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Nanoparticle-based approaches for the control and management of fall armyworm (Spodoptera frugiperda)

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ABSTRACT

The fall armyworm, or *Spodoptera frugiperda*, is a serious crop pest that reduces crop yields significantly. Creating environmentally friendly and efficient fall armyworm (FAW) pest management techniques is essential for sustainable agriculture. In order to protect against these insects and maintain the nation's food security, pesticides are used indiscriminately. Nonetheless, as part of eco-friendly management, new methods for managing these insect pests have been introduced, with the usage of nanotechnology being promoted, due to the dangerous consequences of chemical pesticides. Nanotechnology plays a vital role in designing and preparing target-oriented and controlled-release pesticides. Chemical alteration is one way to accomplish this, and this new technology holds enormous promise for developing innovative formulas. This article explores the use of certain nanomaterials in the management of fall armyworm, emphasising their benefits, drawbacks, and how they work. It is possible to significantly increase crop protection and productivity by integrating nanotechnology into pest management methods.

INTRODUCTION

The Global menace, Fall armyworm **(***Spodoptera frugiperda)***:** *Spodoptera frugiperda* J.E. Smith (Lepidoptera), sometimes known as fall armyworm (FAW), is a major global pest of maize crops and a member of the Noctuidae family. After being discovered for the first time in America, this pest then moved to Asia-Pacific and Africa. It has grown to be a major worldwide concern since 2018 (Deshmukh *et al.,* 2021). Fall armyworms feed on wheat, maize, barley, cotton, soybeans, sorghum, and tomatoes. It results in significant crop losses, which have an impact on economies around the globe. Its favourite plant is maize, and it can reduce yields by 15–73%. It attacks the maize plant from the time it is a seedling until the beginning of ear growth. There are two types of FAW: the rice strain and the maize strain. The maize strain is more common and damages different areas of the crop, which is problematic for the farmer. (Sun *et al.,* 2021).

Common pesticides used to control FAW populations include organophosphates, carbamates, and pyrethroids. The two most important aspects influencing this control are the stage of development and the time of administration. However, the use of these chemicals has caused harm to the environment, stays in the environment, and causes pest resistance to chemical control; their applications are typically limited. As a result, scientists are currently concentrating on sustainable alternatives to the toxic pesticides that have been used for many years.

The use of nanotechnology in contemporary agriculture is a relatively new idea. In this context, monodisperse, analogous, and morphologically identical particles with diameters ranging from 10 to 100 nm are referred to as nanoparticles. When compared to other pesticides, their exceptional stability and great water solubility are noteworthy. Fortunately, in contrast to conventional chemical pesticides, nanoparticles do not provide health risks to the environment or the general public. Since nanoparticles typically penetrate plant cells, they transform into nanocarriers, which makes them effective at capturing pests.

Nano particles in action: Tracking their journey in fall armyworm management

Many attempts have been made to manage insects which provide effectiveness and are at the same time eco-friendly in nature. Nanoparticles have been widely used in modern agricultural pest management systems. Other advantages of the use of nanoparticle insecticides are the possibility of preparing formulations that contain insoluble compounds that can be more readily dispersed in solution. It reduces the problems associated with drifting and leaching, due to its solid nature, and leads to a more effective interaction with the target insect. These features enable the use of a smaller amount of active compound per area, as long as the formulation may provide an optimal concentration delivery for the target insecticide for longer times. Hence, nanotechnology can be applied in several ways in order to enhance the efficacy of insecticides in crops.

The NPs, zinc oxide (ZnO-NPs) and silicon dioxide (SiO_2-NPs) nanoparticles, caused visible damage such as a reduction in larvae body length, alterations in their morphology, especially in the dorsal and ventral regions because interfere with the developmental

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physiology of the insect and, at high concentrations, cause its mortality. Pink and dark spots, generalised malformations, body necrosis, and mummified bodies (death). The ZnO-NPs and SiO_2-NPs nanoparticles present an efficient and innovative solution for the control of *S. frugiperda*. (Ruiz-Aguilar *et al*., 2025). Exposure to ZnO NPs caused body deformities in all stages of the lifecycle from larvae to adults, body malformations instigated after the ingestion of baby corn dipped in ZnONPs (Pittarate *et al*., 2021). The study conducted by Mashood *et al.* (2021) concluded that green-synthesised ZnO nanoparticles can regulate the population of S. *frugiperda* by causing larval mortality and structural deformations, making it a promising tool in integrated pest management program.

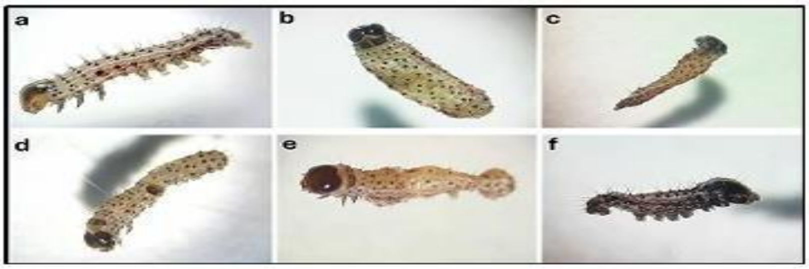

Fig. 1: Mortality of *S. frugiperda* on 2nd larval instar where (a) denotes control and (b) to (f) shows deformed larvae treated with different concentrations of SiNPs (Ruiz-Aguilar *et al*., 2025)

a) Control and malformed pupae

b) Control and malformed adult

Fig. 2: Deformities of pupal and adult stages of *S. frugiperda* on 2nd larval instar treated with green synthesized zinc oxide nanoparticles from *Calotropis procera* (Masood *et al*., 2024)

Advantages of Nanotechnology in pest management:

Because of their huge surface area, nanoparticles can interact with pests more effectively and deliver active chemicals to the target site exactly. Their efficacy can be extended and the frequency of applications decreased by engineering them for a delayed or stimuli-responsive release. Higher efficacy necessitates lower application rates, and nanoparticles can be engineered to cause less runoff or leaching and collateral damage to non-target species. At lesser dosages, nanoparticles can increase insecticides' ability to enter the bodies of pests and raise fatality rates.

Disadvantages of Nanotechnology in pest management:

There is still a chance of negative impacts on beneficial insects, birds, and aquatic life, even if some studies have shown that they are less toxic than traditional pesticides. As with traditional pesticides, there is a chance that pests will become resistant to nanopesticides. The cost of developing and implementing some nano-based pest control techniques can be high.

Conclusion

Nanotechnology plays a vital role in designing and preparing target-oriented and controlled-release pesticides in the modern agricultural pest management system. The use of nanoparticle insecticide formulations containing insoluble compounds can be more readily dispersed in solution, thereby reducing the drifting and leaching losses due to their solid nature, and leads to a more effective interaction with the target insect. These features enable the use of a smaller amount of active compound per area delivery for the target insecticide for longer times.

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NANOTECHNOLOGY: SHAPING THE FUTURE OF AGRICULTURE

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INTRODUCTION: NANOTECH AND THE HIDDEN WONDERS WITHIN NANOSCALE

Nanotechnology is a science, which deals with materials ranging from 1 to 100 nm, where matter exhibits distinct physio-chemical properties not observed in its larger bulk counterparts, opening the door to numerous novel application not only in agriculture but a wide spectrum of other scientific and industrial fields (Altammar 2023). Incorporating nanotechnology into agriculture has opened the way for efficient nutrient delivery, identification of plant pathogens, improved pest management and notable gains in overall crop productivity (Figure.1).

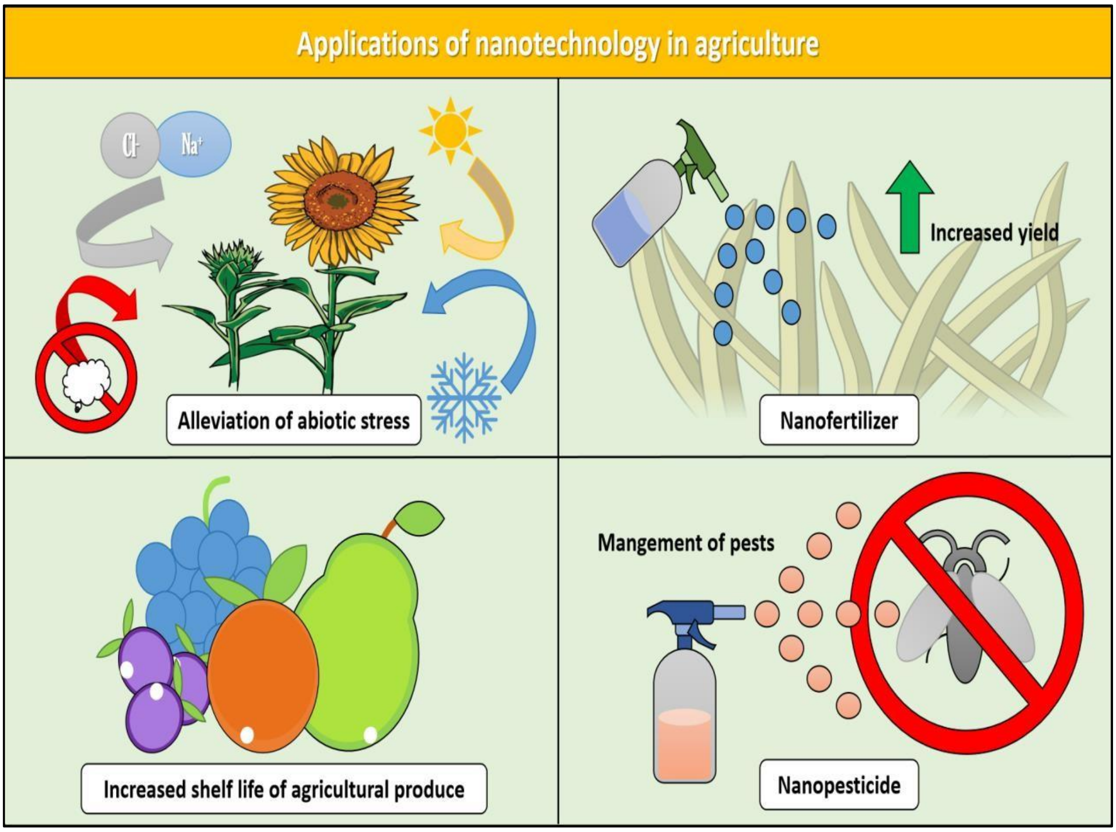

Figure. 1: Applications of nanotechnology in agriculture

1. APPLICATIONS IN AGRICULTURE

1.1 Nanofertilizers

Nanofertilizers out perform conventional fertilizer just as a crushed sugar cube dissolves faster due to its surface is exposed to water, nanofertilizers work better due their extremely small size and high surface area, allowing plants to absorb nutrients more readily with lesser losses as compared to conventional fertilizers as they are prone to leeching, volatilization and run off. Nanofertilizers offer controlled/slow release, high absorption efficiency, better yield, reduced losses and lower dosage requirement (Babu et al. 2022). Although nanofertilizers have not fully replaced conventional fertilizers, their combined use has exhibited reduced fertilizer dosage and significantly enhance crop yields, as reported by Kumar et al. (2020) (Table. 1).

Table.1: Comparative yield under Farmer's Fertilizer Practice (FPP) and Nano-N+ FPP-50% N

Sr. No.	Crop Name (No. Of trials)	FPP Mean yield (Kg/ha^{-1})	FPP-50% N + 2 spray's of Nano-N Mean yield (Kg/ha^{-1})	% Increase over FPP
1.	Wheat (431)	4,354	4,779	9.76
2.	Field pea (26)	2,092	2,270	8.50
3.	Lentil (5)	1,677	1,715	2.26
4.	Amaranthus (3)	2,626	2,927	11.45
5.	Mustard (44)	1,708	1,837	7.55
6.	Potato (127)	32,298	35,414	9.65
7.	Garden pea (12)	9,484	10,247	8.05
8.	Tomato (5)	30,354	35,534	17.07
9.	Cauliflower (4)	32,276	34,521	6.96

Source: Kumar et al. (2020)

1.2 Nanopesticides

Nanopesticides refer to formulations incorporating engineered materials or carriers operating within the nanometre range (1-200 nm). These nanoscale delivery systems-such as polymer-based nanoparticles, nanoemulsions, nanosuspensions, and inorganic metal or mineral nanostructures, offer improved solubility, greater stability, and more precise release of active ingredients than conventional products. By increasing the bioavailability and persistence of the active compounds and by promoting stronger adhesion to plant surfaces and targeted tissues, these formulations often achieve comparable or superior pest suppression at reduced application rates. Their controlled-release behaviour minimizes losses by photodegradation, runoff and spray drift, thereby reducing the overall environmental burden. By facilitating deeper penetration into pest tissues and enhancing the stability of biopesticidal agents. Taken together, these features renders nano-enabled formulations more efficient, sustainable and ecologically compatible options for crop protection within contemporary agricultural systems (Wang et al. 2022, Wei et al. 2025). Commercial nano-formulated pesticides have only recently entered agricultural markets. One example is Pilarquim's PILARTEP, released in early 2022 as a nano-suspension concentrate and among the first publicly marketed nano-enabled plant-protection products. According to the company claims, the nano-formulation exhibits roughly 3.15-fold faster crop absorption, greater active-ingredient uptake and longer residual activity than the conventional version. Field trials also show effective pest and disease control at 25-50% reduced application rates. These improvements are linked to smaller particle sizes (<600 nm), with some variants near 300 nm, which enhance surface area, dispersion, adhesion and rainfastness on plant surfaces. Parallelly, nano based sensors may also support early pest detection and treatment monitoring. Emerging nano-RNAi approaches add a anew route for targeted pest suppression, though further working on environmental and agricultural studies (Mathew et al. 2025).

1.3 Nanoparticles for managing abiotic stress and post harvest applications

Nanoparticles can alleviate stress induced by abiotic environmental factors such as drought, salinity and heavy metal stress, by improving nutrient availability, enhancing antioxidant activity and strengthening the physiological responses. By regulating various reactive oxygen species assisted mechanisms (Dilnawaz et al. 2023). Nanotechnology is also incorporated as edible films and coatings, that can be applied to fresh produce to protect it by reducing moisture loss, slowing respiration, maintaining texture and suppressing microbial growth. These nano based solutions serves as barriers to gas and moisture exchange, thereby extending the shelf life of processed foods. Pt/DMS (platinum-loaded dendritic mesoporous silica) was employed as an ethylene-scavenging material to extend the shelf life of *Musa nana* bananas, taking advantage of its characteristic central-to-radial pore architecture (Wei et al. 2023).

2. CHALLENGES OF NANOTECHNOLOGY

Several studies have reported clear evidence of nanoparticle-induced toxicity, underscoring the need for careful evaluation before widespread application. Nanotoxicity studies in agriculture remain limited and insisting evidence warns of potential risks to plants, animals, microbes and even human. Moreover, producing nanomaterials at large volumes with acceptable cost continues to be a major challenge (Pathak et al. 2020).

3. CONCLUSION

Nanotechnology is emerging as a transformative approach within agricultural systems, offering advanced strategies to optimize nutrient delivery, enhancing stress tolerance, pest management and over all crop performance. While certain limitations and safety concerns still require careful investigation, its contribution to sustainable and efficient farming practices is increasingly evident. With continued research and the development of safer, economically viable nano-based solutions, nanotechnology has the potential to modernize traditional agricultural knowledge with future ready practices.

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Use of Drones in Pesticide Application: Emerging Trends in Chhattisgarh

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Introduction

Rapid technological advancements over the past decade have significantly transformed agricultural practices, particularly in the domain of crop protection. Among these innovations, drones, also referred to as Unmanned Aerial Vehicles (UAVs), have emerged as a promising tool for precision agriculture. Initially developed for aerial surveillance and large-scale farm operations, drone technology has gradually evolved through miniaturization and cost reduction, making it increasingly accessible to small and marginal farmers. In India, systematic experimentation and field-level demonstrations of agricultural drones began around 2018, leading to broader institutional recognition. A major milestone was achieved in 2022 with the launch of the Kisan Drones Scheme by the Ministry of Agriculture and Farmers Welfare, which permitted drone-based spraying of registered agrochemicals under defined standard operating procedures. This marked a transition from experimental trials to regulated operational use.

Drone-assisted pesticide application addresses several persistent challenges in conventional agriculture, including labour shortages, rising costs of manual spraying, health hazards due to chemical exposure, uneven spray coverage, and excessive use of water and pesticides. Equipped with GPS, automated flight paths, and precision nozzles, drones enable uniform and targeted spraying while minimizing drift and resource wastage. Consequently, this technology aligns well with the principles of precision farming, environmental sustainability, and occupational safety. The present article reviews the applications, efficiency, and comparative advantages of drone-based pesticide spraying over manual methods, with particular emphasis on adoption status, regulatory frameworks, and recent initiatives in Chhattisgarh. By synthesizing research evidence and field experiences, the study highlights the transformative potential of drones in enhancing pest management and improving farm productivity.

Application of drones in agriculture:

- **Crop monitoring and Disease detection:** An efficient technique for estimating disease, pest infestation, nutrient deficiencies, and crop loss.
- **Field Mapping and Land survey:** Slow gradients, soil variation, and boundaries can all be found using GIS, mapping, elevation and water irrigation management, field boundary mapping, and 2D and 3D farmland maps. The design of drainage irrigation facilities and resource planning can both benefit greatly from this comprehensive information, which can also aid in land use management.
- **Crop Insurance and yield estimation:** The rapid survey after damages like flood, drought or pest outbreak helps the quick assessment for insurance.
- **Drones-as-service:** The facility is drawn as a service, according to the service model. They give small landowners access to financial and religious resources.

Comparison between manual and drone spray

Parameter	Manual Spraying	Drone Spraying
Time Required per Acre	4 to 6 hours	8 to 10 minutes
Labour Requirement	2 to 3 workers	1 trained operator
Health Risk	High (direct exposure to chemicals)	Very low (no direct exposure)
Chemical Efficiency	Significant wastage	Up to 30 per cent chemical savings
Application Rate	490 Liter/ha	27 Liter/ha
Field Capacity	0.08 ha/hour	4.04 ha/hour
Coverage Uniformity	Non-uniform and inconsistent	Highly uniform and precise
Terrain Adaptability	Limited (mainly flat areas)	Excellent (works in hilly and waterlogged fields)
Long-term Cost	Higher due to labour and inputs	Lower after initial investment
Water Usage	Very high	Reduced by up to 90 per cent
Precision Level	Low accuracy	High accuracy with GPS/AI integration

Status of drones in Chhattisgarh

In addition to raising awareness of drones across the country and their use in agriculture, Chhattisgarh has taken a number of significant steps to incorporate the new technology into the state.

- **MOU by IGKV, Raipur:** A memorandum of understanding was signed by the state's Indira Gandhi Krishi Vishwavidyalaya and the Catalyst Foundation to train farmers, students, and young people in drone operations. The local drone facilities were encouraged by this initiative.
- **Workshop boosts tech skills in Dhamtari:** A five-day hands-on drone training workshop was organised from July 7-11 (2025) at the Technology Village Centre, Sirri Village, Dhamtari district. The initiative aimed to introduce modern technology and practical skills to students from rural backgrounds. The International Institute of Information Technology, Naya Raipur (IIIT-NR) and Chhattisgarh Council of Science and Technology (CGCOST) jointly conducted the workshop.
- **Kisan Drone Yojana (Sub-Mission on Agricultural Mechanization-SMAM):** This scheme provides subsidies for drone purchases:
    - Small and marginal farmers, SC/ST, women, and North Eastern state farmers: Up to 50% subsidy (max ₹5 lakhs).
    - Other farmers: Up to 40% subsidy (max ₹4 lakhs).
    - Cooperative societies, FPOs, and rural entrepreneurs: Up to ₹4 lakhs for Custom Hiring Centres (CHCs).
    - Agricultural graduates establishing CHCs: Up to 50% subsidy (max ₹5 lakhs).
    - Institutions like ICAR, Krishi Vigyan Kendras (KVKs), and State Agricultural Universities: Up to ₹10 lakhs or 100% of drone cost.
- **NAMO Drone Didi Scheme:** In Rajnandgaon district, the village of Achholi in Dongargarh is showcasing a unique example of women's empowerment through agricultural innovation. This initiative empowers women's Self-Help Groups (SHGs) by providing drones at an 80% subsidy (up to ₹8 lakhs) and training for drone operation. In Chhattisgarh, this scheme is fostering rural entrepreneurship and women's economic empowerment.
- **Bank of India's Akashdoot Scheme:** Offers loans up to 85 per cent of drone cost (max ₹25 lakhs) for custom hiring activities, with a repayment period of 5 years and a 6-month moratorium.

These schemes are complemented by state-level efforts to establish drone service centers and provide free training through KVKs and agricultural colleges.

Beyond Farming: Public Services and Safety

- **Durg Police** have inducted advanced surveillance drones for crowd monitoring, traffic management, and disaster response, showcasing how drones can support public safety and smart policing.
- In forest areas such as the **Udanti-Sitanadi Tiger Reserve**, drones are aiding wildlife protection, helping staff monitor encroachments, forest health, and rapid response to emergencies like fires.

Regulatory Requirements

- All drones above 250 grams must be registered on India's Digital Sky Platform and display a Unique Identification Number (UIN).
- Drone pilots must follow airspace colour codes: green zones allow unrestricted flights, yellow zones require permissions, and red zones are no-fly areas.
- Anyone using drones for commercial purposes—including agriculture and pesticide spraying, must hold a Remote Pilot Certificate obtained by completing DGCA-approved training and exams.
- Violations such as unauthorized flights, operating in restricted areas, or flying unregistered drones can result in heavy penalties or confiscation.
- New laws, like the Civil Drone (Promotion and Regulation) Bill, 2025, allow the central and state governments to issue further rules, so local restrictions may also apply.

Future Recommendations

1. **Expand Agricultural Drone Integration:** Chhattisgarh's economy is deeply rooted in agriculture. Drones should be further integrated to enhance crop monitoring, precision spraying, and soil health assessment. Subsidized schemes and pilot programs can help farmers adopt drone services, especially smallholders who lack capital.
2. **Strengthen Regulatory and Policy Frameworks:** Clear, forward-looking policies will accelerate drone adoption while ensuring safe airspace usage, which includes local drone policy guidelines and data privacy laws.

3. **Boost Capacity Building and Skill Development:** To support the growing drone ecosystem, Chhattisgarh needs a skilled workforce, which includes training hubs and streamlined centres, Youth engagement programs, and upskilling for public servants.
4. **Promote Innovation and Local Manufacturing:** Supporting local innovation will reduce dependence on imports and strengthen the state's industrial base, which includes Innovation grants and incubators, supporting start-ups and Drone testing zones.
5. **Enhance Public Service and Emergency Applications:** Drones can significantly improve government service delivery and emergency management, which includes Disaster response and management, Healthcare logistics and Infrastructure monitoring.
6. **Foster Data Ecosystems and Analytics:** Drones generate vast amounts of data that can be transformed into actionable insights, which include Centralized data platforms and AI & geospatial tools.
7. **Raise Awareness and Public Engagement:** Building trust and understanding among citizens and stakeholders is crucial for the widespread adoption of awareness campaigns, success stories and other initiatives.

Conclusion

Drone technology represents a significant advancement in precision agriculture, offering clear benefits over manual pesticide spraying in terms of time efficiency, labour reduction, input savings, and operator safety. The growing adoption of agricultural drones in Chhattisgarh, supported by government schemes, institutional initiatives, and training programs, reflects the state's commitment to modernizing farm practices. While challenges related to cost, skills, and regulatory compliance remain, continued policy support, localized research, and service-based models can accelerate adoption. Overall, drone-assisted spraying has strong potential to enhance pest management efficiency, improve farm productivity, and support sustainable agricultural development in Chhattisgarh.

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FORMATION AND STRENGTHENING OF FARMER PRODUCER ORGANIZATIONS (FPOS): A PATHWAY TO EMPOWERING SMALL AND MARGINAL FARMERS

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Introduction

Agriculture in India is dominated by small and marginal farmers who face multiple constraints such as low productivity, high input costs, limited access to technology and weak bargaining power in markets. To overcome these challenges, Farmer Producer Organizations (FPOs) have emerged as a sustainable institutional mechanism. A FPO is a collective of farmers registered as a legal entity, enabling them to act as producers, aggregators, processors and marketers. By collectivizing, farmers can enhance their economies of scale, reduce risks and strengthen their bargaining power.

Concept and Legal Framework of FPOs

FPOs are generally registered under the following legal frameworks: Companies Act, 2013 (Producer Company provisions), State Cooperative Societies Act, Mutual Benefit Societies Act and Societies Registration Act, 1860.

The Producer Company model is the most common, as it provides flexibility of a private company while protecting farmers' ownership and control. This model balances social objectives with commercial orientation, making it suitable for agricultural enterprises.

Formation Process of FPOs

The formation of an FPO can be broadly classified into the following steps:

1) Awareness creation and mobilization of farmers:
   Farmers need to be sensitized about the advantages of collective action through meetings, campaigns and demonstrations. Mobilization of farmers into smaller Farmer Interest Groups (FIGs) to encourage collective participation.

2) Cluster and Commodity Focus :

   A core group of progressive and motivated farmers is then identified to act as promoters and lead the initiative. Select a cluster based on homogeneity of crops, livestock or allied enterprises.

3) Registration of FPO :

   Once the cluster and focus commodities are finalized, the FPO moves toward legal registration. This involves drafting the Memorandum of Association (MoA) and Articles of Association (AoA) that define the objectives, structure and governance mechanisms of the organization. The FPO is then registered under the appropriate legal framework, most commonly under the Companies Act, 2013, as a Producer Company. After registration, the organization opens a bank account in its name to facilitate financial transactions and ensure transparency in operations.

4) Business Plan Preparation :

   Preparation of a comprehensive business plan is a crucial step. This plan outlines both short-term (1–2 years) and long-term (5–7 years) goals, focusing on key areas such as input procurement, value addition, marketing and financial sustainability. The business plan serves as a roadmap for the FPO's growth and helps in attracting support from financial institutions and government schemes.

Strengthening of FPOs

For strengthening of FPOs involves continuous capacity building, institutional development, financial mobilization and business diversification.

- Capacity building includes conducting training programs on governance, leadership, financial management, record keeping and digital literacy to empower the members and board of directors. Exposure visits to successful FPOs are also arranged to help members understand best practices and gain confidence in managing their own organization.
- Institutional strengthening is achieved by forming a Board of Directors (BoD) and sub-committees responsible for specific functions such as finance, marketing and operations. A Chief Executive Officer (CEO) is appointed to manage day-to-day affairs, while regular meetings are conducted to ensure transparency and accountability in decision-making.
- Financial strengthening is another critical aspect, which involves mobilizing share capital from members and leveraging government schemes such as the Small Farmers Agribusiness Consortium (SFAC) Equity Grant Scheme, which provides financial

assistance of up to ₹15 lakh. Additionally, the Credit Guarantee Fund enables FPOs to obtain collateral-free loans from banks, thereby improving access to credit.

- For business development, FPOs focus on providing essential services to their members, such as the supply of quality inputs like seeds, fertilizers, and equipment at lower costs through bulk purchasing. They also engage in collective marketing by aggregating produce, grading and selling directly to markets or processors to secure better prices. Many FPOs also venture into value addition by establishing processing units, branding and packaging their products to enhance profitability. The integration of Information and Communication Technology (ICT) tools further helps in accessing real-time weather information, market prices and digital record-keeping, which improve efficiency and decision-making.

Government Support Mechanisms

Government support plays a pivotal role in the success of FPOs.

- The Central Sector Scheme for the Formation and Promotion of 10,000 FPOs (2020–2024) with a total budget of ₹6,865 crore has been a major initiative in this direction.
- Implemented through agencies such as NABARD, SFAC and NCDC, this scheme provides financial, technical and institutional support.
- Cluster Based Business Organizations (CBBOs) are appointed to provide handholding support to FPOs for five years, ensuring that they become self-reliant and sustainable.
- Schemes like the Equity Grant and Credit Guarantee Fund strengthen the financial base of FPOs, while digital initiatives such as e-NAM connect them to broader markets.

Benefits of FPOs

- Help to reduce input costs through bulk purchasing of seeds, fertilizers and equipment, allowing farmers to buy at lower prices.
- By selling produce collectively, farmers can eliminate middlemen and get better prices, leading to increased income and stronger bargaining power.
- Enable farmers to access institutional credit and government subsidies more easily since they are registered entities recognized by financial institutions.
- Promotes value addition by engaging in processing, grading, packaging and branding of agricultural produce, which helps increase profit margins.
- Also encourage entrepreneurship among rural communities by developing managerial and marketing skills among their members.

- Empower women and youth by providing leadership roles, training and employment opportunities within the organization.

Challenges and Strategies

- Low farmer participation, as many farmers lack awareness or trust in collective organizations. To overcome this, it is important to build trust through transparent operations and by demonstrating quick, tangible benefits to members.
- Weak governance which can lead to poor decision-making and internal conflicts. This can be addressed by organizing regular training programs, ensuring democratic elections and maintaining accountability in all operations.
- Limited financial resources often restrict FPO activities and growth. To solve this, FPOs should leverage government grants, bank loans and CSR funding and encourage members to contribute equity capital.
- Market risks such as fluctuating prices and competition from traders can also affect profitability. These can be mitigated by entering forward contracts, diversifying crops and investing in value addition through processing and packaging.
- A lack of professionalism in management is another common issue, as many FPOs are managed by individuals without business experience. Hiring trained managers and linking with Cluster Based Business Organizations (CBBOs) can improve efficiency and provide technical guidance.

Case Studies

1. Groundnut FPO, Ananthapuramu: Reduced seed costs by 20% and marketed groundnut oil collectively.
2. Turmeric FPO, Nizamabad: Established processing plant, branded turmeric powder and initiated exports.

Conclusion

The formation and strengthening of FPOs is a transformative approach to empower smallholder farmers in India. By collectivizing, farmers can overcome structural constraints in agriculture and integrate with modern value chains. For sustainability, FPOs must be nurtured with continuous training, financial support, transparent governance and market linkages. Strong institutional support is essential to ensure that FPOs evolve from nascent groups to vibrant agribusiness enterprises.

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Kouna for Climate Resilience and Rural Livelihoods in Northeast India

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Introduction

Northeast India is becoming increasingly susceptible to climate extremes, including frequent flooding and extended waterlogging, which collectively reduce land productivity and endanger rural livelihoods. In this context, nature-based solutions provide sustainable approaches to climate adaptation, and Kouna has emerged as a promising yet underutilised resource for enhancing both climate resilience and livelihood opportunities. Club rush or water rush, is locally called Kauna in Manipur and belongs to the family Cyperaceae, genus *Schoenoplectus*, with the species *Schoenoplectus lacustris* (Linn.) Palla. It is an aquatic, terete herb that thrives in wetlands and waterlogged environments, and is valued for its strong, flexible stems, which are traditionally used in weaving and handicraft production. Kauna is a native, eco-friendly reed of Manipur, widely utilised to craft durable mats, baskets, and furniture, contributing to both income generation and cultural preservation. The species is particularly appreciated for its moisture resistance and long service life (Monsang and Meeyo, 2023). Although Kouna is locally abundant and holds considerable ecological and livelihood potential, its applications remain largely confined to traditional uses, indicating a need for greater exploration and value addition (Sougaijam et al., 2025).

Kouna, often considered weeds in wetlands, represent a **hidden green economy** for Northeast India. Their ability to thrive in extreme hydrological conditions makes them ideal for reclaiming degraded floodplains and drought-stressed lowlands. When integrated with community enterprises—such as fibre crafts, biochar production, and organic soil amendments—Kouna converts ecological restoration into **sustainable income streams**. This approach supports rural livelihoods while preserving wetland biodiversity, offering a scalable model for climate adaptation and rural entrepreneurship.

Fig. 1: Kouna (*Schoenoplectus lacustris*) produtcs

Uses and Benefits of Water Rush (Kouna)

Water rush, locally known as Kouna or Kauna in Manipur, is a multipurpose wetland plant that offers significant ecological, economic, and socio-cultural benefits. Its utilisation is closely linked with nature-based solutions, especially in flood- and waterlogging-prone regions of Northeast India.

Uses

1. **Handicrafts and Weaving:** The most prominent use of Kouna is in traditional weaving. Its long, soft, and flexible yet strong stems are used to produce mats, baskets, bags, cushions, furniture, window blinds, and other utility and decorative items. Indigenous communities, such as the Meitei, have refined these skills over generations, making Kouna weaving a vital traditional craft (Monsang and Meeyo, 2023).

2. **Eco-friendly Interior and Lifestyle Products:** Kouna-based products are increasingly recognised as sustainable alternatives to plastic and synthetic materials in home decor and lifestyle applications. Their natural appearance, durability, and moisture resistance make them suitable for nature-friendly interior design and sustainable living products (Sougaijam et al., 2025).

3. **Livelihood and Income Generation:** Cultivation, harvesting, processing, and weaving of Kouna provide employment opportunities, particularly for rural and wetland-dependent communities. The plant requires minimal investment for cultivation and for setting up infrastructure to manufacture its diverse artistic products, yet it offers high profitability. Once established, it can remain productive for over 30–35 years with proper maintenance and can be harvested three times a year (Singh, 2016). Women

artisans play a central role in Kouna-based enterprises, making it an important resource for gender-inclusive livelihood development (Monsang and Meeyo, 2023).

4. **Utilisation of Marginal and Wetland Areas:** Kouna grows well in wetlands, marshes, and waterlogged fields where conventional crops cannot be cultivated. Its use enables productive utilisation of such marginal lands, converting climate-stressed ecosystems into income-generating landscapes.

5. **Cultural and Traditional Significance:** Beyond economic value, Kouna holds cultural importance in Manipur. Traditional weaving patterns, community knowledge, and craft practices linked to Kouna contribute to the preservation of indigenous heritage and identity, utilising traditional weave patterns such as Nga Maku, Jali, Lei Mayek, Chuthek Mayek, Binni Mayek, Chumsha Mayek, and Faklong (Param Mayek) (Sougaijam et al., 2025). Kouna grass products are increasingly popular due to their eco-friendly nature, unique aesthetics, and durability. Crafted through a traditional, labour-intensive weaving process passed down through generations, their production involves harvesting, cleaning, drying, and skilful weaving of locally sourced, renewable grass.

Benefits

1. **Climate Resilience and Adaptation:** As an aquatic plant, Kouna thrives under flooded and waterlogged conditions, making it highly suitable for regions increasingly affected by floods and erratic rainfall (Singh, 2016). Its cultivation supports climate-resilient livelihoods by providing an adaptive crop option in vulnerable ecosystems. In flood-affected areas, it can reclaim waterlogged lands by gradually improving soil structure and organic matter content. Their biomass contributes to carbon sequestration and enhances soil fertility when managed properly. Over time, it can transform unproductive wetlands into ecologically functional landscapes, suitable for integrated farming or agro-ecological interventions.

2. **Environmental and Ecosystem Benefits:** Kouna contributes to wetland ecosystem health by stabilising soil, reducing erosion, and supporting aquatic biodiversity. Wetlands dominated by Cyperaceae species play an important role in nutrient cycling and water purification, thereby enhancing ecosystem services. They act as natural biofilters, absorbing excess nutrients and pollutants, thereby improving water quality

in flood-prone landscapes. In drought-prone lowlands, it can help retain moisture and restore degraded soils.

6. **Sustainability and Low Environmental Footprint:** Kouna is a renewable, biodegradable, and low-input resource. Its production requires minimal external inputs such as fertilisers or pesticides, aligning well with sustainable and nature-based development approaches. These products are sustainable, generate no waste, and have a minimal carbon footprint, making them an environmentally responsible and long-lasting choice.

3. **Economic Empowerment and Rural Development:** It offers a wide range of livelihood opportunities for rural and tribal communities through its multipurpose use. The leaves and stems are traditionally used for handicrafts and mat weaving, providing a steady source of income for local artisans. Dried cattail biomass can be utilised for bioenergy and biochar production, supporting waste-to-wealth initiatives and renewable energy generation. Additionally, it can serve as an effective animal bedding material and can be converted into compost to enhance soil fertility. The fibrous nature of the plant also makes it suitable for paper pulp and other fibre-based products. Collectively, these activities are well suited to women-led enterprises, self-help groups, and community-based micro-industries, promoting inclusive, sustainable, and locally driven economic development. Value addition through handicraft production enhances income levels and strengthens local value chains (Sougaijam et al., 2025).

4. **Durability and Functional Advantages:** Kouna products are naturally moisture-resistant, lightweight, and long-lasting. These properties make them suitable for daily household use, especially in humid and flood-prone regions where synthetic materials often degrade quickly.

Fig 2: Kouna basket in the market (Source: https://www.makonhome.com/shop)

5. **Climate Resilience and SDG Linkages:** Kouna-based systems strengthen the adaptive capacity of communities facing climate risks such as flooding and land degradation, while simultaneously contributing to multiple Sustainable Development Goals. By generating income and diversifying livelihoods, they help alleviate poverty (SDG 1: No Poverty) and promote inclusive, community-based employment opportunities (SDG 8: Decent Work and Economic Growth). Their role as nature-based solutions enhances resilience to climate variability and supports mitigation and adaptation efforts (SDG 13: Climate Action). In addition, Kouna cultivation and utilisation aid in wetland conservation, biodiversity support, and sustainable land use, thereby contributing to ecosystem protection and restoration (SDG 15: Life on Land).

Conclusion

Kouna offer a range of benefits that make it a valuable resource for sustainable living, income generation, and climate adaptation. From food to biofuel to water purification, these versatile plants have much to offer in terms of environmental and economic sustainability. By harnessing the potential of Kouna, people can improve their livelihoods while also promoting the health of wetland ecosystems and the circular green economy.

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APPLICATIONS OF NANOFERTILIZERS IN AGRICULTURAL AND HORTICULTURAL CROPS

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Nanofertilizers

Nanofertilizers are synthesized or modified form of traditional fertilizers, fertilizers bulk materials or extracted from different vegetative or reproductive parts of the plant by different chemical, physical, mechanical, or biological methods with the use of Nano technological tools used to improve soil fertility, productivity and quality of agricultural produces.

Applications of nanofertilizers in agriculture:

Nanofertilizers have been classified into three groups

1. Nanoformulation of micronutrients.
2. Nanoformulation of macronutrients.
3. Biofertilizers Based nanofertilizers

Macronutrient-Based Nanofertilizers

Nanofertilizer formulations and found a consistent increase in growth, yield, quality, and nutrient uptake in crop with respect to conventional urea. Nanohydroxyapatite-based fertilizer with respect to regular P fertilizers. The use of hydroxyapatite NPs led to enhanced plant growth parameters, chemical contents, and anticancer activity of leaves in comparison to different sources of P Nanofertilizers. Nano-K was most effective in increasing the leaf area, grain yield, biological yield, harvest index, potassium percentage, and chlorophyll content, disease and pest resistance, and drought tolerance owing to improved nutrient absorption.

Micronutrient-Based Nanofertilizers:

Iron chelate nanofertilizer is highly stable and provides slow release of iron in a broad pH range. Iron nanofertilizer significant increase in growth parameters, photosynthetic pigments, and total protein contents. Application of zinc nanofertilizers to plants can be accomplished by various methods such as by soil mixing, foliar spray, and/or seed-priming method. Out of these, the seed-priming method is simple, more efficient, and cost effective. Improvement in stress tolerance in wheat was achieved with the employment of Copper nanofertilizers. A substantial increase in root length, height, fresh and dry weights of pigeon pea seedlings was noticed when treated with biogenic Cu nanofertilizers having 20 nm size. Molybdenum nanofertilizers solution as a micronutrient source of Mo for chickpea and reported that application of Mo nanofertilizers intact or in combination with microbial treatment had the potential to improve the yield, performance, and disease resistance of legume as well as other crop species **(Amin, A. M *et al.,* 2020).**

Biofertilizers-Based Nanofertilizers:

The nanoscale formulation of a biofertilizer conferring structural protection to biofertilizer nutrients and plant-growth-promoting bacteria, via nanoencapsulation-mediated coating of nanoscale polymers. The nanoencapsulation approach could be used as a dynamic mechanism to elongate the structural protection of being delivered biofertilizer, enhance its chemical shelf life and dispersion in fertilizer formulation, allowing a controlled release.

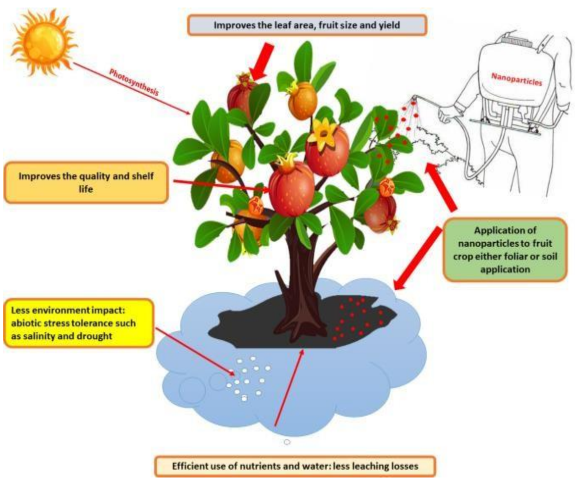
Advantages of Nanofertilizers over Conventional Chemical Fertilizers

The advantages of nanofertilizers include their high nutrient concentration, slow release of nutrients, and improved plant uptake. Nanofertilizers can also enhance the physical and chemical properties of soils, and their use can help to reduce fertilizer use and the environmental impacts of agriculture **(Babu, S *et al.,* 2022).** Nanofertilizers boast high nutrient concentrations, enabling lower application rates than their traditional counterparts. As a result, fertilizer costs can be reduced, and the associated environmental impacts from production and transportation are mitigated. Slow-release nanofertilizers can provide a steady supply of nutrients to plants over an extended period, improving plant growth and yield. Improved uptake of nutrients by plants can lead to increased growth and yield and reduced nutrient losses to the environment. Nanofertilizers can help improve fertilizer efficiency, and their use can reduce the overall environmental impact.

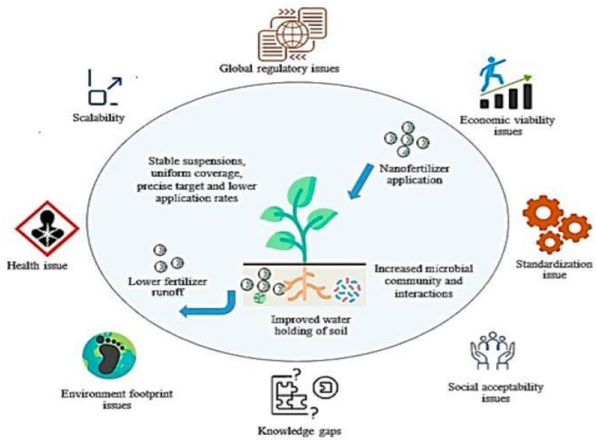
Application of nanofertilizer in horticultural crops

Foliar spray of nanofertilizers, nano-Zn and nano-B on pomegranate (cultivar Ardestani) led to increase in pomegranate fruit yield, fruit quality, including T.S.S., maturity index, juice and deceases in total acidity. Spraying mango trees with nano-zinc at 1 mg/L before flowering improved yield and fruit quality as well as raised resistance of malformation. Maximum proliferation was observed in 100 mg/L of enriched nano chelated iron wherein the growth of shoots, leaves and nodes increased showing that it can be used for increasing plant growth. Ca nano based fertilizers increased foliage development and chlorophyll content in vines.

Apple cultivars Red Delicious, Golden Delicious and Starking Delicious potted plants were given nano biofertilizer at 1 g/pot and dosage had greater impact on growth of apple plants. Treatment of Bitter almond seeds with nanofertilizers improved seed germination by 50 % at younger stages compared to chemical fertilizer treatment. It was observed that best yield, improved berry colouration and highest quality fruits were obtained when the vine was treated with amino mineral nanofertilizer at 0.1 %. Application of nutrients and injection of nano NPK fertilizers improved vegetative growth and increased yield of date palm **(Basavegowda, N. and Baek, K.H. 2021)**



Application of nanofertilizer in horticultural crops



Advantages of nanofertilizer application in the field

Conclusion

The scientific essence of nano fertilizers is to boost agricultural outputs, characterized by correct selection and uniform dispersal of seeds, thorough irrigation and adequate as well as regulated use of fertilizers. Several factors determine this phenomenon, including soil type, chemical combination with other nutrients, leaching effect, and uptake efficiency of plants. Nano biofertilizers hold a great potential to boost the agricultural output at the desired rate when used in optimum concentrations while overcoming the limitations of conventional fertilizers.

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The Soil-Water Connection: Managing Moisture for Better Crops

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Introduction

Soil and water form the foundation of all agricultural production. The ability of soil to capture, store, and supply water directly determines how well crops grow, resist stress, and produce yield. When soil moisture is balanced, plants receive the water and nutrients they need for healthy growth. However, too little moisture causes drought stress, while excess water limits aeration and root development. As climate variability increases and water resources become more limited (Pinke *et al.,* 2022), understanding the soil–water relationship has become essential for farmers, researchers, and extension workers. Effective soil moisture management not only improves crop performance but also enhances water-use efficiency, making it a key strategy for sustainable agriculture.

Why Soil Water Matters

Water in the soil performs three critical functions simultaneously: it supplies plants with water lost through transpiration, dissolves and transports nutrients to roots, and shapes soil physical structure and biological activity. When soil moisture remains within a crop's optimal range, photosynthesis and nutrient uptake proceed efficiently; when moisture is too low or too high, growth is constrained and yields decline. Understanding how much water a soil can store and when that water is available to plants is therefore central to crop management (Allen *et al.,* 1998).

The Basics: Retention, Infiltration, and Movement

Three fundamental physical processes determine how water behaves in soil.

Soil Water Retention

Different soils retain different amounts of water at varying tensions. The relationship between soil water content and matric potential, represented by the soil-water retention curve, defines key thresholds such as field capacity and permanent wilting point. Mathematical formulations such as the van Genuchten model are widely used to describe this relationship and predict plant-available water (Ghanbarian-Alavijeh *et al.,* 2010).

Infiltration and Percolation

Water must first infiltrate the soil surface following rainfall or irrigation. Infiltration rates depend strongly on soil texture and structure: sandy soils allow rapid infiltration but retain less water, while clay soils infiltrate more slowly yet store more water. Surface crusting and compaction can severely reduce infiltration, whereas good aggregation and organic matter improve water entry and reduce runoff (USDA NRCS, Infiltration Fact Sheet).

Hydraulic Movement and Redistribution

Once water enters the soil, it moves through gravity and capillary forces. In coarse-textured soils, water drains rapidly downward, whereas in fine-textured soils capillary forces redistribute moisture laterally and upward. Root systems and soil heterogeneity further modify these patterns, making localized monitoring and management essential.

How Much Water Do Crops Need?

Crop water requirements are commonly estimated using evapotranspiration (ET), which combines evaporation from the soil surface and transpiration from plants, along with crop coefficients that adjust reference ET to specific crops and growth stages. International guidelines such as FAO Irrigation and Drainage Paper No. 56 provide standardized methods for estimating ET and converting it into irrigation schedules (Allen *et al.,* 1998; FAO, 1977). Proper irrigation planning aligns water supply with crop demand and minimizes waste.

Practical Soil Moisture Management Techniques

No single approach suits all farms, but several well-established practices help maintain soil moisture within an optimal range.

Improve Soil Organic Matter

Incorporating composts, manures, and cover crops increases soil organic matter, improving aggregation and water-holding capacity. Higher organic matter allows soils to store more water during wet periods and release it slowly during dry spells, enhancing crop resilience (Pinke *et al.,* 2022).

Mulching and Surface Covers

Mulches and crop residues reduce evaporation, moderate soil temperature, and protect surface structure. These practices are especially beneficial in semi-arid and irrigated systems, where evaporation losses can be substantial (FAO, 1977).

Conservation Tillage and Reduced Disturbance

Reduced tillage preserves soil pore networks and surface residues that enhance infiltration and moisture retention. Long-term studies show that conservation tillage systems often maintain higher soil moisture than conventional tillage (USDA NRCS).

Irrigation Scheduling and Matching Method to Need

Modern irrigation management emphasizes scheduling based on crop growth stage, recent weather conditions, and soil moisture status rather than fixed calendars. Both ET-based scheduling and soil moisture–based scheduling can substantially improve water productivity when properly implemented (Allen *et al.,* 1998; Ebstu *et al.,* 2025; Kumar *et al.,* 2025).

Deficit Irrigation and Stage-Targeted Watering

For some crops, applying less than full water requirements during non-critical growth stages while ensuring adequate water during sensitive stages such as flowering can conserve water without major yield penalties. This strategy requires detailed knowledge of crop sensitivity (FAO, 1977; Allen *et al.,* 1998).

Physical Soil Amendments and Structure Management

Amendments such as gypsum improve infiltration in sodic soils, while deep ripping or subsoiling can alleviate compaction. Raised beds and furrows help direct water into the active root zone, increasing irrigation efficiency (USDA NRCS).

Technology: Sensors, Models, and Precision Irrigation

Soil moisture monitoring tools now range from simple tensiometers to capacitance probes and wireless IoT-based sensor networks. These technologies allow real-time tracking of soil moisture and enable automated or decision-supported irrigation. Recent reviews demonstrate that sensor-based irrigation scheduling often outperforms calendar-based approaches in terms of water savings and yield stability, particularly when sensors are calibrated to local soil conditions (Ebstu *et al.,* 2025; Kumar *et al.,* 2025).

Decision-support models and smartphone applications that integrate weather data, crop coefficients, and soil properties are increasingly accessible to farmers and extension systems, translating measurements into actionable irrigation advice.

Soil Texture and Crop Selection: Work with What You Have

Soil texture imposes physical limits on water management. Sandy soils require frequent, small irrigations and benefit greatly from organic matter additions, whereas clay soils require careful management to prevent surface sealing and poor drainage. Matching crop species and varieties to soil water dynamics is a practical and cost-effective strategy (FAO, 1977; Allen *et al.,* 1998).

The Yield Connection: How Soil Moisture Translates to Production

Research consistently shows a strong, often nonlinear relationship between soil moisture and crop yield. Water deficits during sensitive growth stages can sharply reduce yields, whereas modest deficits during tolerant stages may have minimal impact. Improved irrigation timing, moisture-conserving soil practices, and crop varieties adapted to local moisture regimes increase water productivity, defined as yield per unit of water used (Pinke *et al.,* 2022).

Climate Change and Uncertainty: Why Soil Water Resilience Matters

As rainfall variability and extreme events increase, soils that store and gradually release water provide critical buffering against droughts and intense rainfall (Pinke *et al.,* 2022). Building soil resilience through organic matter enhancement, improved structure, and surface protection is therefore a climate-smart investment that supports both short-term productivity and long-term sustainability.

Practical Checklist for Farmers and Extension Workers

- Know your soil through texture and organic matter testing to estimate available water capacity.
- Time irrigation to crop growth stages, avoiding stress during flowering and fruit set.
- Build soil organic matter with cover crops and composts.
- Protect the soil surface with mulches and residues.
- Match irrigation method and frequency to soil texture.
- Use FAO guidelines and local extension advice, and calibrate sensors for local conditions.

Conclusion

The soil–water connection is simple in principle but complex in practice. Small improvements—such as increasing organic matter, adopting sensor-based irrigation, or refining irrigation timing—can deliver substantial gains in yield and water savings. Farmers who understand their soils and integrate traditional knowledge with modern monitoring tools achieve both higher productivity and more efficient water use. In an era of growing water scarcity and climate uncertainty, effective soil moisture management is both sound agronomy and responsible stewardship.

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What Drones Are Teaching Us About Insect Pests in Crop Fields

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Abstract

Drones are reshaping pest detection and management by offering rapid, high-resolution imaging, multispectral and thermal sensing, automated trapping and precision spraying. These tools reveal pest hotspots, early damage and microclimate conditions driving outbreaks. With machine learning and cloud analytics, drone imagery becomes actionable risk maps that guide targeted interventions. This review summarises advances in platforms, sensors, data processing, and practical applications in surveillance and control, including developments in India. It also highlights the benefits, limitations, and priorities for scaling drone-enabled pest management in smallholder and commercial systems, showing that drones accelerate detection, support site-specific control, and integrate well with precision agriculture.

Introduction

Agricultural pest management has long depended on field scouting and reactive spraying, which often miss early and patchy infestations and limit subfield prioritization. Unmanned aerial vehicles (UAVs), commonly referred to as drones, now provide fast, repeatable and high-resolution coverage of large areas at far lower cost than manned aircraft or intensive ground surveys (Alsadik *et al.,* 2024; Guebsi *et al.,* 2024).

Equipped with RGB, multispectral, hyperspectral and thermal sensors, drones can capture early stress signals and damage patterns associated with insect feeding or vector-borne diseases. Advances in machine learning and deep learning have enabled near-real-time conversion of UAV imagery into pest hotspot and risk maps (*Zhu et al., 2024*), supporting threshold-based and site-specific interventions rather than blanket pesticide applications. These advantages have been widely reported across diverse crops and pest systems (*Guebsi et al., 2024*).

Beyond detection, drones also support active pest control. Experimental and commercial trials demonstrate their ability to spray liquids or granules, deploy pheromone formulations and release biological control agents with high spatial precision (*Subramanian, 2021; Talaeizadeh et al., 2025*). In India, the development of standard operating procedures (SOPs) and regulatory guidelines has further supported the safe adoption of agricultural spraying drones.

Drone Platforms and Sensors for Pest Work

Agricultural pest management primarily employs two types of UAV platforms: multirotor drones and fixed-wing drones. Multirotor drones provide stable hovering, fine waypoint control and high positional accuracy, making them suitable for detailed imaging and targeted spraying. Fixed-wing drones, in contrast, offer longer endurance and are better suited for surveying large agricultural landscapes (*Guebsi et al., 2024*).

RGB Cameras

High-resolution RGB imagery is widely used for visual scouting, damage assessment and the generation of orthomosaics and three-dimensional canopy models. When combined with expert rules or convolutional neural networks, RGB imagery can detect defoliation, discolouration, and canopy gaps associated with insect pest damage (*Zhu et al., 2024*).

Multispectral Sensors

Multispectral sensors capture reflectance in visible and near-infrared bands, enabling the calculation of vegetation indices such as NDVI and red-edge indices. Pest feeding and early disease symptoms often produce characteristic spectral changes that can be detected before visible damage appears (*Alsadik et al., 2024*).

Thermal Cameras

Thermal sensors identify canopy temperature anomalies caused by altered transpiration and physiological stress due to insect or pathogen attack. When combined with multispectral data, thermal imaging helps distinguish pest-induced stress from water or nutrient stress (*Alsadik et al., 2024*).

Hyperspectral Sensors

Hyperspectral imaging provides fine spectral resolution, allowing detection of subtle biochemical changes associated with pest or pathogen infestation. Although UAV-mounted hyperspectral sensors remain costly and operationally complex, they are increasingly used in research for early pest detection (*Guebsi et al., 2024*).

Light Detection and Ranging (LiDAR)

LiDAR systems capture detailed information on canopy height and structure. Changes in canopy architecture caused by lodging, defoliation or heavy herbivory can enhance pest detection models when combined with optical data (*Guebsi et al., 2024*).

Onboard Traps, Collectors and Acoustic Sensors

Innovative UAV payloads such as automated insect traps, sticky cards and acoustic sensors enable direct insect sampling and wingbeat-based species identification. These tools complement remote sensing and are particularly useful in inaccessible or hazardous locations (*Subramanian, 2021*).

Spraying and Dispensing Systems

Agricultural spraying drones are equipped with tanks, pumps and atomizers that enable low-volume, controlled pesticide application. Reviews highlight their ability to improve deposition efficiency while reducing operator exposure, provided that droplet size, flight height and wind conditions are carefully managed (*Talaeizadeh et al., 2025*). UAVs are also being tested for deploying pheromone dispensers and emulsions for mating disruption (*Subramanian, 2021*).

Practical Applications in Pest Management

Early Detection and Hotspot Mapping

Drones can detect subtle canopy changes associated with early pest infestation, particularly for pests with aggregated or patchy distributions such as defoliators, borers and sap feeders. Hotspot maps derived from UAV imagery guide focused ground scouting and targeted treatments, reducing labour and chemical inputs (*Alsadik et al., 2024; Guebsi et al., 2024; Zhu et al., 2024*).

Targeted Pesticide Application and Volume Reduction

Once pest hotspots are identified, UAV sprayers can selectively treat affected areas rather than entire fields. Field demonstrations in India show that this approach can significantly reduce pesticide volume, application time and farmer exposure when SOPs are followed (*Talaeizadeh et al., 2025*).

Pheromone and Mating Disruption Delivery

Drones offer an efficient means of applying pheromone formulations in orchards and large fields, where manual placement is challenging. Studies indicate that UAV-based pheromone delivery can effectively disrupt mating while minimizing chemical use, making it particularly suitable for organic and low-input systems (*Subramanian, 2021*).

Biological Control Agent Release and Habitat Management

UAVs have been tested for releasing sterile insects, parasitoids and entomopathogenic fungi directly over pest-infested zones. Although still limited in scale, these trials demonstrate strong potential for enhancing biological control and supporting integrated pest management (IPM) programs (*Subramanian, 2021*).

Rapid Damage Assessment after Outbreaks

Following pest outbreaks, extreme weather events or invasions such as locusts and fall armyworm, drones enable rapid damage assessment and monitoring of control operations. Their effectiveness in fast-response surveys has been documented across regions (*Guebsi et al., 2024*).

Case Studies and Demonstrations

Drone-Enabled Monitoring of Defoliators

Field trials show that UAV imagery can reliably detect defoliation patterns caused by armyworms and other chewing pests. Rapid mapping supports spot treatments and reduces whole-field spraying, lowering chemical use and labour requirements (*Alsadik et al., 2024; Guebsi et al., 2024; Zhu et al., 2024*).

UAV-Based Pheromone Delivery in Speciality Crops

Research in speciality crops such as berries demonstrates that drones can successfully apply pheromone emulsions for mating disruption where ground methods are impractical. Results confirm UAVs as a viable complement to manual dispensers (*Subramanian, 2021*).

Limitations, Challenges and Risks

Sensor and Model Limitations

Some pests, particularly root feeders or early internal feeders, do not produce detectable canopy signatures. Separating pest-induced stress from nutrient or water stress requires multisensor data and extensive ground validation, and model transferability across regions remains a challenge (*Alsadik et al., 2024; Zhu et al., 2024*).

Operational Constraints

Battery life, payload capacity and weather conditions limit UAV operations, especially for spraying missions. Spray drift and off-target deposition remain concerns, making adherence to operational guidelines critical (*Talaeizadeh et al., 2025*).

Regulatory, Safety and Social Issues

Drone use is governed by aviation and agricultural regulations, and operations near populated areas raise safety and privacy concerns. High initial costs and training requirements pose barriers for smallholders, although the Indian government pilots and SOPs are improving adoption and confidence (*Subramanian, 2021*).

Ecological and Resistance Risks

Although targeted spraying reduces overall chemical use, improper application may still harm non-target organisms. Overreliance on drone-based chemical control without IPM integration could contribute to resistance development, emphasizing the need for monitoring and diversified control strategies (*Subramanian, 2021*).

Conclusion

Drones demonstrate that insect pest management can be more spatially precise, timely and data-driven than conventional approaches. By revealing hidden damage patterns and enabling targeted interventions such as spot spraying and aerial pheromone delivery, UAVs reduce chemical inputs and improve control efficiency. Continued investment in validated detection methods, operator training, regulatory clarity and service delivery models will be essential. When embedded within IPM and extension systems, drone technologies have strong potential to enhance sustainable pest management across both smallholder and commercial agriculture.

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Why Extreme Weather Is Becoming Every Farmer's Biggest Challenge

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Abstract

Extreme weather events have increased in frequency, intensity, and unpredictability across the world, posing escalating risks to agricultural production. In India, where nearly half of the population depends on farming, these changes have direct implications for food security, livelihoods, and national economic stability. This article explores the scientific basis behind extreme weather trends and their impacts on crop growth, soil systems, pests and diseases, farm economics, and adaptation pathways. Using global and India-specific evidence, it highlights why extreme weather is emerging as the most formidable challenge for farmers today.

1. Introduction

Agriculture depends heavily on stable weather patterns. Traditionally, farmers have relied on predictable monsoons, seasonal temperature cycles, and established climatic rhythms to plan crop calendars, irrigation schedules, and input use. However, over the past few decades, these patterns have become increasingly erratic. India has witnessed more frequent heatwaves, prolonged dry spells, unseasonal rains, sudden cloudbursts, cyclones, and floods (IPCC, 2022; IMD, 2023).

Scientific assessments, including the Intergovernmental Panel on Climate Change Sixth Assessment Report (AR6), confirm that climate-induced extreme events are accelerating globally and disproportionately affecting agriculture (IPCC, 2022). As a result, farmers—particularly smallholders are facing unprecedented uncertainty and risk in production decisions.

2. Understanding Extreme Weather Trends

Extreme weather refers to climate events that fall far outside historical averages. Several interconnected trends are increasingly influencing agricultural systems in India.

2.1 Rising Frequency of Heatwaves

India has recorded a sharp increase in heatwave frequency and duration. Observations from the India Meteorological Department indicate that central and northwestern India now experience more heatwave days annually, with summer maximum temperatures frequently exceeding 45°C (IMD, 2023).

2.2 Increased Heavy Rainfall and Cloudbursts

Although total monsoon rainfall has not declined uniformly, its temporal and spatial distribution has become highly erratic. IMD analyses show that extreme rainfall events have increased by more than 75 per cent in several Indian states over the past three decades, increasing flood risks and crop damage (IMD, 2023).

2.3 Extended Dry Spells and Drought

The monsoon season is increasingly characterized by short periods of intense rainfall followed by prolonged dry spells. This pattern disrupts soil moisture availability and crop water demand. A regional analysis published in *Nature Communications* reported a significant increase in drought frequency across South Asia since 2000 (Singh *et al.,* 2020).

2.4 More Intense Cyclones

The Arabian Sea, historically less active than the Bay of Bengal, is now producing more intense cyclones. Climate modelling and observational studies indicate rising cyclone intensity affecting coastal regions of Gujarat, Maharashtra, and Karnataka (Resmi *et al.,* 2021).

2.5 Unseasonal Rains and Temperature Fluctuations

Unseasonal rainfall during harvest periods, sudden cold spells during flowering, and warmer-than-normal winters are increasingly reported by farmers. These anomalies disrupt crop phenology and often promote pest outbreaks (IMD, 2023).

3. How Extreme Weather Affects Crop Production

3.1 Heat Stress Reduces Yield and Quality

Crop plants function within specific thermal thresholds. When temperatures exceed these limits:

- Pollination is impaired in cereals such as wheat, maize, and rice
- Grain-filling duration is shortened
- Elevated night temperatures increase respiratory losses

Experimental and field studies by the Indian Council of Agricultural Research show that a 1°C rise in minimum temperature can reduce wheat yields by 4–5 per cent in northern India (ICAR, 2020).

3.2 Erratic Rainfall Disrupts Crop Calendars

Excess rainfall leads to waterlogging, nutrient leaching, delayed sowing, lodging, and flower drop, while delayed monsoon onset postpones planting operations and reduces yield potential (IMD, 2023).

3.3 Flooding and Soil Erosion

Flooding can destroy standing crops within hours. Repeated flood events alter soil texture through silt deposition, while surface runoff removes fertile topsoil, reducing long-term productivity (FAO, 2016).

3.4 Drought Limits Crop Growth and Seed Germination

Soil moisture stress delays germination, restricts root growth, and reduces nutrient uptake. Pulses, oilseeds, and vegetable crops are particularly sensitive to drought conditions (World Bank, 2021).

3.5 Unseasonal Rains Damage Harvested Crops

Rainfall during harvest seasons has increased in several regions, leading to sprouting, fungal infections, grain discolouration, quality deterioration, and reduced market prices (IMD, 2023).

Overall, extreme weather exerts multidimensional pressure on crop productivity and stability.

4. Impacts on Pests, Diseases, and Weeds

4.1 Warmer Temperatures Accelerate Insect Growth

Insects are ectothermic organisms, and higher temperatures accelerate their development. This leads to increased generations per season and higher pest pressure during critical crop stages. Pests such as whiteflies and armyworms are now reported more frequently across regions (World Bank, 2021).

4.2 Expansion of Invasive Pests

Climate change facilitates the establishment and spreads of invasive pests, including fall armyworm, rugose spiralling whitefly, and tomato pinworm. Warmer winters improve overwintering survival and geographic expansion (World Bank, 2021).

4.3 Disease Emergence

High humidity and elevated temperatures favour fungal and bacterial diseases such as rice blast, vegetable wilts, and pulse rusts, increasing disease incidence and severity (FAO, 2016).

5. Effects on Soil Health and Water Resources

5.1 Soil Degradation

Heavy rainfall accelerates erosion, while drought leads to soil crusting and reduced microbial activity. Both extremes contribute to declining soil organic carbon levels (FAO, 2016).

5.2 Disrupted Nutrient Cycles

High temperatures increase nitrogen volatilization, while intense rainfall causes nutrient leaching and runoff, lowering fertilizer-use efficiency and increasing production costs (FAO, 2016).

5.3 Water Scarcity

Droughts reduce groundwater recharge, and over-extraction during dry periods intensifies water scarcity. This heightens vulnerability during subsequent drought years (World Bank, 2021).

5.4 Salinization in Coastal Areas

Cyclones and storm surges cause saltwater intrusion into agricultural lands, damaging paddy fields and horticultural crops in coastal regions (Resmi *et al.,* 2021).

6. Economic Implications for Farmers

6.1 Increasing Production Costs

Farmers face rising expenditures on irrigation, re-sowing, pesticides, fertilizers, and labour required for emergency protective measures (ICAR, 2020).

6.2 Higher Risk of Crop Failure

Even well-managed crops may fail under extreme weather conditions. Crop insurance claims have increased sharply in climate-vulnerable districts, reflecting growing production risk (ICAR, 2020; IMD, 2023).

6.3 Market Instability

Weather shocks disrupt supply chains, causing sharp price spikes during shortages and market gluts following localized bumper harvests, increasing income volatility for farmers (World Bank, 2021).

7. Conclusion

Extreme weather has become one of the most formidable challenges facing modern agriculture because it disrupts every component of the farming system—from soil health and crop physiology to pest dynamics and farm profitability. As climate change intensifies, India's agriculture must transition toward climate-resilient practices, improved forecasting, sustainable resource management, and stronger institutional support systems. Without timely adaptation, extreme weather threatens food security, rural livelihoods, and national economic stability. Understanding its scientific basis and agricultural impacts is essential for building a resilient farming future.

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SMART FARMING: BUILDING RESILIENCE FOR TOMORROW

(An overview of IoT, AI, sensors, and drones in Indian farms)

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Abstract

Smart farming, which incorporates modern technologies such as Internet of Things (IoT), artificial intelligence (AI), drones, and precision agriculture tools, is rapidly transforming global agricultural practices. Indian agriculture faces numerous challenges, including climate unpredictability, limited resources, pest outbreaks, and market instability. By providing real-time data, predictive analytics, and efficient resource management, smart farming empowers farmers to make informed decisions and adapt to these challenges. This article examines how smart farming enhances resilience in Indian agriculture, discussing its technologies, benefits, challenges, and future prospects.

Keywords: Smart farming, precision agriculture, IoT, AI, resilience, Indian agriculture.

1. Introduction

Agriculture continues to form the backbone of India's economy, supporting millions of rural livelihoods. However, the sector is increasingly vulnerable to climate change, irregular rainfall, pest infestations, and depletion of natural resources. Traditional farming techniques alone cannot ensure sustainable productivity and food security.

Smart farming, often termed precision or digital agriculture, integrates technology and data analytics to monitor crops, soil, and environmental conditions. These systems enable farmers to make evidence-based decisions, optimize the use of inputs such as water and fertilizers, and improve overall crop productivity while minimizing environmental harm (Raj and Prahadeeswaran, 2025).

The goal of this article is to explore how smart farming contributes to resilience in Indian agriculture, supporting sustainability, productivity, and economic stability.

2. Smart Farming: Concepts and Technologies

2.1. Definition and Scope

Smart farming refers to the use of advanced technologies and data-driven approaches to manage crops and livestock more efficiently. Unlike conventional farming, smart agriculture relies on real-time information, predictive models, and precision interventions to maximize outcomes (Basir et al., 2024).

2.2. Key Technologies

- **Internet of Things (IoT):** Sensors deployed in soil, crops, and water systems collect real-time data on moisture, temperature, and nutrient content.
- **Artificial Intelligence (AI) & Machine Learning:** These technologies enable predictive analytics for early disease detection, pest management, and yield estimation (Mansoor et al., 2025).
- **Drones and Satellite Imaging:** These tools allow aerial surveillance of crops, enabling early identification of stress conditions and precise application of inputs.
- **Automated Machinery:** Equipment such as self-driving tractors, automated irrigation systems, and robotic harvesters reduce labour dependency and improve operational efficiency.

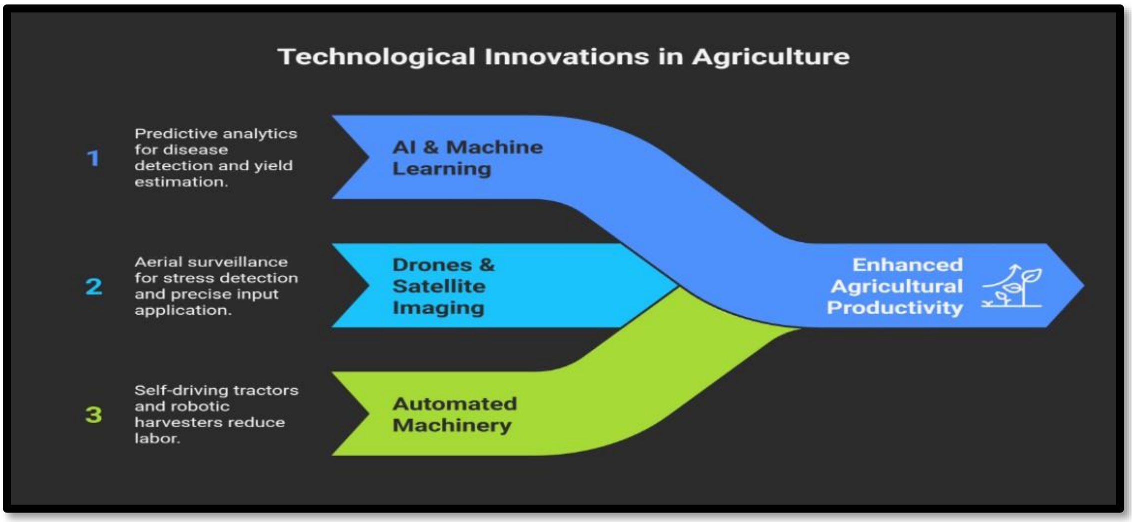

Figure 1: Technological innovations in agriculture

- Mobile Apps and Cloud Platforms: Farmers can access real-time analytics, expert guidance, and market information remotely, enhancing decision-making capabilities.

2.3. Benefits of Smart Farming

- Efficient use of resources, including water, fertilizers, and pesticides.
- Improved crop yield and quality.
- Reduction in environmental impact and greenhouse gas emissions.
- Enhanced decision-making and reduced risk exposure for farmers.

3. Building Resilience in Indian Agriculture

3.1. Climate Resilience

Agriculture in India is heavily dependent on monsoon rainfall. Smart farming tools, such as precision irrigation systems and real-time weather monitoring, enable farmers to adapt to climatic variability. For instance, IoT-enabled irrigation can deliver water efficiently during drought conditions, ensuring stable crop growth (Raj and Prahadeeswaran, 2025).

3.2. Pest and Disease Management

AI-powered systems can detect early signs of pest infestations and diseases, allow timely intervention and reduce crop loss. Preventive management is both cost-effective and more efficient than reactive measures.

3.3. Economic Resilience

By optimizing input usage and increasing yields, smart farming enhances economic stability. It also facilitates the cultivation of high-value crops and enables participation in digital marketplaces, mitigating the impact of price fluctuations (Basir et al., 2024).

3.4. Resource Sustainability

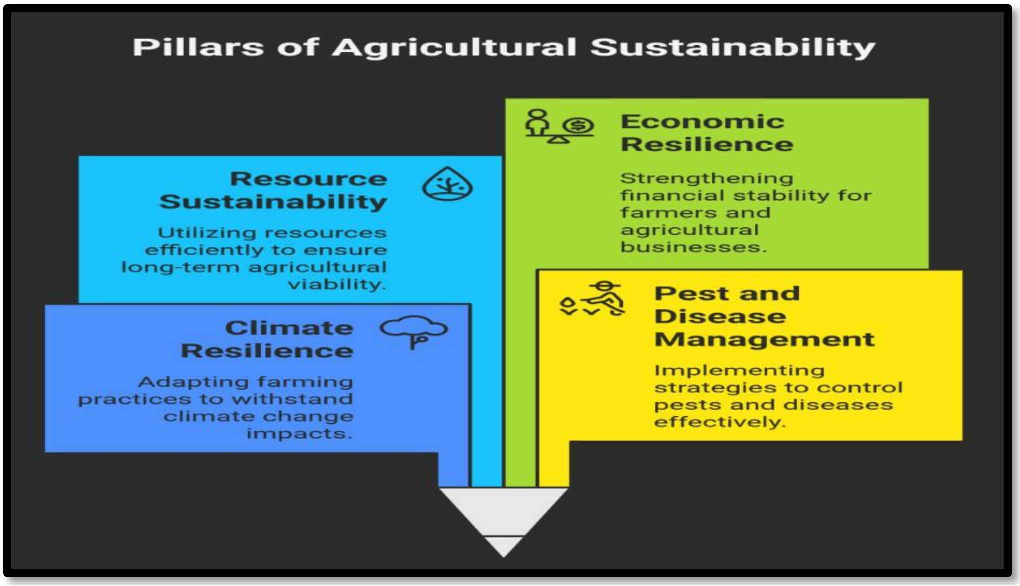

Figure 2: Pillars of Agricultural Sustainability

Smart farming ensures sustainable use of water, fertilizers, and energy, which helps maintain long-term soil health. For example, IoT-based drip irrigation systems have been reported to reduce water consumption by 30–40% while maintaining crop productivity (Mansoor et al., 2025).

4. Case Studies in India

- **Precision Irrigation in Punjab:** Implementation of IoT-enabled drip irrigation systems increased wheat yields by 15–20% (Raj and Prahadeeswaran, 2025).
- **Drone Monitoring in Maharashtra:** Aerial surveillance helped identify early pest infestations in cotton fields, reducing pesticide usage by 25% (Padhiary et al., 2025).
- **AI-Based Advisory in Andhra Pradesh:** Mobile applications providing AI-driven fertilizer and irrigation recommendations improved crop productivity for smallholder farmers.

5. Challenges in Adoption

Despite its potential, smart farming faces several obstacles in India:

- **High Initial Investment:** Advanced machinery, drones, and sensor systems require significant capital outlay.
- **Limited Awareness and Training:** Many farmers lack knowledge of digital tools or the skills to operate them.
- **Connectivity Limitations:** Poor internet access in rural areas hinders real-time data usage.
- **Data Privacy Concerns:** Collection of farm-level data raises questions about ownership and security.

6. Policy Support and Future Directions

6.1. Government Initiatives

- **Digital Agriculture Mission:** Supports the adoption of AI and IoT in farming practices.
- **National e-Governance Plan in Agriculture (NeGP-A):** Provides information dissemination through digital platforms, empowering farmers with timely data (Basir *et al*., 2024).

6.2. Future Trends

- **Blockchain Integration:** For crop traceability and ensuring fair pricing.
- **Advanced Predictive Analytics:** AI-driven climate-smart solutions for forecasting weather and pest outbreaks.

- **Low-Cost IoT Solutions:** Affordable sensor systems for smallholder farmers.
- **Collaborative Models:** Partnerships between farmers, tech startups, and government agencies for scalable implementation (Mansoor *et al*., 2025).

7. Conclusion

Smart farming represents a paradigm shift in agriculture, offering technology-driven resilience against climate variability, pest threats, and market instability. By enabling informed decision-making, reducing input wastage, and increasing productivity, these practices equip Indian farmers to face future challenges effectively. With supportive policies, farmer training, and technological accessibility, smart farming can secure sustainable production, environmental stewardship, and economic stability for the country (Raj & Prahadeeswaran, 2025; Basir et al., 2024).

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