant nutraceutical and pharmacological properties. Scientific evidence supports its antioxidant, anti-inflammatory, anti-ulcer, hepatoprotective, antidiabetic, cardioprotective, neuroprotective, and antimicrobial activities (Al-Snafi, 2013; Choudhary *et al.*, 2018). Traditional medicinal systems have long recommended the fruit for the management of gastric disorders, urinary ailments, fever, and general debility (Kirtikar and Basu, 2006; Nadkarni, 2011). Although promising results have been obtained from experimental studies, well-designed clinical trials are needed to validate its therapeutic efficacy in humans and facilitate its integration into evidence-based healthcare.

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Millets: The Next Frontier in Sustainable Agriculture and Food Security



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The world is facing major issues of food security and sustainable agriculture. “Population growth, shifting climate patterns and limited natural resources necessitate the urgent identification of alternative crops which can grow in different conditions and provide suitable nourishment. Millets are sometimes called ancient grains and are increasingly being touted as a feasible response to these major challenges. These hardy, drought-resistant grains have been feeding humans for millennia, but have often been overlooked in the glamour of the larger cereal crops such as rice, wheat and maize. However, with increasing knowledge of their nutritional content, ability to grow in several agro-ecological circumstances and minimal environmental footprint, millets are emerging as a significant component in global sustainable agriculture and food security projects. As the globe moves towards healthier food grains, the global demand for millets is likely to reach \$12 billion by 2025. India, which produces about 12 million tons a year, is one of the big millet producers and could benefit from the trend. Millets use less water and inputs and so are regarded to be excellent crops for “climate smart agriculture” as the world is facing increasing problems of drought and its severe impact on agricultural crop production. They also provide oxygen and use maximum levels of carbon dioxide from the air which is helping in minimizing climate change. Millet is

a cereal grain of the Poaceae family and is termed as super food. “Growing these climate-smart crops is a step toward a healthier world and more sustainable agriculture.” India has suggested to declare 2023 as “International Year of Millets”. 2018 has been declared as “National Year of Millets”.

Millets are a category of small-grain cereal crops grown as food crops from the grass family. Most are dry country plants with little seeds. Pearl millet is the most cultivated, followed by foxtail millet, proso millet, finger millet, kodo millet, small millet and barnyard millet. Millet is also known to help digestion and growth of beneficial bacteria in the gut. High in fiber both soluble and insoluble. Millet is also a good source of potassium, vitamins A and B, phosphorous, calcium, iron and antioxidants.

Finger Millet: It is rich in all nutrients especially iron, calcium and phosphorous. It is a slow digester and has great anti-oxidant properties. Finger millet is a storehouse of health benefits such as strengthening the bones, regulating blood cholesterol levels, helping in weight loss and decreasing the incidence of anaemia. It can be eaten in many ways like in roti or porridge or in pancakes. The superb malting qualities have led to the increasing use of the special characteristics of the grain in food processing.

Sorghum: Sorghum is an ancient crop and is widely used as a staple food in India. Jowar is better than the rice and wheat as it is rich in nutrients and helpful in curing a number of health conditions. Policosanols – Sorghum wax contains a lot of this compound which helps reduce cholesterol.



Pearl Millet: Pearl millet is a good source of all nutrients like the regularly eaten grains such as wheat and rice. Pearl millet is full of fiber and helps in weight loss and digestion. It contains phosphorus, which is beneficial for bone health. This millet is rich in magnesium and helps in lowering the severity of respiratory problems like asthma.

Proso Millet: Proso millet is abundant in fiber, protein and minerals. Proso millet protein contributes to raising HDL cholesterol and reducing LDL cholesterol. It contains a good deal of lecithin and it helps in the maintenance and repair of the neurological health system. Proso millet is rich in B-complex vitamins, folic acid, and niacin. It may be effective in the treatment of cardiovascular disorders and cancer with its antioxidant qualities.

Foxtail Millet: Foxtail millet provides all elements including protein, vitamins and minerals in sufficient amount. The grains are coarser than ordinary cereals, which increases digestibility to 79%. It may provide many health benefits including reducing the risk of some degenerative disorders. Today it is known as a heart-healthy food because of its high magnesium content. Foxtail millet is utilized in various food preparations as cereal porridge, pancakes, noodles, soup and alcoholic beverages.

Barnyard Millet: It is said that barnyard millet has a nutritious composition superior or equivalent to other grains. The higher level of crude fibre in barnyard millet helps in gradual release of carbs in the blood which helps in

maintaining the blood sugar level. Barnyard millet has strong iron concentration, around 15.6-18.6mg/100g, so it is the ideal food for anaemic people. This millet is rich in polyphenols and carotenoids compared to other cereal grains.

Kodo Millet: Kodo millet is a nutritious grain similar to rice and can be used as a rice replacement and for weight loss. Kodo is a great source of antioxidants and bio active substances which can aid with life style diseases. It is also high in lecithin and this helps the neurological system perform properly.

Millets can help increase the food processing industry which is a focus area to uplift the economy of the state and country. They have the capacity to save us from countless lifestyle problems and damaging environmental tragedies.

Millets: The Rise and Fall

Millets have been grown for thousands of years and were previously staple crops in many parts of the world. But as modern agriculture improved and the emphasis turned to high-yielding cereal crops such as wheat and rice, millet cultivation declined substantially. In recent years, millets have attracted increased interest due to their various health benefits, environmental sustainability and resilience to climate change.

Millets: Nutritional Powerhouses

Millets are rich in nutrients such as protein, fiber (2-7%), vitamins, fat (3%), carbs (65%), essential amino acids (9) and minerals. They are gluten-free and low on the glycemic index, so they are a good option for people with celiac disease or diabetes. Millets are rich sources of antioxidants and phytochemicals which have been connected with several health advantages such as reduction in the risk of heart disease, diabetes and some malignancies. Millets have 60 % more crude protein than maize and barley, 40 % more lysine and methionine and 30 % more threonine. Millets are also rich sources of hormonally active lignans and phytosterols which are utilized as nutraceutical and functional food ingredients against various health issues.

Millet and resilience to climate variability

Climate-resilient millets are called 'Miracle Grains' as they can adapt to a range of ecological conditions with less irrigation water, and more efficient in low-nutrient soils. They are relatively environmentally tolerant and require low inputs of chemical fertilisers. The need to revive interest in millet groups as nutritious crops that can contribute to improving food and nutrition security and reducing malnutrition.



Millet and Sustainable Agriculture

Millets are an important component of sustainable agriculture due to their special properties and farming approaches. These are hardy crops that require little water and fertilizer and are therefore suitable for cultivation in dry and semi-arid areas where there is little water available. Millets also have shallow root systems which help in preventing soil erosion, improving soil structure and nutrient cycling. Their ability to grow in various agro-climatic situations enhance biodiversity and minimize dependency on monoculture farming, thereby increasing the resilience of ecosystems. Furthermore, millets can be intercropped with other crops or included into crop rotation systems, aiding in pest and disease management while enhancing overall agricultural production. The promotion of millets is an effective way to encourage sustainable agriculture practices, preserving natural resources, reducing environmental degradation and enhancing food security for communities across the world. Millets have a shallow root system that helps in reducing soil erosion and improving the soil fertility. They also demand less water, fertilizers and pesticides, lowering the environmental footprint of agriculture. "Moreover, millets can be grown as intercrop or in rotation with other crops, which enhances soil health and biodiversity.

Growing Millet: Challenges and Opportunities

Millets have many benefits, but there are hurdles in getting wider acceptance. Key hurdles facing millet growers include limited access to quality seeds, lack of automation and poor market demand. However, there are also great prospects for innovation and investment in millet farming including creation of enhanced seed types, value

added products and market linkages. Millets are nutritious and climate resilient, thus presenting solutions to address climate change and food security concerns. But there are certain gaps that need to be fixed. Millets have low yield and hence, there is a need to introduce high yielding cultivars. Minimum support price for millets has not been fixed and they are sold at cheaper prices resulting in low income creation. In the case of pearl millet, efforts should be made to enhance the shelf life of the flour. The amount of sugar and oil added during processing of millets should be regulated to maintain the nutritional quality of the product.

Millets in Old and New Food

Millets are traditional foods, an important part of the diet in many cultures, especially in Asia and Africa. But they are becoming famous in the Western world due to their nutritional value and adaptability. Millets can be used to make a range of foods including porridges, flatbreads, salads and desserts. They have a delicate flavor and texture that also means they can be substituted for rice, couscous or quinoa in recipes.

Government Policies and Promotion of Millets

Globally, millets are gaining recognition from governments to address food security and environmental problems. A number of countries have implemented measures to encourage the cultivation of millets, including subsidies for farmers, research and development programs, and public awareness campaigns. International bodies like the Food and Agriculture Organization and the International Crops Research Institute for the Semi-Arid Tropics are aggressively pushing millets as a sustainable crop. Agricultural research can develop new varieties of millet that are more resistant to pests and diseases, produce higher yields and have improved nutritional content. Agricultural extension services can help farmers adopt best practices for growing millet, including soil and water conservation, insect management and crop rotation. Farmers might be motivated to grow millets through subsidies and incentives. Governments can encourage the development of millet markets by setting up local and regional marketplaces and marketing millet-based food products. Nutrition education can inform citizens about the nutritional benefits of millets and how to prepare and cook them.



Millets: A Potential Solution to Food Security

Malnutrition is a major concern at the moment. 40 percent of youngsters in India are malnourished. Three out of five children are underweight and the infant mortality rate is 32 per 1000 live births. Diabetes and obesity are common, especially among the younger generations. India has the second-highest number of diabetics in the world, with 77 million individuals suffering from the disease, second only to China. That will affect 79.4 million people by 2030. You can include items with low glycemic index and nutrition dense diet. In the country, millet production has gone down yet it is still viewed as a nutrient dense crop. As the world's population continues to rise, feeding everyone is getting increasingly difficult. Millets provide an alternative source of healthy food that can be cultivated under different agro-climatic conditions. Promoting the development of millet can help countries diversify their dependence on a limited number of staple crops and increase the resilience of their food systems to climate change and other external shocks.

Summary

To conclude, millets can make an important contribution to sustainable agriculture and food security. They are a great tool in the fight against hunger and malnutrition due to their nutritional benefits, climate resilience and low environmental footprint. But to tap into this potential, governments, farmers, researchers and consumers will need to make coordinated efforts to overcome the hurdles and leverage the benefits offered by millets. Millets have potential to address many of the present day concerns such as water scarcity, nutritional deficiencies and climate change. Furthermore, they can also solve the problem of widespread malnutrition in our country. Millets require about 80% less water than rice, wheat or sugarcane crops. One of the lesser known benefits of millets is that they protect the soil fantastically. The disappearance of millets is a severe loss to agriculture and society.

Millets are gaining popularity across the globe with people becoming more aware of its health and lifestyle benefits.

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Biofortification of Maize: A sustainable path to overcome nutrient deficiency



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Introduction

Maize is one of the most popular staple crops in the world, it provides of millions of people with their main source of energy across the developing nations beside rice and wheat. It assumes worldwide significance as a source of food, feed and diverse industrial byproducts (Gupta *et al.*, 2015). This wide spread reliance on maize a severe nutritional challenge. Traditional maize cultivars, however, are deficient in vital micronutrients like Vitamin A, Iron and Zinc as well as crucial amino acids like lysine and tryptophan resulting in serious public health crisis known as “hidden hunger” despite their high calorie content. Due to this dependent populations are contributing to impaired vision, weakened immunity, stunted growth and cognitive delays (Bouis and Saltzman, 2017).

Consequently, vulnerable populations that depend heavily on maize faces risks of severe health disorders, including anemia, stunted physical growth, weakened immune systems, cognitive delays and visual impairments or blindness.

To combat this global crisis, requires addressing these shortcomings, especially in rural and resource constrained area. At the forefront of this moment is biofortification, an innovative and strategic intervention that enhances the nutritional profile of the crops from the seed based method, which has become a viable and affordable option. Utilizing traditional plant breeding, agronomic practices and modern biotechnological tools such as genetic modification and CRISPR-Cas9 gene editing scientists can embed essential vitamins and minerals directly into the plants genetics. Unlike traditional fortification, which adds nutrients during post-harvest food processing, biofortified crops compound their nutritional benefits with every planting season. By integrating nutrition directly into the food system from the bottom up, biofortified maize offers a highly cost-effective, self-sustaining, and sustainable agricultural solution to eradicate micronutrient malnutrition globally.

What is biofortification

By means of selective breeding, genetic alteration, or soil based nutrients enrichment by following agronomical practices, biofortification improves the nutritional profile of the crops at the genetic level. According to Saltzman *et al.*, (2013), biofortification starts in the seed and provides a self-sustaining method of gradually improving food quality, in contrast to standard fortification, which adds nutrients after harvest.

The main goal is to increase the micronutrient content of common crops in order to reduce hidden hunger and make sure that nutrition is incorporated into food systems from the bottom up.

Why focus on Maize?

Because maize is so widely grown and consumed, it is an ideal choice for biofortification. Enhancing the nutritional value can have direct impact on millions of people who are at risk.

Efforts have focused primarily on increasing:

- Pro vitamin A (beta-carotene): deficiency (VAD) cause visual disablement, reproductive disorders, diminishing body growth, and weak immune system in humans.
- Zinc: supports immunity, growth and wound healing.
- Iron: deficiency causes retardation in growth associated with delayed sexual and bone maturation.
- Tocopherols (vitamin E) deficiency also affects immune system and reproductive function.

Globally, more than two billion people are affected by malnutrition. The major proportion of Indian population (21.9%) lives in extreme poverty which forces them to feed with micronutrient deficient diet. It is estimated that 38.4 per cent of the Indian children (<5 year) are suffered with stunted growth, while 35.7 per cent are underweight and 21.8 per cent are wasted (Global Nutrition Report 2017). Moreover, 58.4 per cent of the children (6-59 months), 53 per cent of the adult women (15-49 years) and 22.7 per cent of adult males are found to be anemic in India. Every year, India loses over \$12 billion annual GDP due to vitamin and mineral deficiency alone.

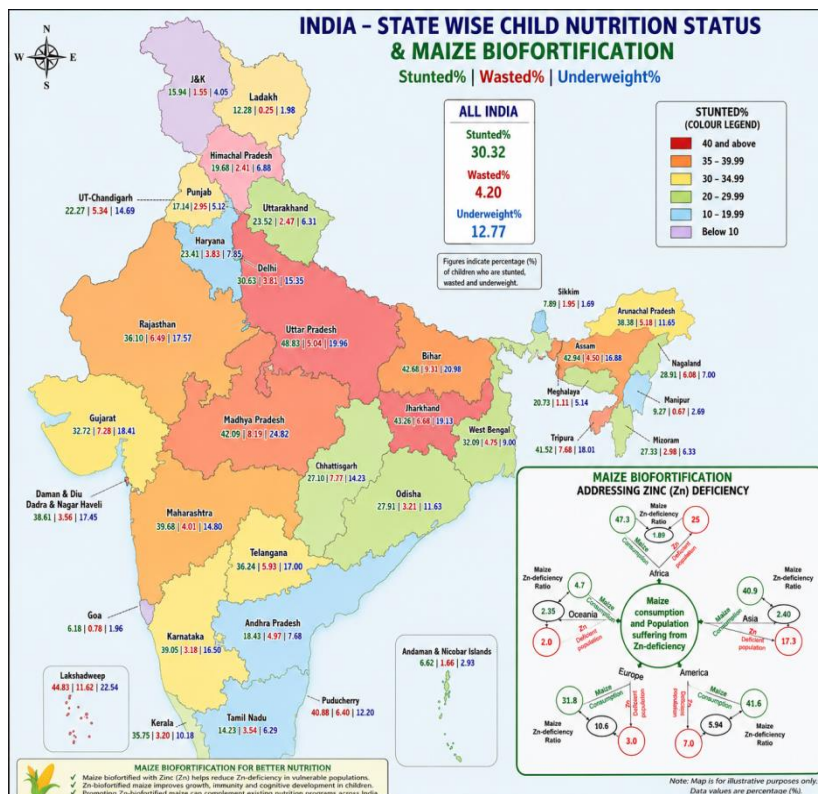


Fig. 1: India-state wise children nutrition status and biofortification in Maize crop
Nutritional benefits of biofortified maize on human health

Micronutrients such as lysine, tryptophan, pro vitamin-A (proA), Vitamin E, iron (Fe) and zinc (Zn) are deficient in normal endosperm in maize. There are rich source of nutrients like fruits, vegetables, meat and capsule/syrup which are rich in micronutrients, but seasonal availability and high cost makes them non-sustainable. Biofortified maize can provide a viable, sustainable and cost effective solution to hidden hunger (Bouis and Saltzman, 2017).



Fig. 2: Visuals of some of the biofortified maize hybrids released for commercial cultivation in India

Table. 1: List of biofortified maize hybrids released for commercial cultivation in india

S.No	Name of Varieties/hybrid	Provitamin-A (ppm)	Lysine (%)	Tryptophan (%)	Maturity Days	Average Yield (q/ha)	Adoption	Institution	Year of release
1	Vivek QPM 9	-	4.19	0.83	88	52 q/ha	Kharif season in Jammu & Kashmir, Himachal Pradesh, Uttarakhand (Hill region), North Eastern states, Maharashtra, Karnataka, Andhra Pradesh, Telangana and Tamilnadu	Developed by ICAR-Vivekananda Parvatiya Krishi Anusandhan Sansthan, Almor	2008
2	Pusa HM 4 Improved	-	3.62	0.91	87	64.2q/ha	Kharif season in Punjab, Haryana, Delhi, Uttarakhand (plains) and Uttar Pradesh (Western region)	Developed by ICAR-Indian Agricultural Research Institute, New Delhi by improving HM 4 developed by CCS-Haryana Agricultural University, Hisar	2017
3	Pusa HM 8 Improved	-	4.18	1.06	95	62.6 q/ha	Kharif season in Maharashtra, Karnataka, Andhra Pradesh, Telangana and Tamil Nadu	Developed by ICAR-CCS-Haryana Agricultural University, Hisar	2017
4	Pusa HM 9 Improved	-	2.97	0.68	89	52 q/ha	Kharif season in Bihar, Jharkhand, Odisha, Uttar Pradesh (Eastern region) and West Bengal	Developed by ICAR-CCS-Haryana Agricultural University, Hissar	2017
5	Pusa Vivek QPM 9 Improved	Country's first provitamin-A rich maize 8.05	2.67	0.74	93 (NHZ) and 83 (PZ)	55.9 q/ha (NHZ) and 59.2 q/ha (PZ)	Kharif season in Jammu & Kashmir, Himachal Pradesh, Uttarakhand (Hill region), North Eastern states, Maharashtra, Karnataka, Andhra Pradesh, Telangana and Tamilnadu	Developed by ICAR-Vivekananda Parvatiya Krishi Anusandhan Sansthan, Almor	2017
6	Pusa VH 27 Improved	5.49	-	-	84	48.5 q/ha	Kharif season in Bihar, Jharkhand, Odisha, Uttar Pradesh (Eastern region) and West Bengal	Developed by ICAR-Vivekananda Parvatiya Krishi Anusandhan Sansthan, Almor	2020
7	Pusa HQPM 5 Improved	6.77	4.25	0.94	111 (NHZ), 92 (NWPZ), 88 (NEPZ), 98 (PZ) and 91 (CWZ)	72.6 q/ha (NHZ), 75.1 q/ha (NWPZ), 53.5 q/ha (NEPZ), 71.2 q/ha (PZ) and 51.2 q/ha (CWZ)	Kharif season across the country	Developed by ICAR-CCS-Haryana Agricultural University, Hissar	2020
8	Pusa HQPM 7 Improved	7.1	4.19	0.93	97	74.5 q/ha	Kharif season in Maharashtra, Karnataka, Andhra Pradesh, Telangana and Tamil Nadu	Developed by ICAR-CCS-Haryana Agricultural University, Hissar	2020
9	IQMH 201 (LQMH 1)		3.03	0.73	101	84.8 q/ha	Kharif season in Jammu & Kashmir, Himachal Pradesh, Uttarakhand and North Eastern states	Developed by ICAR-IIMR, Ludhiana	2020

Benefits of QPM

1. It contains lysine and tryptophan which is two to three times more when compared to normal maize.
2. Its biological value is equivalent to 90% OF milk.
3. It possessed decreased leucine-isoleucine ratio, which helps in combining pellagra by increasing niacin biosynthesis.
4. Increase in growth rate, weight and height in infants and young children by feeding of QPM.
5. Diseases like Marasmus and kwashiorkor are prevented by feeding QPM.
6. The palatability, taste and cooking quality of traditional food prepared from QPM are more desirable due to its softness, sweetness and long shelf life.

Benefits of Provitamine A rich maize:

1. Higher bioavailability and retention of vitamin A compared to normal corn.
2. Prevention of colour blindness and xerophthalmia in children and pregnant women.
3. Provides antioxidant activities to prevent macular degeneration and chronic diseases.
4. High carotenoids maize can substitute color additives in feed of poultry birds.
5. Balanced body growth and reduced malnutrition in children.
6. Repairing of epithelial cells, and maintenance of immune and reproductive systems.
7. Provitamin A rich maize fed chickens produces eggs with high vitamin A which can be beneficial to poor populations

Benefits of other biofortified maize:

1. Zinc biofortified maize can improve the zn absorption in children.
2. Vitamin E rich maize scavenges various reactive oxygen species and free radicals in human body and protects the cells from damage caused by free radicles.
3. Low phytic acid maize varieties can increase the bioavailability of certain minerals, especially calcium, magnesium, zinc and iron in human.
4. Biofortified maize like sweet corn have multiple benefits in various soups, syrups and snack items as it is already rich in fiber, minerals, antioxidants and certain B vitamins.

A series of maize based ready-to-cook (RTC) and ready-to-eat (RTE) products have been developed like Maize-based vermicelli, crisp, noodles and papad by UAS, Mandya are being marketed in the brand name of 'Maizy' in the state of Karnataka. Dry milled QPM-based products like roasted flour, dalia, suji, multigrain flour, maize grit, namkeen products etc. offer immense promise to start entrepreneurship.

Conclusion

Biofortified maize offers a practical, budget friendly way to improve both food and nutritional security in tribal and high altitude regions where maize is a dietary staple. Introducing these nutrient rich crops into school lunch programs and Anganwadis across the country would go a long way in meeting kid's daily micronutrient needs and fighting malnutrition. To build on this, plant breeders must focus on combining several key nutritional genes into single, high-yielding variety (genotypes).

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Nature's Rainbow on Your Plate: The Science and Nutritional Power of Colourful Vegetables



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Abstract

Vegetables are an essential component of a healthy and balanced diet, providing vitamins, minerals, dietary fibre and a wide range of biologically active compounds. The attractive colours of vegetables are mainly due to natural pigments such as chlorophylls, carotenoids, anthocyanins and betalains. These pigments are often associated with important phytochemicals that contribute to the nutritional and functional value of vegetables. Red vegetables such as tomato are rich in lycopene, orange vegetables such as carrot provide β -carotene, green vegetables contain chlorophyll and other beneficial compounds, while purple vegetables are important sources of anthocyanins. The concept of "Eating the Rainbow" encourages the consumption of vegetables of different colours to obtain a diverse range of nutrients and phytochemicals. From a Vegetable Science perspective, colourful vegetables have significant potential in nutritional breeding, biofortification, protected cultivation, value addition and nutritional security.

Introduction

Vegetables are an important part of the human diet and are recognized as valuable sources of vitamins, minerals, dietary fibre and bioactive compounds. In addition to their nutritional value, vegetables display a remarkable range of colours, including green, red, orange, yellow, purple and white. These colours are not merely responsible for visual appeal; they are often associated with specific natural pigments and phytochemicals. The concept of "Eat the Rainbow" emphasizes consuming a variety of vegetables with different colours. Each colour group may provide a different combination of nutrients and bioactive compounds. Therefore, including a wide range of colourful vegetables in the daily diet is an easy way to improve dietary diversity.

What Gives Vegetables Their Colour?

The colour of vegetables is mainly determined by natural pigments:

Chlorophylls – responsible for the green colour of spinach, amaranths, peas and broccoli.

Carotenoids – produce yellow, orange and red colours and include β -carotene, lutein and lycopene.

Anthocyanins – provide red, blue and purple colours in vegetables such as purple cabbage and purple brinjal.

Betalains – contribute red-violet and yellow colours, particularly in beetroot. These pigments and associated phytochemicals contribute to the nutritional and functional quality of vegetables.

The Rainbow of Vegetables

Red Vegetables – The Lycopene Group: Tomato is one of the most important red vegetables. Its red colour is mainly associated with lycopene, a carotenoid pigment with antioxidant properties.

Examples: Tomato, red capsicum, red chilli and red cabbage.

Major compounds: Lycopene, anthocyanins and phenolic compounds.

Orange Vegetables – Carotenoid Powerhouses: Orange-coloured vegetables are particularly rich in carotenoids such as β -carotene. β -carotene can be converted into vitamin A in the human body and is important for normal vision and immune function.

Examples: Carrot, pumpkin, orange-fleshed sweet potato and squash.

Major compounds: β -carotene, α -carotene and other carotenoids.

Yellow Vegetables – A Source of Protective Phytochemicals: Yellow vegetables contain carotenoids and other phytochemicals. They add colour and variety to meals while contributing valuable nutrients.

Examples: Yellow pumpkin, yellow capsicum and yellow zucchini.

Major compounds: Carotenoids, flavonoids and phenolic compounds.

Green Vegetables – Chlorophyll-Rich Foods: Green vegetables are rich in chlorophyll and provide vitamins, minerals, fibre and numerous phytochemicals. Dark-green vegetables such as spinach, amaranths, moringa leaves and broccoli are particularly valuable. Cruciferous vegetables such as broccoli also contain glucosinolates, which have attracted considerable scientific interest.

Examples: Spinach, amaranths, broccoli, peas, beans, cabbage, okra and moringa leaves.

Major compounds: Chlorophyll, lutein, folates, glucosinolates and phenolic compounds.

Purple Vegetables – Anthocyanin-Rich Sources: Purple and blue colours are commonly associated with anthocyanins, a group of flavonoid pigments with antioxidant properties.

Examples: Purple cabbage, purple brinjal, purple carrot and purple cauliflower.

Major compounds: Anthocyanins and other flavonoids.

White Vegetables – Nutritionally Valuable: White and pale-coloured vegetables should not be overlooked. They contain several nutrients and bioactive compounds despite having less intense pigmentation.

Examples: Garlic, onion, cauliflower, radish and turnip. Onion and garlic contain sulphur-containing compounds, while cauliflower contains glucosinolates.

Why Should We “Eat the Rainbow”?

Different coloured vegetables contain different combinations of nutrients and phytochemicals. Therefore, consuming vegetables of several colours can increase dietary diversity.

A colourful diet can provide:

- Vitamins and minerals
- Dietary fibre
- Carotenoids
- Flavonoids
- Anthocyanins
- Phenolic compounds
- Glucosinolates
- Other bioactive phytochemicals

The objective is not to consider one colour superior to another, but to encourage variety in vegetable consumption.

Colourful Vegetables and Vegetable Breeding

The nutritional importance of colourful vegetables has created new opportunities for vegetable breeding. Modern breeding programmes increasingly consider nutritional quality along with yield, quality, pest and disease resistance and environmental adaptability.

Examples include:

- Orange-fleshed sweet potato with high provitamin A carotenoid content.
- Deep-red tomato with high lycopene content.
- Purple carrot and purple cabbage rich in anthocyanins.
- Dark-green leafy vegetables rich in micronutrients and phytochemicals.

Thus, vegetable breeding is increasingly moving towards the development of nutrient-rich and health-oriented cultivars.

Role in Nutritional Security

Vegetables are important for nutritional security because they supply a broad range of micronutrients and bioactive compounds. Kitchen gardens, nutrition gardens, urban farming, protected cultivation and community gardens can improve access to diverse vegetables. Encouraging people to grow and consume vegetables of different colours can help improve dietary diversity at the household level.

Maintaining Quality from Farm to Plate

The nutritional and sensory quality of vegetables can be affected by maturity, harvesting, handling, storage and cooking. Proper post-harvest management is therefore essential.

Important practices include:

- Harvesting at the appropriate maturity stage.

- Avoiding unnecessary mechanical damage.
- Maintaining suitable storage conditions.
- Minimizing prolonged storage.
- Using appropriate cooking methods.
- Consuming a diverse range of fresh vegetables.

Future Prospects

The concept of colourful vegetables has considerable scope in modern Vegetable Science. Future research can focus on:

- Breeding vegetables with enhanced phytochemical content.
- Biofortification of vegetable crops.
- Development of nutritionally superior cultivars.
- Protected cultivation of high-value colourful vegetables.
- Processing and value addition of colourful vegetables.
- Promotion of underutilized colourful vegetables.
- Consumer awareness regarding vegetable diversity.

Conclusion

Colourful vegetables are a valuable component of a healthy and diverse diet. Their colours reflect the presence of natural pigments such as chlorophylls, carotenoids, anthocyanins and betalains, along with a variety of phytochemicals. Red tomatoes, orange carrots, green leafy vegetables, yellow pumpkins and purple vegetables each contribute different nutritional and bioactive components. The concept of “Eating the Rainbow” provides a simple and attractive approach to encourage people to consume a greater diversity of vegetables. For Vegetable Science, it also highlights opportunities in nutritional breeding, biofortification, protected cultivation, value addition and nutritional security. Thus, “Nature’s Rainbow on Your Plate” is more than a colourful concept—it represents the diversity, nutritional richness and future potential of vegetable crops.

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Role of Plant Physiology in shaping Rice Production



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Rice is more than just a staple food—it is the lifeline of over half of the world's population. The branch of science that deals with how the plants grow, adapt, and survive is plant physiology, it also explains how the plants function throughout their life cycle. Unlike humans, rice plants cannot move to escape heat, drought, floods, or salinity. Instead, they rely on sophisticated physiological mechanisms that help them capture sunlight, absorb nutrients, regulate water, and cope with environmental stress. Understanding these processes is becoming increasingly important as climate change threatens rice production across many regions.

Photosynthesis

The most vital process, photosynthesis helps plants convert sunlight, water, and carbon dioxide into sugars that fuel growth and grain development. Healthy leaves with high photosynthetic efficiency produce more energy, resulting in better tillering, stronger stems, and fuller grain filling.

Recent research has highlighted the enormous potential of improving photosynthetic efficiency to meet future food demands. Scientists are exploring approaches such as enhancing carbon fixation and introducing C₄ photosynthetic traits into rice to increase productivity while reducing resource use (Furbank et al., 2023). Likewise, Xiong (2024) emphasized that improving photosynthesis through physiological and genetic interventions could significantly enhance grain yield under changing climatic conditions.

Water

Rice is traditionally grown in flooded fields, but the crop still experiences water stress during dry spells. Water plays several vital roles beyond keeping the plant hydrated—it transports nutrients, cools leaves through transpiration, and maintains cell turgor necessary for growth. Modern irrigation techniques, such as alternate wetting and drying (AWD), help conserve water while maintaining productivity. Understanding how rice regulates water movement through its roots and leaves enables farmers to produce more grain using less water.

Heat stress

Rising temperatures are among the greatest threats to rice cultivation, particularly in tropical and subtropical regions where the crop is already grown close to its optimum temperature range. Heat stress during the reproductive stage, especially at flowering, is one of the most damaging environmental factors affecting rice production. Exposure to temperatures above the optimum can reduce pollen viability, impair anther dehiscence, hinder pollination and fertilization, and ultimately lead to poor grain set and substantial yield losses. In addition, prolonged heat stress disrupts photosynthesis by damaging chloroplasts and photosynthetic enzymes, increases respiration rates, destabilizes cell membranes, and accelerates the production of reactive oxygen species (ROS), which can cause oxidative damage to plant cells.

To combat these challenges, plant physiologists are investigating a range of physiological traits associated with heat tolerance. Characteristics such as cooler canopy temperature, maintenance of chlorophyll content, efficient antioxidant defense systems, membrane thermostability, and sustained photosynthetic efficiency under high temperatures are increasingly being used as selection criteria in rice breeding programs. Advances in high-throughput phenotyping and molecular physiology have enabled researchers to identify heat-tolerant genotypes more efficiently, facilitating the development of climate-resilient rice cultivars. As global temperatures continue to rise, integrating physiological knowledge with modern breeding approaches will be essential for safeguarding rice productivity and ensuring food security (Jagadish et al., 2023).

Salinity and Flooding

Rice cultivation increasingly faces challenges from salinity and flooding, particularly in coastal and low-lying regions. Excess salt disrupts water uptake and causes ion toxicity, while prolonged flooding limits oxygen availability to roots.

Interestingly, rice has evolved remarkable physiological adaptations that allow it to survive these stresses. Recent studies have shown that specialized root structures, shoot elongation responses, and efficient oxygen transport systems help rice tolerate flooding and waterlogging (Lin et al., 2024). Understanding these adaptive mechanisms is guiding the development of resilient rice varieties capable of withstanding extreme weather events associated with climate change.

Hormones

Inside every rice plant, hormones such as auxins, gibberellins, cytokinins, abscisic acid, and ethylene coordinate growth and development. They regulate seed germination, root formation, flowering, grain filling, and responses to environmental stress.

Rather than acting independently, these hormones function as an interconnected signalling network. Their concentrations and interactions change continuously in response to developmental cues and environmental factors such as temperature, water availability, light, and nutrient status. Under drought conditions, increased ABA levels trigger stomatal closure to reduce water loss, while interactions between ABA, auxins, and cytokinins help redirect plant resources from growth toward survival. Similarly, during flooding, ethylene accumulation activates genes that enable rice plants to elongate their stems or conserve energy, depending on the variety and stress intensity.

Recent advances in plant physiology, molecular biology, and genomics have greatly enhanced our understanding of this complex hormonal crosstalk. Identification of key genes and signalling pathways that regulate hormone biosynthesis and response, enabling the development of rice varieties with improved tolerance to heat, drought, salinity, and flooding. Harnessing these hormonal mechanisms through modern breeding and biotechnology offers promising opportunities to enhance rice productivity and resilience in the face of climate change, ensuring sustainable food production for future generations.

The Future of Rice Physiology

Emerging technologies such as drone-based phenotyping, remote sensing, artificial intelligence, high-throughput phenotyping, and molecular biology are transforming rice research. Scientists can now monitor photosynthesis, water use, and stress responses in real time, allowing faster development of climate-resilient rice varieties. Integrating plant physiology with genomics and precision agriculture will play a crucial role in ensuring global food security in the coming decades.

Conclusion

Plant physiology may seem invisible, but it influences every stage of rice production—from seed germination to harvest. By understanding how rice plants function, scientists and farmers can develop smarter strategies to improve productivity, conserve natural resources, and withstand climate challenges. As the demand for rice continues to grow, the future of sustainable agriculture depends not only on better farming practices but also on unlocking the remarkable physiological potential hidden within every rice plant.

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Microgreens: The Tiny Superfood Taking Over Kitchens Everywhere



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Introduction

Microgreens are young vegetable greens — just a root, stem, and first set of leaves — harvested only 2-3 inches tall, right after their earliest true leaves appear. Small as they are, these little greens pack an outsized amount of nutrition into every bite. They can be grown from a huge range of vegetables and herbs — radish, broccoli, cauliflower, beet, carrot, spinach, arugula, basil, and many more — each ready to harvest in just 12-14 days. Despite their tiny size, they carry bold flavors that closely echo their mature counterparts: radish microgreens taste peppery like radish, beet microgreens taste earthy like beetroot, and so on. Nutritionally, microgreens often contain up to five times the vitamins and carotenoids of full-grown vegetables, and studies link this concentration to benefits like lower cancer risk, better heart health, stronger bones, and protection against diseases like Alzheimer's. First used as a decorative garnish in the 1980s, microgreens have since grown into a major health food trend worldwide. In India, they're still a niche addition — though upscale restaurants in cities like Delhi, Mumbai, and Bengaluru have started using them in salads, appetizers, and even desserts and mocktails.

Sprouts vs. Microgreens: What Sets Them Apart

Sprouts and microgreens often get lumped together, but they're quite different in how they grow and what they offer. Sprouts are nothing more than seeds that have just begun to germinate, while microgreens go through a longer growing process that allows them to develop actual stems and true leaves. This extra stage of growth is what gives microgreens a noticeably richer nutrient profile compared to sprouts. Timing is another key difference. Sprouts are ready to eat in just 2-5 days, while microgreens take longer — anywhere from 7 to 21 days, depending on which vegetable or herb is being grown. That extra growing time pays off nutritionally. Microgreens tend to be more nutrient-dense and flavourful than sprouts, thanks to higher concentrations of enzymes, flavonoids, and natural aromatic compounds. They also come with a practical safety advantage — because of how they're grown, microgreens carry a much lower risk of bacterial contamination than sprouts do. Growing conditions differ too: microgreens thrive in slightly cooler, less humid environments than sprouts require. And when it comes to eating them, only the leaves and stems of microgreens are consumed, unlike sprouts, which are typically eaten whole, root and all.

Why Microgreens Deserve a Place in Your Kitchen

1. **Simple to Cultivate:** Since they're harvested right at the first-leaf stage, microgreens don't demand the time, space, or expertise that a full vegetable garden would. A sunny windowsill, a small balcony, or even a corner of your kitchen counter is enough to get started, making them one of the easiest crops for beginners to try.
2. **Fast Turnaround:** From seed to harvest takes roughly two weeks, making microgreens one of the quickest home-grown foods around. This short growing cycle means you don't need much patience — or a green thumb — to enjoy a fresh, homegrown harvest on a regular basis.
3. **Bold Taste in a Tiny Package:** Despite their size, microgreens deliver concentrated bursts of flavour that closely resemble their mature counterparts, only more intense. This is exactly why chefs and food enthusiasts around the world prize them so highly, using them to add a pop of flavour and visual appeal to everything from salads to gourmet plates.

Growing Microgreens at Home

- **Seeds:** Regular vegetable seeds won't work here — you'll need seeds specifically labelled for microgreen growing, as these are chosen and prepared for quick, dense growth.

- **Soil:** Choose a clean potting mix free of chemicals or pesticide residue. This keeps your greens genuinely organic and safe to eat, since you'll be consuming the entire visible plant.
- **Container:** Any shallow tray, pot, or vessel around 4-5 inches deep will work well, as microgreens don't need much room for their roots to develop.
- **Light:** Aim for at least 3-4 hours of natural sunlight daily. A bright windowsill or a sunlit balcony creates the perfect environment for steady, healthy growth.
- **Water:** Keep the soil consistently moist without letting it get waterlogged. A gentle hand-mister works best, delivering a fine spray that hydrates the delicate greens without disturbing or drowning them.

Steps to Growing Fresh, Flavourful, and Healthy Microgreens

1. **Prepare the Container:** Fill your tray or pot with soil, keeping it about 3-4 inches deep. Since microgreen roots stay shallow, there's no need for anything deeper.
2. **Scatter the Seeds:** Spread the microgreen seeds evenly across the top of the soil. They don't need to be perfectly spaced — a simple hand-sprinkle across the surface works just fine.
3. **Add a Light Covering:** Sprinkle a thin layer of soil over the seeds, then gently press down on the surface. This helps the seeds settle in and make good contact with the soil.
4. **Moisten the Soil:** Mist the surface with water until it's evenly damp throughout, being careful not to soak or flood it.
5. **Let It Rest and Germinate:** Keep the container at normal room temperature for about two days, allowing the seeds to sprout. Once germination begins, move it to a sunny spot — ideally somewhere it can soak up 3-4 hours of sunlight each day.
6. **Water Twice Daily:** Continue misting the growing greens two times a day. Within another 3-4 days, you'll start to see tiny leaves unfurling above the soil, with delicate shoots forming beneath them.
7. **Harvest at the Right Time:** Once your microgreens reach about 2-3 inches in height, they're ready to be cut. Using scissors or a sharp knife, hold the greens upright and slice them just above the soil line, right where the roots begin.
8. **Rinse and Store:** Give the freshly cut microgreens a rinse under cold water before using them in your meal. For the best nutritional benefit, eat them as soon as possible after harvesting. If you're not using them right away, pat them dry, wrap them in paper, and store them in the refrigerator.

How Microgreens Support Your Health

Diets rich in vegetables are consistently associated with a reduced risk of various illnesses, largely because vegetables deliver generous amounts of vitamins, minerals, and protective plant compounds. Microgreens, being nutritionally concentrated, may offer similar — or even amplified — protection against the following conditions:

Heart Health: Microgreens are packed with polyphenols, a group of antioxidants known to support cardiovascular health. Research suggests that regularly consuming microgreens may help bring down triglyceride levels and reduce "bad" LDL cholesterol.

Alzheimer's Disease: Foods high in antioxidants — particularly polyphenols — have been associated with a lower likelihood of developing Alzheimer's disease, making antioxidant-rich microgreens a potentially valuable addition to a brain-healthy diet.

Diabetes: Antioxidants may help ease the cellular stress that interferes with sugar being properly absorbed into cells. In laboratory settings, fenugreek microgreens were shown to improve sugar uptake at the cellular level by as much as 25-44%.

Cancer Risk: A diet rich in antioxidant-heavy fruits and vegetables — especially those high in polyphenols — has long been linked to a reduced risk of several cancer types. Given their concentrated polyphenol content, microgreens may offer comparable protective benefits.

Chronic Inflammation: Persistent inflammation is one of the body's clearest warning signs of underlying disease. A vegetable-rich diet, including regular servings of microgreens, has been shown to help lower markers of inflammation while also contributing to a reduced risk of multiple cancer types.

The Most Widely Grown Microgreen Varieties

Microgreens come from a wide range of plant families. Popular choices include cruciferous vegetables like cauliflower, broccoli, and cabbage, along with radish, carrot, garlic, onion, amaranth, beetroot, spinach, and even

melon, cucumber, and squash varieties. Beyond vegetables, microgreens can also be grown from cereal grains such as rice, oats, wheat, corn, and barley, as well as legumes like chickpeas, beans, and lentils.

Flavour varies widely across these different types — some carry a neutral, mild taste, while others lean spicy, tangy, or slightly bitter, depending entirely on which plant they come from.

A Colourful Spectrum of Microgreens

Just like fruits and vegetables, microgreens come in a variety of colors — and each color signals a different set of beneficial plant compounds, known as phytochemicals, along with unique micronutrients.

- **Red varieties** are rich in lycopene, a powerful antioxidant known for its protective properties.
- **Orange and yellow varieties** contain carotenoids such as beta-carotene and lutein, both of which the body converts into vitamin A.
- **Blue and purple varieties** get their colour from anthocyanins, compounds that help shield cells from damage.
- **Green varieties** offer a broad mix of phytochemicals, including saponins, indoles, and carotenoids.
- **Brown and white varieties**, such as garlic, contain allicin, a compound valued for its natural antibacterial properties.

Conclusion

- Microgreens prove that good things really do come in small packages. From their remarkable nutrient density to their bold, distinctive Flavors, these tiny greens offer an easy way to elevate everyday meals without demanding much time, space, or gardening experience. Whether grown on a sunny windowsill or picked up from a local market, microgreens bring a genuine boost to both the taste and nutritional value of your diet.
- As more people look for simple, natural ways to eat healthier, microgreens are steadily earning their place — not just as a garnish, but as a genuine addition to daily nutrition. With their ease of cultivation, quick turnaround, and impressive health benefits, there's never been a better time to bring these nutrient-packed greens into your kitchen and start reaping their rewards, one tiny leaf at a time.

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Bhumyamalaki (*Phyllanthus amarus*): A Comprehensive Review on Production Technology and Therapeutic Potential



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Abstract

Phyllanthus amarus (Bhumyamalaki) is an important medicinal herb belonging to the family Euphorbiaceae, valued for its rich phytochemical composition and diverse therapeutic properties. The plant contains bioactive compounds such as phyllanthin and hypophyllanthin, which contribute to its hepatoprotective, antiviral, antibacterial, antifungal, and antioxidant activities. Traditionally, it has been widely used in Ayurveda for the management of jaundice, liver disorders, urinary ailments, diabetes, oedema, and skin diseases. The crop thrives well under tropical and subtropical conditions and can be cultivated successfully in well-drained soils with proper nutrient and moisture management. Commercial cultivation involves propagation through fresh seeds, nursery raising, timely transplanting, balanced fertilization, and adequate irrigation while avoiding waterlogging. Improved varieties such as Navyakrit and CIM-Jeevan offer higher herbage yield and enhanced phyllanthin content, making the crop suitable for medicinal plant cultivation.

Key words: Bhumyamalaki, *Phyllanthus amarus*, Euphorbiaceae, Medicinal herb, Phyllanthin

Introduction

Phyllanthus amarus is a member of the Euphorbiaceae family, has a variety of chemical compounds. *Phyllanthus* means "leaf and flower" as both the fruits and flowers are positioned on the same axil. It is an important medicinal plant that grows in India during the rainy season as a weed. The genus *Phyllanthus* has been extensively used to treat intestinal parasites, diabetes, and problems with the liver, kidneys, and bladder. The main components are lignans like Phyllanthin (0.4 to 0.5 %) and hypophyllanthin. Roots contain kaempferol, rhamnopyranoside and eridictyol rhamnopyranoside. *P. amarus* can be found along roadsides, in valleys, along riverbanks and around lakes in all of the world's tropical climates. This plant is a common arable weed found in tropical America, the Bahamas, the West Indies, southern Florida and the Old World's tropics. In vitro experiments have revealed a significant anti-hepatitis-B virus antigen activity. Additionally, the plant has been shown to have antiviral, antifungal, antibacterial, and anticrustacean properties. A root infusion works well as a tonic. Jaundice is commonly treated with fresh roots, a plant decoction in a cup of milk, or powdered dried leaves. To treat oedema and ulcers, roots and leaves are combined with rice water. A infusion of the leaves is applied to the scalp as a cooling remedy.



Description of the plant

It has an erect stem that is typically 30 to 70 cm tall, with thin, spreading leaf branches above and a naked underside. Numerous, subsessile, pale green, glaucous beneath, elliptic to oblong, obtuse, with stipules subulate, usually distichously imbricating. Male and female flowers are solitary, monocious, yellowish, and emerge along the leaf axis. The smooth, oblate capsule has a light brown seeds that are 0.9–1.0 mm long and 0.7–0.8 mm radially and tangentially.



Varieties

Navyakrit (CIMAP) - High herbage (980 kg dry herbage/ha) and active constituents (40% more phyllanthin content).

CIM-Jeevan- Released in 2003. Developed through mutation breeding. Growth habit erect. Fresh herb yield is 90-100 q/ha. Dry herb yield is 18-20 q/ha. Phyllanthin content is 0.70-0.77%. Hypophyllanthin content is 0.32-0.37%.

Soil and Climate

Phyllanthus grows well as tropical and sub tropical rainfed crop. Well drained Sandy loamy/black soil pH of 6.5 to 7.5 is preferred. The plant can thrive in a variety of soil types, including lateritic, calcareous, black clay, and red loam. However, well-drained red loam soils are ideal for commercial farming. Although the crop dislikes water logging, it needs consistent watering throughout its life to yield good returns.

Propagation

Phyllanthus is generally propagated through seeds. As the seeds require exposure to light for germination they are classified as photoblastic. Seed collection is carried out after the plants have completely matured and dried allowing the fruits to split open naturally. Because the seeds remain viable only for a short period freshly harvested seeds are preferred for nursery raising. For uniform sowing, the seeds are blended with fine sand and broadcast on raised nursery beds enriched with well-decomposed organic manure. Under favourable conditions, germination begins within 4-6 days and the young seedlings are nurtured in the nursery for approximately 20 days before they are ready for transplanting. About 1 kg of seeds is required for raising seedlings to plant in one ha.

Land Preparation

Plough the land twice/thrice and level the top soil by adding 10 t of farm yard manure/ha.

Transplantation

Healthy vigorous seedlings that are 3 to 4 weeks old or 15 cm tall are taken out from the nursery and moved to the main field, which can accommodate 8 lakh seedlings per hectare. Appropriately sized beds are prepared up, and the seedlings are planted in the ridges at a spacing of 20 x 15 cm.

Manuring

Apply 10-20 tons of FYM to promote healthy vegetative development. For improved growth and herbage yield, 100:50:50 kg of NPK per hectare is ideal. The remaining N is given in two split doses, the first at 30 day and the second at 60 day. The full dose of P and K, as well as half of the dose of N, are given as basal.

Irrigation

The field should receive a thorough irrigation immediately before and after transplanting to help the seedlings establish successfully. In regions that receive regular rainfall during the crop growth period additional irrigation is generally unnecessary. However during prolonged dry spells supplemental watering is essential to maintain healthy plant growth with irrigation once a week being sufficient under normal dry conditions. Care should be taken to avoid waterlogging.

Harvesting and yield

The plant can be started in September or October if it is cultivated in June or July. Harvesting in September is best for high phyllanthin content. The plants reach their peak growth within 80 to 100 days from the planting date. To preserve the hypophyllanthin and chlorophyll the herbage is dried in the shade. Complete drying takes 4-6 days (10% moisture). The herbage must be raked frequently to prevent the growth of mold and fungus. Average yields varies from 400 to 500 kg/ acre of dry herb or 5 tons/ acre of fresh herbage on. Up to 1000 kg of dry herbage can be produced per acre depending on the amount of organic manures used and the soil nutritional state.

Plant protection

In general, this herb requires less in the manner of pest and disease control. The pest in this crop during the early phases of plant growth is a green-colored semilooper. There have also been reports of insect pests such stem weevils and leaf-eating caterpillars, which can be managed by applying a 0.2% Nuvacron spray.

Disease like to powdery mildew at the growing period. Applying fungicides that is sulphex @ 0.25%, can effectively reduce powdery mildew.

Conclusion

Phyllanthus amarus has emerged as an important medicinal herb owing to its remarkable therapeutic properties and increasing demand from the herbal and pharmaceutical industries. Its cultivation is relatively simple, requiring good-quality seed, well-drained soil, balanced nutrient management, and timely irrigation for optimum growth and yield. The availability of improved varieties with higher herbage production and increased phyllanthin content further enhances its commercial value. In addition to its economic potential, the plant plays a significant role in traditional medicine, particularly in the treatment of liver disorders and several other health conditions.

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Seaweed Farming in India: Current Status and Future Prospects



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Abstract

Seaweed farming is emerging as one of the most promising sectors of India's Blue Economy. Seaweeds are marine macroalgae that grow naturally in coastal waters and have extensive applications in food, pharmaceuticals, cosmetics, fertilizers, animal feed, biofuels, and biotechnology industries. With a coastline of more than 11,000 km and favorable tropical conditions, India possesses enormous potential for seaweed cultivation. In recent years, government initiatives, technological advancements, and increasing industrial demand have accelerated the growth of the seaweed sector. This article discusses the present status, cultivation practices, economic importance, challenges, and future prospects of seaweed farming in India.

Introduction

Seaweeds are multicellular marine algae found in coastal and shallow marine environments. They are broadly classified into:

1. Red algae (*Rhodophyceae*) – e.g., *Kappaphycus alvarezii*, *Gracilaria edulis*
2. Brown algae (*Phaeophyceae*)– e.g., *Sargassum spp.*
3. Green algae (*Chlorophyceae*)– e.g., *Ulva spp.*

Globally, seaweed farming contributes significantly to the marine economy, especially in countries such as China, Indonesia, South Korea, Japan, and the Philippines. India is gradually developing its seaweed sector as a sustainable livelihood option for coastal communities and as a source of valuable marine bioresources. ([Department of Forestry])

Importance of Seaweed Farming

1. Nutritional Value: Seaweeds are rich in:

Proteins, Vitamins (A, B, C, E), Minerals (iodine, calcium, iron), Dietary fiber, Antioxidants

2. Industrial Applications: Seaweeds are used for producing:

Agar, Carrageenan, Alginate, Pharmaceuticals, Cosmetics, Nutraceuticals, Bioplastics, Biofertilizers

3. Environmental Benefits:

1. Absorb carbon dioxide (Blue Carbon)
2. Improve water quality
3. Reduce nutrient pollution
4. Provide habitat for marine organisms
5. Support climate change mitigation

4. Livelihood Generation: Seaweed farming offers an alternative income source for: Fishermen, Women self-help groups, Coastal youth, Aquaculture farmers.

Seaweed Resources in India

India possesses rich seaweed biodiversity with more than 850 species reported along its coastline. Major seaweed-rich regions include: ([Department of Forestry]) Gulf of Mannar (Tamil Nadu), Palk Bay (Tamil Nadu), Gujarat Coast (Okha, Dwarka, Kutch), Maharashtra Coast, Goa, Kerala, Andhra Pradesh, Lakshadweep Islands, Andaman and Nicobar Islands

Major cultivated species include: *Kappaphycus alvarezii*, *Gracilaria edulis*, *Ulva spp*, *Sargassum spp*, *Gelidiella acerosa* ([Department of Forestry])

Current Status of Seaweed Farming in India

1. Production Status: Seaweed farming in India has expanded significantly over the last decade. According to government reports, India produced approximately 72,385 tonnes (wet weight) of farmed seaweed in 2023. The major cultivated species are: *Kappaphycus alvarezii* and *Gracilaria edulis*.

2. Government Initiatives: The Government of India has identified seaweed cultivation as a priority activity under the Pradhan Mantri Matsya Sampada Yojana (PMMSY). Support is provided for: Installation of seaweed rafts, Monoline and tube-net systems, Seaweed seed banks, Hatcheries, Multipurpose Seaweed Parks, Training and capacity building, Market development and value addition. Approval of seaweed projects worth more than ₹194 crore. Establishment of a Multipurpose Seaweed Park in Tamil Nadu. Development of seaweed seed banks. Designation of CMFRI Mandapam as a Centre of Excellence for seaweed development.

3. Potential Cultivation Area: Research institutions such as ICAR-CMFRI and CSIR-CSMCRI have identified **384 potential sites covering about 24,707 hectares suitable for seaweed cultivation across India's coastal states and Union Territories.

4. Seaweed Farming Methods

1. Raft Method: Floating bamboo or HDPE rafts are used. Seaweed fragments are tied to ropes. Suitable for sheltered coastal waters. Most common method in Tamil Nadu.

2. Monoline Method: Nylon ropes are stretched between anchors. Seed materials are tied at regular intervals. Low-cost and easy to maintain.

3. Tube-Net Method: Seedlings are placed inside tubular nets. Protects crops from grazing fishes. Suitable for high-energy coastal environments.

Economic Importance

Seaweed farming offers several economic benefits: Seaweed cultivation requires relatively low investment compared to many aquaculture activities and can provide multiple harvests annually.

Sector	Application
Food Industry	Edible seaweeds, supplements
Pharmaceutical Industry	Drug formulations
Cosmetic Industry	Skin-care products
Agriculture	Biofertilizers, biostimulants
Animal Feed	Feed additives
Bioenergy	Bioethanol and biofuel production

Seaweed Farming in Gujarat

For a fisheries and aquaculture graduate from Gujarat, seaweed farming is particularly relevant. The coastal stretch from Kutch to Devbhumi Dwarka and Okha is emerging as an important seaweed cultivation zone. The Gujarat Government has initiated programs for: Seaweed seed bank development, Processing units for carrageenan and alginate extraction, Establishment of a Centre of Excellence for seaweed research and utilization at Okha under Kamdhenu University.

Challenges in Seaweed Farming

Despite its potential, several constraints remain:

- 1) Technical Challenges
 - Limited availability of quality seed material
 - Disease and epiphyte infestation
 - Seasonal fluctuations in growth
- 2) Environmental Challenge
 - Cyclones and rough seas
 - Rising sea temperatures
 - Coastal pollution
- 3) Marketing Challenges
 - Limited processing industries
 - Price fluctuations
 - Weak value chains
- 4) Policy and Infrastructure Constraints
 - Licensing and coastal regulations

- Lack of cold chain and storage facilities
- Inadequate farmer awareness

Future Prospects

India's seaweed sector has tremendous growth potential. The Government has set an ambitious target of 1.12 million tonnes of seaweed production by 2030 through expansion of cultivation infrastructure, improved seed quality, research support, and value-chain development.

Emerging Opportunities

1. Blue Economy Development: Seaweed cultivation is becoming a major component of India's Blue Economy strategy.
2. Climate Change Mitigation: Seaweeds act as carbon sinks and contribute to carbon sequestration.
3. Export Potential: Global demand for: Carrageenan, Agar, Alginate, Nutraceuticals, Functional foods is increasing rapidly.
4. Integrated Multi-Trophic Aquaculture (IMTA): Integration of seaweed with: Fish culture, Shrimp farming, Shellfish farming can improve sustainability and profitability.
5. Marine Biotechnology: Seaweed-derived compounds have applications in: Pharmaceuticals, Biomedical products, Antimicrobial agents, Bioactive compounds
6. Employment Generation: The seaweed sector is expected to create thousands of jobs for coastal communities, women entrepreneurs, and fisherfolk.

Conclusion

Seaweed farming represents a sustainable and high-potential sector within Indian aquaculture and the Blue Economy. India's vast coastline, favorable environmental conditions, rich seaweed biodiversity, and strong government support provide an excellent foundation for future expansion. Although challenges related to seed supply, infrastructure, and market development remain, ongoing initiatives under PMMSY, research support from CMFRI and CSMCRI, and increasing industrial demand are expected to transform seaweed farming into a major contributor to coastal livelihoods, environmental sustainability, and economic growth. With proper policy support and technological advancement, India has the potential to become a leading global producer of cultivated seaweed in the coming decades.

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ARTIFICIAL INTELLIGENCE APPLICATION IN AGRONOMY



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Abstract

Artificial intelligence is steadily reshaping agronomy, the science of soil management and crop production, by turning routine farm decisions into data-driven ones. This article surveys the major ways AI is being applied on and around the farm today: computer vision and deep learning for crop monitoring and disease detection, machine learning-based irrigation and soil management, yield prediction models built on satellite and climate data, and autonomous robotics for planting, weeding, and harvesting. Drawing on recent research reviews and market analysis, it shows how these tools are helping farmers use water, fertilizer, and labour more efficiently at a time when population growth and climate volatility are putting increasing pressure on food systems. The article also considers the practical barriers to adoption, including cost, rural connectivity, and farmer trust in automated systems, concluding that AI is best understood not as a replacement for agronomic expertise but as its latest and most powerful extension.

Introduction

Walk through a farm today and you might not notice anything different at first glance the same rows of corn, the same tractors rumbling along the furrows. But look a little closer and you'll spot a drone hovering over the crop canopy, a soil sensor blinking quietly in the dirt, or a farmer checking a phone app instead of squinting at the sky. Behind all of it sits artificial intelligence, quietly doing work that used to take an agronomist a full season to figure out.



Agronomy the science of soil management and crop production has always been about reading signals: how much water a field needs, when a disease is about to strike, which patch of land is underperforming and why? For centuries, farmers relied on experience and intuition to read those signals. Now, AI is learning to read them too, and often faster and more precisely than the human eye ever could.

AI Powered Crop Monitoring and Disease Detection

One of the most visible uses of AI in agronomy is crop monitoring through computer vision. Drones and satellites fitted with multispectral cameras fly over fields and capture images that reveal things invisible to the naked eye subtle shifts in leaf colour that hint at nutrient deficiency, moisture stress, or the early stages of disease. Machine learning models trained on thousands of such images can flag a problem area days before it would show up as visible wilting or yellowing. This isn't just a lab experiment. Editorial reviews of the field describe how AI and Internet of Things systems are now widely used to monitor crop growth, detect pests and diseases, and even guide targeted spraying and pollination, cutting down on both labour and chemical use. In practical terms, that means a farmer no longer needs to walk every acre to find trouble spots the system points them straight to the field that needs attention.

Deep learning has become a particular workhorse here. Convolutional neural networks, the same type of model that powers facial recognition on smartphones, are now trained to recognize crop diseases from photographs of leaves, often catching infections at a stage early enough to save the harvest.

Precision Irrigation and Soil Management

Water scarcity is one of agriculture's oldest headaches, and AI is helping tackle it in a very direct way: by telling irrigation systems exactly how much water to use, and when. Soil moisture sensors feed real time data into algorithms that adjust irrigation automatically, replacing the old habit of watering on a fixed schedule regardless of actual need.

The results can be striking. In Napa Valley, an AI driven irrigation system helped a vineyard cut its water use dramatically while also improving grape yields, and a similar project in Australia reported a substantial jump in irrigation efficiency after adopting AI based water management. These aren't marginal gains in regions facing chronic drought, that kind of efficiency can be the difference between a viable harvest and a failed one.

The same logic applies underground. AI models are increasingly used to interpret soil sensor data and satellite imagery together, building a picture of nutrient levels across a field so fertilizer can be applied only where it's needed, rather than blanketed across an entire plot.

Yield Prediction and Forecasting

Perhaps the least glamorous but most economically important use of AI in agronomy is yield prediction. Long before combine harvesters roll into a field, machine learning models are already estimating how much grain, fruit, or vegetable that field will produce, based on satellite imagery, weather patterns, soil data, and historical trends.

Researchers have compiled long lists of studies applying these techniques across different crops and regions, from mapping irrigation infrastructure via satellite to using climate variables to forecast rice yields with support vector machines. For agribusinesses, insurers, and even national food security planners, these forecasts are becoming an essential planning tool, not just a curiosity.

Agricultural Robotics and Automation

Labor shortages have pushed another branch of AI into the spotlight: agricultural robotics. Autonomous machines now navigate fields to plant seeds, pull weeds, and even harvest delicate fruits that once required a human hand. This is a genuinely difficult engineering problem a robot must perceive an uneven, unpredictable outdoor environment and make real time decisions but the pace of progress has been rapid, driven by the same climate pressures and labor shortages reshaping the rest of agriculture.

Broader Impact and Market Outlook

It's easy to treat all this as a story about gadgets, but the underlying stakes are much bigger. The world's population keeps growing, arable land is not, and the climate is becoming less predictable by the year. Feeding people under those conditions requires squeezing more value out of every drop of water, every gram of fertilizer, and every acre of land and that is precisely the kind of optimization problem AI is good at solving. Market analysts have taken notice too. The AI in precision agriculture sector, still a relatively small niche just a few years ago, is now projected to grow at roughly 20% a year through the mid-2030s, a sign that adoption is moving from early pilot projects to mainstream farm operations.

Conclusion

Artificial intelligence has moved well beyond the experimental stage in agronomy. From drones that spot disease before it spreads, to algorithms that decide exactly how much water a vineyard needs, to robots that can pick fruit without bruising it, AI is now woven into the everyday decisions that determine how much food a field produces. The evidence reviewed here suggests this is not a passing trend: market growth projections, expanding research output, and real-world efficiency gains all point toward deeper adoption in the years ahead. At the same time, the technology's success will depend on closing the gaps that remain affordable access for smallholder farmers, reliable rural connectivity, and models robust enough to work across different soils and climates. Handled well, AI stands to make agronomy more precise, more sustainable, and more resilient, helping ensure that farming can keep pace with a growing and increasingly unpredictable world.

The Importance of Cover Crops in Agriculture Systems



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Abstract

Cover crops plants grown to protect and enrich soil between cash crop cycles rather than for harvest have re-emerged as a cornerstone practice in sustainable agriculture. This article examines how cover crops improve soil health, manage nutrients naturally, suppress weeds, conserve water, support biodiversity, and mitigate climate change, while also delivering measurable economic benefits to farmers. It reviews common cover crop species and their specific roles, addresses the practical challenges of adoption, and considers the policy and technology trends shaping the future of cover cropping. The evidence points to a clear conclusion keeping soil covered and biologically active year-round is one of the simplest, most cost-effective strategies available for building resilient, productive farming systems.

What are cover crops?

Cover crops are non-cash crops such as legumes, grasses, brassicas, and various broadleaf species that are planted between main crop cycles, alongside a primary crop, or during fallow periods. Unlike cash crops grown for grain, fiber, or produce, cover crops are typically terminated before or at planting of the next primary crop, either by mowing, crimping, grazing, or incorporation into the soil, or through natural winterkill in colder climates.

Common categories include

- Legumes (clover, vetch, cowpea, field peas) valued for biological nitrogen fixation
- Grasses and cereals (cereal rye, oats, barley, annual ryegrass) valued for fibrous root systems and rapid biomass
- Brassicas (radish, mustard, turnip) valued for deep taproots that break up compacted soil
- Multi species mixes ("cocktails") combining several functional groups to capture multiple benefits simultaneously

The choice of species, timing, and termination method depends heavily on regional climate, cash crop rotation, and the specific soil or pest challenges a farm is trying to address.

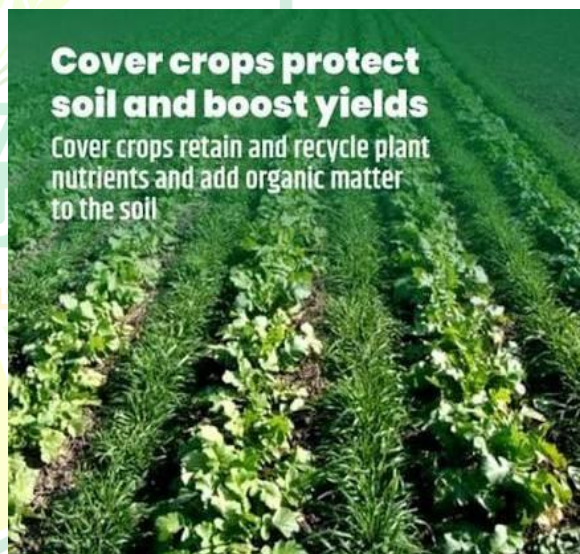
Building and protecting soil health

Preventing erosion

Roots hold soil particles in place, and above ground biomass shields the surface from the impact of rain and wind. Studies from the USDA Natural Resources Conservation Service have consistently shown that cover cropped fields lose dramatically less topsoil than bare fields during heavy rain events.

Building organic matter

As cover crop residue decomposes, it adds organic material to the soil, feeding microbial life and improving the soil's structure, water holding capacity, and nutrient content over time.



Improving soil structure

Root systems especially deep tap rooted species like daikon radish break up compacted soil layers, improve aeration, and create channels for water infiltration.

Managing Nutrients Naturally

Nitrogen fixation

Legume cover crops such as clover, vetch, and field peas host nitrogen fixing bacteria in their root nodules, converting atmospheric nitrogen into a form usable by plants. This can significantly reduce the need for synthetic nitrogen fertilizer in the following cash crop.

Nutrient scavenging

Non-legume cover crops like cereal rye and oats are excellent "nutrient scavengers." They absorb residual nitrogen and other nutrients left in the soil after harvest, preventing them from leaching into groundwater or running off into streams and rivers. When the cover crop is terminated, those nutrients are released back into the soil for the next crop to use.

Reducing fertilizer runoff

By capturing excess nutrients, cover crops help address one of agriculture's most significant environmental problems nutrient pollution, which contributes to algal blooms and "dead zones" in water bodies like the Gulf of Mexico.

Suppressing Weeds Naturally

Dense cover crop stands compete with weeds for light, water, and nutrients, physically crowding them out. Some cover crops, like cereal rye, also release natural allelopathic compounds that inhibit weed seed germination. This can reduce a farm's reliance on herbicides, lowering both input costs and the environmental footprint of weed control.

Conserving and Managing Water

Improved infiltration

Enhanced soil structure and organic matter allow rainfall to soak into the ground rather than running off, reducing flooding risk and replenishing groundwater.

Reduced evaporation

A layer of cover crop residue on the soil surface acts as mulch, reducing water loss through evaporation and helping soil retain moisture during dry periods.

Drought resilience

Soils with higher organic matter content can hold more water, giving crops a buffer during dry spells an increasingly valuable trait as climate variability increases.

Climate Change Mitigation

Carbon sequestration

Growing plants pull carbon dioxide from the atmosphere and through root systems and decomposing residue, transfer some of that carbon into the soil, where it can remain stored for years.

Reduced synthetic input use

Because cover crops can reduce dependence on synthetic fertilizers (which are energy intensive to produce) and herbicides, their use indirectly lowers the carbon footprint of a farming operation.

Resilience to extreme weather

Healthier soils with better structure and water holding capacity are more resilient to the droughts and intense rainfall events that are becoming more frequent with climate change.

Challenges and Considerations

Upfront costs and labor

Seed costs, additional planting and termination passes, and equipment needs add short term expenses before benefits are realized.

Timing constraints

Cover crops need to be planted and terminated at the right times relative to cash crops, which can be logistically challenging, especially in regions with short growing seasons.

Water competition

In dry climates, a poorly managed cover crop can compete with the following cash crop for scarce soil moisture if not terminated at the right time.

Short term yield uncertainty

Some farmers report a short adjustment period as their systems transition, though most research shows yields stabilize or improve within a few years of consistent use.

Conclusion

Cover crops represent a simple but powerful idea keep the soil covered, alive, and working, even when no cash crop is growing. In doing so, they address some of agriculture's most stubborn challenges erosion, nutrient loss, water management, weed pressure, and climate vulnerability all while offering real economic value to the farmers who use them. They are not a silver bullet, and successful implementation requires knowledge, planning, and patience. But as more farmers, researchers, and policymakers recognize their multifaceted benefits, cover crops are poised to remain a cornerstone of resilient, sustainable agriculture for decades to come. In many ways, the humble cover crop is a reminder that some of the best solutions to modern farming challenges are rooted in age old wisdom take care of the soil, and it will take care of you.



Human Infections Caused by Larval Cestodes: Recent Advances and Current Perspectives



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1. Introduction

Human infections caused by cestode larvae, or metacestodes, are among the most significant yet historically ignored zoonotic parasitic diseases in the world. These infections occur when people unintentionally serve as tapeworms' intermediate hosts and develop space-occupying cystic lesions in vital organs. Among the biggest threats to public health and socioeconomic advancement are cystic echinococcosis (CE) brought on by *Echinococcus granulosus sensu lato*, alveolar echinococcosis (AE) brought on by *Echinococcus multilocularis*, and cysticercosis brought on by *Taenia solium* larvae. Coenurosis (induced by *Taenia multiceps* or *Taenia serialis*) and sparganosis (produced by *Spirometra* spp. plerocercoids) are less frequent but clinically serious larval cestode diseases.

These illnesses are typically localised, yet they are found all over the world. In low- and middle-income countries (LMICs), where parasite transmission is facilitated by poverty, poor sanitation, intimate human-livestock contact, and inadequate veterinary infrastructure, they are highly prevalent. They disproportionately impact pastoralist and rural groups that are marginalised. Clinical symptoms usually appear months to years after infection because these metacestodes grow slowly within host tissues. Active clinical management is hampered, diagnosis is routinely delayed, and transmission dynamics are obscured by this protracted, sneaky incubation phase.

2. Global Distribution and Public Health Milestones

The recognition of larval cestode infections as primary public health priorities has evolved noticeably over the past several decades.

2.1 Historical Recognition and WHO Roadmaps

Cystic echinococcosis was first formally emphasized as a major zoonotic threat during the First Joint WHO/FAO Expert Committee on Zoonoses in 1950. That same year, the World Health Assembly passed **Resolution WHA3.23**, acknowledging echinococcosis as a dual threat to human health and livestock economics.

A critical shift occurred with **Resolution WHA66.12 (2013)**, which integrated both echinococcosis and *Taenia solium* taeniasis/cysticercosis into the portfolio of **Neglected Tropical Diseases (NTDs)**.

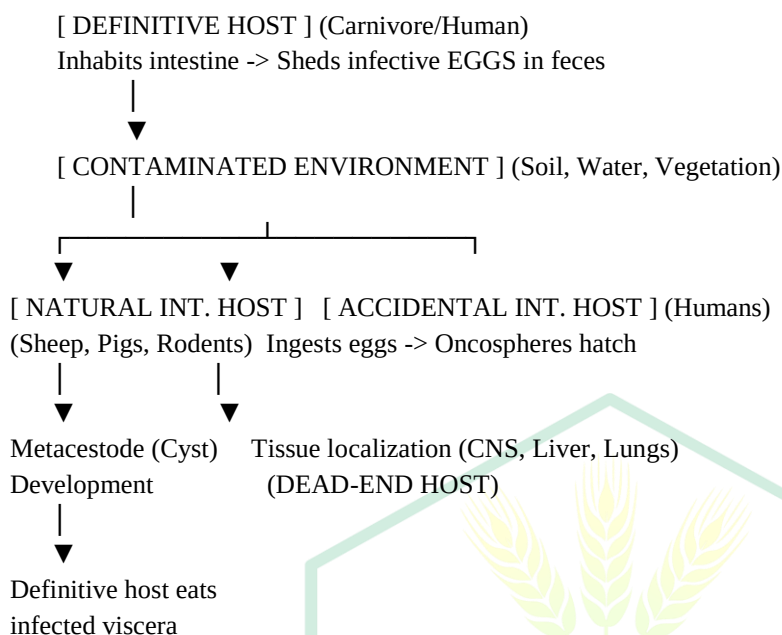
2.2 Current Epidemiological Trajectories

The World Health Organization's *Ending the neglect to attain the Sustainable Development Goals: A road map for neglected tropical diseases 2021–2030* established explicit frameworks for monitoring and control. Epidemiological evaluations using Global Burden of Disease (GBD) datasets reveal contrasting global trends:

- **Cystic Echinococcosis:** Systematic analysis indicates a steady historical decline in the age-standardized incidence rate (ASIR) and disability-adjusted life years (DALYs) globally between 1990 and 2019, driven largely by targeted control interventions in regions like China and parts of Latin America (Tian et al., 2024). However, models project an uptick in crude global cases over the next decade due to demographic shifts and persistent transmission pockets in hyper-endemic regions (Tian et al., 2024).
- **Neurocysticercosis (NCC):** Localization of *T. solium* larvae within the central nervous system remains the most devastating manifestation of cysticercosis. Global mapping indicates that NCC accounts for approximately 30% of preventable epilepsy cases in endemic pockets, and in specific highly impoverished agrarian settings, it is tied to up to 70% of seizure disorders. Data estimates place the global cohort of symptomatic or asymptomatic NCC patients between 2.56 and 8.30 million individuals.

3. Taxonomy, Life Cycles, and Biological Vectors

The transmission dynamics of zoonotic larval cestodes depend entirely on predator-prey lifecycles, where humans act as accidental "dead-end" intermediate hosts.



3.1 *Echinococcus granulosus sensu lato* (Cystic Echinococcosis)

E. granulosus s.l. requires a two-host lifecycle. Domestic dogs and other wild canids serve as **definitive hosts**, harboring the adult tapeworms in their small intestines and shedding microscopic, highly resilient eggs in their feces. Ungulates (sheep, goats, cattle, camels) serve as the natural **intermediate hosts**.

Humans become infected via the fecal-oral route through direct contact with infected canids or by consuming egg-contaminated water, soil, or fresh produce.

3.2 *Echinococcus multilocularis* (Alveolar Echinococcosis)

The lifecycle of *E. multilocularis* relies primarily on a sylvatic (wildlife) cycle. Wild carnivores, particularly red foxes (*Vulpes vulpes*) and Arctic foxes (*Vulpes lagopus*), act as the primary definitive hosts, while small rodents (voles, lemmings) serve as intermediate hosts. Human infection follows accidental ingestion of eggs shed by foxes or domestic dogs that have hunted infected rodents.

3.3 *Taenia solium* (Taeniasis / Cysticercosis)

Taenia solium presents a distinct biological paradigm where humans fulfill two separate roles:

1. **Definitive Host (Taeniasis):** Acquired by ingesting undercooked pork containing viable larval cysts (*Cysticercus cellulosae*). The tapeworm matures in the human small intestine, shedding proglottids laden with eggs.
2. **Accidental Intermediate Host (Cysticercosis):** Triggered when a human ingests *T. solium* eggs via external fecal-oral contamination or internal autoinfection (reverse peristalsis). The hatched oncospheres cross the intestinal mucosa, enter the bloodstream, and encyst within musculature, ocular structures, or the central nervous system (NCC).

4. Pathogenesis and Organ Tropism

The clinical manifestations of metacestode infections depend on organ tropism, growth rate, and the host's immunopathological response.

4.1 Cystic Echinococcosis (Fluid-Driven Expansion)

Once an *E. granulosus* oncosphere reaches its target organ—principally the liver (70%) or lungs (20%)—it differentiates into a unilocular, fluid-filled hydatid cyst. The cyst wall consists of an outer acellular laminated layer and an inner nucleated germinal layer that buds off brood capsules containing protoscolices.

Pathogenesis is mechanical and immunological. Slowly expanding cysts compress parenchyma, bile ducts, or blood vessels, resulting in portal hypertension or cholestasis. Cyst rupture, whether spontaneous or traumatic, risks severe systemic consequences: the release of highly antigenic hydatid fluid can trigger profound anaphylactic shock and secondary dissemination, seeding the peritoneal or pleural cavities with hundreds of new metacestodes.

4.2 Alveolar Echinococcosis (Invasive, Tumor-Like Proliferation)

In contrast to the structured, unilocular growth of CE, *E. multilocularis* displays an entirely different pathogenic profile. The metacestode behaves like a malignant epithelial tumor. It exhibits continuous external budding of small, irregular vesicle structures that aggressively infiltrate the surrounding hepatic tissue.

The parasite lacks a limiting laminated membrane, allowing it to destroy tissue, provoke extensive granulomatous and necrotic reactions, and even metastasize hematogenously to distant organs like the lungs or brain. Left untreated, hepatic tissue is replaced by a hard, fibrous mass with a central necrotic cavity, carrying a high mortality rate.

4.3 Neurocysticercosis (Neuroinflammation and Seizure Dynamics)

The pathogenesis of *T. solium* cysticerci within the central nervous system is a dynamic process divided into distinct evolutionary stages:

Pathological Stage	Morphology	Host Immune Status	Clinical Presentation
Vesicular	Translucent membrane, viable invaginated scolex, minimal fluid.	Immune tolerance; minimal surrounding inflammation.	Often asymptomatic or presenting with mild, non-specific headaches.
Colloidal Vesicular	Cyst fluid becomes turbid; capsule thickens; scolex degenerates.	Intense acute inflammatory response against parasite antigens.	Focus for focal seizures, intracranial hypertension, and focal deficits.
Granular Nodular	Cyst collapses; replaced by granulomatous tissue.	Transitional phase; decreasing acute inflammation, increasing gliosis.	Persistent seizure activity due to chronic focal tissue irritation.
Calcified	Small, dense, mineralized scar node.	Burned-out infection; persistent astrocytic scar tissue.	Permanent epileptogenic focus; chronic recurrent seizures.

5. Modern Diagnostics and Diagnostic Limitations

Accurate identification of larval cestode infections remains a critical challenge in tropical medicine, largely because typical parasitological methods (like stool microscopy) cannot detect tissue-dwelling metacestodes.

5.1 Neuroimaging (The Gold Standard)

Definitive diagnosis of both CE and NCC relies on high-resolution imaging. Ultrasonography is the primary tool for abdominal CE, allowing clinicians to categorize cysts using the WHO Informal Working Group on Echinococcosis (WHO-IWGE) classification (from active CE1/CE2 to inactive CE4/CE5). For NCC, Computed Tomography (CT) and Magnetic Resonance Imaging (MRI) are indispensable for mapping parenchymal vs. subarachnoid involvement (Hamamoto Filho et al., 2022).

However, these advanced imaging modalities are frequently absent, non-functional, or cost-prohibitive in remote, rural endemic zones.

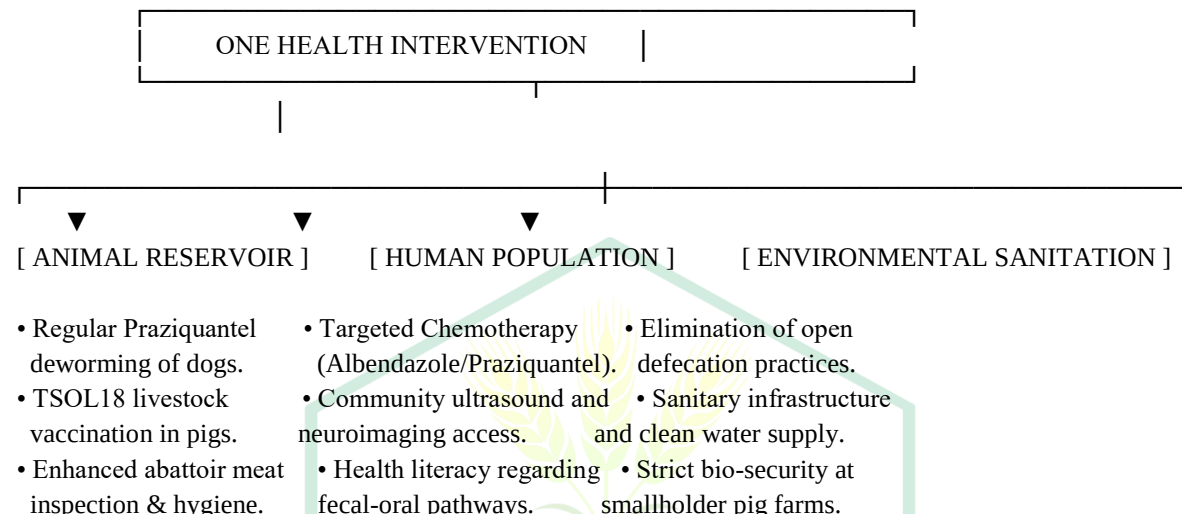
5.2 Immunodiagnosics and Recombinant Antigens

Serology serves as a crucial complementary tool. For echinococcosis, detecting IgG antibodies against crude hydatid fluid antigens is standard, though cross-reactivity with other helminths is a known issue. Advanced assays utilize purified or recombinant antigens (such as Antigen B or AgB) to boost specificity.

For cysticercosis, Enzyme-Linked Immunoelctrotransfer Blot (EBLOT) assays utilizing purified lentil lectin-purified glycoprotein antigens (LLGP) represent the serological benchmark, outperforming conventional ELISA platforms in establishing systemic exposure.

6. One Health Control and Elimination Strategies

Because these parasites circulate continuously between human hosts, domestic livestock, companion animals, and wildlife, eradication cannot be achieved through human medical management alone. Lasting control demands an integrated, intersectoral **One Health** framework.



6.1 Interventions in Definitive Host Reservoirs

The most direct method to break the transmission loop of *E. granulosus* is the systematic deworming of domestic dog populations using **praziquantel** (typically administered monthly or quarterly in hyper-endemic regions). Concurrently, public health campaigns must prevent dogs from accessing raw livestock offal by upgrading slaughterhouse infrastructure and expanding community education.

6.2 Livestock Vaccination and Control

For *T. solium*, remarkable progress has been achieved using a dual-action strategy in porcine reservoirs:

- **The TSOL18 Vaccine:** A highly effective recombinant antigen vaccine administered to young pigs to prevent oncosphere oncogenesis.
- **Oxfendazole Therapy:** Co-administered alongside vaccination to clear any pre-existing viable cysticerci from porcine muscle tissue.

When paired with investments in sanitary infrastructure to eliminate open defecation and enforce penned pig husbandry, these agricultural interventions have demonstrated the potential to eliminate regional transmission pockets. Sustaining these multidisciplinary frameworks over decades requires bridging institutional divides between human public health ministries and veterinary services—making larval cestode control the quintessential test of the One Health paradigm.

Sparganosis: Clinical and Epidemiological Overview

Sparganosis is a neglected waterborne and foodborne zoonosis caused by the migrating plerocercoid larva (**sparganum**) of diphylobothriidean tapeworms belonging to the genus ***Spirometra*** (principally *Spirometra erinaceieuropaei* and *Spirometra mansoni*). Unlike metacestodes that form static, fluid-filled bladders (e.g., cysticercosis), the sparganum is a solid, unsegmented, highly motile ribbon-like worm that causes mechanical destruction and intense eosinophilic inflammation as it tunnels through human tissue.

Transmission Dynamics and Life Cycle

The parasite cycles through definitive carnivore hosts (cats and dogs) and two distinct intermediate hosts (copepods and small vertebrates). Humans inadvertently interrupt this cycle as accidental, dead-end intermediate hosts via three discrete exposure pathways:

- **Waterborne Ingestion (Pathway 1):** Drinking stagnant water containing infected copepods (*Cyclops* spp.) harboring the first larval stage (**proceroid**).
- **Foodborne Ingestion (Pathway 2):** Eating raw or undercooked flesh of secondary intermediate or paratenic hosts—such as frogs, snakes, birds, or wild boars—containing the infective **plerocercoid** stage.
- **Medicinal Poulticing (Pathway 3):** Applying raw frog or snake flesh as traditional poultices to open wounds, ulcers, or eyes. The active larvae directly migrate from the animal tissue into human subdermal or conjunctival layers.

Clinical Pathologies and Organ Tropism

Secreted proteases allow the larva to resist digestion, cross the intestinal barrier, and survive for up to 20 years within host tissues.

- **Subcutaneous and Muscular:** The most frequent clinical manifestation. It presents as a slowly expanding, migratory, occasionally painful nodule—often on the chest wall, abdomen, or lower extremities—shielded by a chronic eosinophilic granuloma. Patients frequently report a distinct subcutaneous "crawling" sensation.
- **Ocular:** Highly destructive and closely tied to traditional poulticing. It triggers severe palpebral edema, lagophthalmos, exophthalmos, retrobulbar abscesses, and potential blindness if the larva penetrates the intraocular space.
- **Cerebral and Internal:** Occurs when larvae enter the central nervous system through the skull base foramina. Mimicking an expanding brain tumor or cerebrovascular accident, it causes localized eosinophilic meningitis, cerebral necrosis, and tract damage. Symptoms include intractable seizures, focal hemiparesis, localized aphasia, and cognitive decline (Liu et al., 2025). Rare systemic migrations can target the lungs, pericardium, or vertebral canal.

Diagnosis and Management Matrix

Diagnostic Modality	Key Clinical Indicators	Limitations / Challenges
Neuroimaging (CT / MRI)	Classic triad: advanced localized white matter degeneration, wandering/tunnel-like ring-enhancing lesions, and shifting lesion locations on sequential scans as the worm relocates (Gong et al., 2023).	Often misdiagnosed as high-grade gliomas or cerebral infarctions on initial presentation.
Serology (ELISA)	High sensitivity using purified or recombinant <i>Spirometra</i> plerocercoid excretory-secretory (ES) antigens.	Notable cross-reactivity with antibodies from <i>Taenia solium</i> and <i>Echinococcus</i> spp.
Histopathology	Identification of solid, unsegmented larvae featuring a characteristic thick tegument, calcareous corpuscles, and absent digestive tract within eosinophilic abscesses.	Confirmatory only post-biopsy or surgical extraction.

- **Definitive Treatment:** The therapeutic benchmark is **complete surgical extirpation** of the live larva. Intact removal is vital; tearing the worm risks localized regeneration or severe anaphylactoid responses driven by spilled parasitic antigens.
- **Chemotherapy:** High-dose **praziquantel** (50–75 mg/kg/day split across several days) is typically reserved for multi-focal, inoperable, or deep parenchymal cerebral presentations, though its standalone clearance efficacy remains variable.

Coenurosis: Clinical and Epidemiological Overview

Coenurosis is a rare, severe zoonotic infection caused by the metacestode (larval) stage of tapeworms in the genus *Taenia*, primarily *Taenia multiceps* and less frequently *Taenia serialis*, *Taenia brauni*, or *Taenia glomeratus*. While it is a critical veterinary condition in sheep and goats, accidental human infection leads to devastating space-occupying lesions in the central nervous system (CNS), eyes, or subcutaneous tissues.

Etiology and Lifecycle Dynamics

The transmission cycle relies strictly on predator-prey dynamics between carnivore definitive hosts and herbivore intermediate hosts:

- **Definitive Hosts:** Canids (dogs, foxes, wolves) harbor adult tapeworms in their small intestines, shedding microscopic, highly resilient embryonated eggs into the environment via feces.
- **Intermediate Hosts:** Sheep and goats serve as natural intermediate hosts for *T. multiceps* (neurocoenurosis), whereas rabbits and rodents serve for *T. serialis* (subcutaneous coenurosis).
- **The Metacestode (Coenurus):** Unlike a *Taenia solium* cysticercus (single scolex) or an *Echinococcus* hydatid cyst (producing internal daughter cysts), a **coenurus** is a fluid-filled, translucent, single-chambered bladder cyst containing **hundreds of invaginated protoscolices** clustered like white nodules along its inner germinal membrane.

Clinical Pathologies and Organ Tropism

Humans intersect this cycle as accidental, dead-end intermediate hosts via the fecal-oral route. Pathology depends entirely on the invading species:

A. Neurocoenurosis (*T. multiceps*)

Mirroring the disease in sheep (known as "gid" or "staggers" due to unstable, circling movements), the larvae cross the human intestinal mucosa, disseminate hematogenously, and exhibit an intense tropism for the CNS.

- **Pathogenesis:** Cysts act as slow-growing, space-occupying lesions causing compression of brain parenchyma, pressure atrophy, and obstruction of cerebrospinal fluid (CSF) flow, culminating in non-communicating **hydrocephalus**.
- **Symptoms:** Severe headaches, papilledema, projectile vomiting, ataxia, focal neurological deficits, and tonic-clonic seizures.

B. Extracranial and Ocular Coenurosis (*T. serialis* / *T. brauni*)

Oncospheres migrate to skeletal muscle, eyes, or subcutaneous planes.

- Subcutaneous presentations manifest as slowly enlarging, painless, fluctuant masses often clinically misidentified as lipomas, fibromas, or congenital anomalies (such as thyroglossal duct cysts).
- Ocular involvement impairs vision and triggers intense local tissue inflammation.

Diagnosis and Management Matrix

Diagnostic/Management Modality	Key Clinical Indicators & Efficacy	Crucial Clinical Caveats
Neuroimaging (CT / MRI)	Identifies thin-walled, non-enhancing or ring-enhancing cystic structures. High-resolution MRI may show multiple mural nodules (protoscolices) along the inner wall.	Must be differentiated from the single-scolex vesicular stage of <i>T. solium</i> or unilocular <i>Echinococcus</i> cysts.
Histopathology	Confirmatory diagnosis post-resection. Demonstrates a thin-walled cyst wall embedded with clustered protoscolices possessing diagnostic double rows of hooklets.	Imaging lacks pathognomonic specificity; definitive confirmation relies heavily on histopathology.
Surgical Excision	Primary curative intervention for accessible, symptomatic space-occupying larval masses. Total intact capsule removal is required.	Intraoperative cyst rupture must be strictly avoided to prevent severe localized anaphylactic shock or granulomatous inflammation.
Chemotherapy	Adjunctive or inoperable therapy using high-dose albendazole or praziquantel , frequently combined with corticosteroids.	Contraindicated in intraocular coenurosis ; parasite death inside the eye releases antigens that cause irreversible inflammatory blindness.

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