Krishi Ujala
July 2025
Volume-3, Issue 7
ISSN: 2584-2471

Table of Contents

ISSN: 2584-2471

Artificial Intelligence in Pest Management

Shudhanshu Baliyan[1], Nikhil Kumar[2*], Vishvendra[2], Ajita Singh[3],

[1]Department of Entomology,
Govind Ballabh Pant University of Agriculture and Technology, Pantnagar, Uttarakhand, 263145,
[2]Department of Entomology,
Sardar Vallabhbhai Patel University of Agriculture and Technology, Meerut, U.P. 250110,
[3]Department of Plant Pathology,
Sardar Vallabhbhai Patel University of Agriculture and Technology, Meerut, U.P. 250110,

[*]Corresponding author mail: nikhilmalik7001@gmail.com

Abstract:

Artificial intelligence (AI) is transforming agricultural pest management through deep learning, computer vision, smart traps, drones, edge computing, and remote sensing. Recent advances enable rapid pest detection, outbreak forecasting, and precision decision-making while reducing reliance on manual scouting. This article reviews AI-based approaches for pest recognition, explainable AI, field deployment, and autonomous response, and discusses current challenges including dataset bias, transparency, connectivity, and farmer adoption. AI has great potential to strengthen sustainable integrated pest management.

Keywords: Artificial intelligence, Deep learning, Precision agriculture, Pest detection, Computer vision, YOLO, Smart traps, Integrated pest management.

Introduction:

Throughout most of agricultural history, correctly identifying an insect pest relied solely on a trained human eye. A skilled agronomist or seasoned farmer could distinguish a harmful stem borer from a similar-looking harmless insect instantly, but such expertise was limited, unevenly spread, and hard to scale across millions of smallholder farms. Today, artificial intelligence is transforming this process, not by replacing human judgment but by embedding it into software that can operate on affordable smartphones, field sensors, or satellite feeds.

Over the past decade, the same family of machine learning methods used for recognizing faces and reading handwriting has been retrained, dataset by dataset, to identify insect wings, feeding damage, and trap-caught specimens. This has led to a rapidly expanding set of AI tools capable of

ISSN: 2584-2471

identifying pests from a single photo, detecting outbreaks before they become visible to the naked eye, and suggesting responses, often within seconds.

This article focuses on the artificial intelligence aspect of the story: the models, datasets, and architectures enabling automated pest recognition. It discusses the actual research and deployments behind the headlines and highlights the real limitations that still exist between a promising laboratory result and a reliable tool that farmers can trust in the field.

Teaching Computers to See Insects: The Rise of Deep Learning

Initial efforts in automated pest detection used traditional computer vision methods, employing handcrafted rules that described pest colour, shape, or texture. While these approaches performed adequately in controlled lab settings, they often struggled in real farm images, where factors like lighting, background clutter, insect posture, and overlapping leaves hindered reliable rule-based recognition. (Popescu *et al.,* 2023)

Convolutional neural networks, a type of deep learning model initially designed for general image recognition, have significantly transformed this process. Instead of being explicitly instructed on which features to identify, these networks learn their own internal representations of pests directly from thousands of labeled example images. They progressively develop layers of increasingly abstract visual features, starting with simple edges and textures in the early layers and culminating in complete pest silhouettes in the deeper layers.

The practical benefits are significant. Researchers evaluating various convolutional architectures like VGG16, ResNet50, and InceptionV3 on crop pest images have achieved classification accuracies nearing ninety-seven percent on benchmark datasets. This consistency is difficult for rule-based systems or many non-expert humans to match reliably across thousands of images (Ayan *et al.,* 2025).

Building the Datasets That Make AI Possible

A deep learning model's effectiveness depends heavily on the quality of its training data, and creating a truly useful pest-recognition dataset is a significant scientific challenge. Initially, pest classification studies faced a shortage of large, diverse, and accurately labeled image datasets, as most

ISSN: 2584-2471

publicly accessible collections at the time focused on common objects such as cats, cars, and flowers rather than agricultural pests.

This gap was filled by creating IP102, a comprehensive benchmark dataset specifically designed for insect pest recognition. It has become a standard testing resource for the field. Reviewers of pest classification literature highlight that the dataset intentionally includes real-world challenges, such as high visual similarity among different pests, significant variation within the same species, and an inherent imbalance in the number of images of common versus rare pests. (Popescu et al., 2023)

Building on this foundation, Ung, Ung, and Nguyen integrated multiple convolutional neural network architectures into an ensemble system, achieving approximately 74% accuracy on the challenging IP102 benchmark and nearly 100% on the simpler, visually distinct D0 dataset. These results surpass previous state-of-the-art performances for those benchmarks (Ung *et al.,* 2021). Such outcomes highlight a common trend in the field: performance improves rapidly on cleaner, simpler datasets, but more difficult, realistic benchmarks reveal the areas where current models still face challenges.

From Classification to Real-Time Detection: YOLO and Smart Traps

Identifying a single, clearly centered pest in a still photo is much simpler than locating multiple, potentially overlapping pests in a cluttered field image. The latter, more challenging task is known as object detection. It has been greatly improved by a class of models called YOLO, short for You Only Look Once. YOLO can quickly detect and draw bounding boxes around all pests in an image in a single pass, making it suitable for real-time video or continuous camera feeds.

This capability has been paired directly with physical pest traps to remove one of the oldest bottlenecks in pest surveillance, manual counting. Researchers Hakim and colleagues built an internet-connected smart trap that lures fruit flies and fall armyworm moths with pheromone bait, photographs whatever the trap catches, and processes those images with a fine-tuned YOLOv8-based model they call Yolo-pest, achieving roughly ninety-four percent detection accuracy under harsh, arid field conditions in a mango orchard and a maize field (Hakim *et al.,* 2025).

Similar YOLO-based detection systems have been extended to distinguish not just pests but also the beneficial insects that farmers want to protect, a genuinely useful refinement given that many natural predators visually resemble the pests they hunt. One recent smartphone application built on this

ISSN: 2584-2471

principle uses explainable feature selection alongside machine learning to separately identify both a common crop pest, the Colorado potato beetle, and a beneficial predator, the seven-spot ladybird, within the same field images, supporting more selective, targeted pesticide use rather than blanket spraying that would harm both pest and predator alike.

AI-enabled smart pheromone/sticky trap equipped with an imaging sensor for automated detection and real-time monitoring of insect pests

Making AI Trustworthy: The Rise of Explainable Pest Recognition

A frequent criticism of deep learning models is their 'black box' nature: they can accurately detect pests with high confidence but do not explain which visual features led to their decision. For farmers and agronomists to trust automated diagnoses—particularly before applying expensive or environmentally sensitive pesticides, this lack of transparency is a major concern.

An increasing focus in pest-recognition research involves integrating explainability directly into the models. Coulibaly and colleagues created a convolutional neural network for insect pest identification that uses visualization tools like Grad-CAM and LIME. These tools reveal the exact areas of a crop image that most affected the model's decision, enabling users to see exactly which parts of the image the AI focused on when making its classification (Coulibaly *et al.,* 2022).

This kind of transparency is important beyond just user trust. By revealing a model's internal reasoning, explainable AI methods help researchers detect situations where the system has learned

ISSN: 2584-2471

incorrect patterns, like identifying pests based on background objects instead of the insect itself. Such failures might go unnoticed until the model makes an expensive error in real-world use.

AI at the Edge: Bringing Intelligence to Low-Connectivity Farms

Much of the research so far relies heavily on significant computing resources and a stable internet connection to upload images to a remote server. For the millions of smallholder farmers in areas with unreliable or no connectivity, this reliance risks transforming AI-driven pest management into a tool that primarily benefits large, well-connected commercial farms.

Tackling this gap has led to a focus on edge computing or edge AI, where machine learning models are compressed and optimized to operate on low-cost, low-power hardware directly in the field. Nyakuri and colleagues introduce a portable device based on Tiny-LiteNet, a lightweight convolutional neural network. At only 1.2 megabytes, it can perform comprehensive pest and disease detection on a Raspberry Pi without needing cloud connectivity, achieving over ninety-eight percent accuracy in tests (Nyakuri *et al.,* 2025).

This move toward small, efficient models challenges the common belief that better AI equals larger models. In pest management, a compact model functioning reliably offline on affordable hardware might provide greater practical benefits than a slightly more accurate model that depends on infrastructure most smallholder farmers lack.

Beyond Detection: AI-Powered Forecasting of Pest Outbreaks

Detecting an existing pest in a field is useful, but predicting future outbreaks offers a greater advantage for AI, enabling proactive responses instead of reactive ones. These forecasting models incorporate past pest data with current weather conditions, satellite crop health indicators, and increasingly, soil and irrigation information. This integration allows for estimating the likelihood of an outbreak days or weeks ahead.

Aziz and colleagues recently review how remote sensing data, when combined with artificial intelligence and machine learning, has supported the creation of web-based decision support tools. These tools can forecast outbreaks of diseases like late blight in tomato and potato crops using historical weather data, and can also be extended to insect pests with similar temperature and humidity sensitivities (Aziz *et al.,* 2025).

ISSN: 2584-2471

From the Lab to the Field: Real-World Deployment

While academic benchmarks and laboratory accuracy are important, the real test for any AI pest-management tool is whether farmers actually use it correctly. Plantix, developed by the German company PEAT GmbH and co-founded by Simone Strey and Rob Strey after fieldwork in Brazil, remains the most widely used example. It allows farmers to photograph damaged crops and instantly receive automated diagnoses for pests or diseases, along with management advice (FAO e-Agriculture; GSMA Mobile for Development). (Chaudhary, 2018)

Tools like these have undergone independent testing rather than being accepted purely on faith. The CABI international research organization, via its Plantwise program, conducted an eighteen-month pilot of Plantix across crops such as rice, groundnut, brinjal, chilli, and banana in Tamil Nadu, India. Malvika Chaudhary, then Asia Regional Coordinator for Plantwise, observed that these tools enable rapid diagnosis of pest and disease-related crop losses, facilitating timely application of effective treatments—including less toxic biological options—before damage spreads widely (CABI.org).

From an AI standpoint, a notable aspect is how these deployments have created a significant positive side effect: a large, ever-expanding real-world image dataset contributed by farmers themselves, rather than being curated in a lab. This dataset enhances the models that farmers depend on. This feedback loop, where daily use directly improves the AI system, is one of the most promising aspects of applied agricultural AI.

The Next Frontier: Robotics, Drones, and Autonomous Response

Detection and forecasting are valuable only if they prompt action, and AI is now being integrated into responses as well as diagnosis. Drones with AI-driven image recognition can pinpoint pest-affected areas in a field and create variable-rate spraying maps, guiding an unmanned aerial sprayer to target only the affected spots instead of treating the whole field uniformly.

A structured review of one hundred published studies on agricultural drone spraying found that integrating these kinds of advanced, AI-guided precision technologies into spraying drones consistently improved both the accuracy of pesticide placement and overall pest control efficacy compared with drones using older, non-targeted spraying methods (published in the journal Drones, 2024). Because the system sprays only where the AI model has flagged a genuine problem, the same review and related

ISSN: 2584-2471

industry analyses point to substantial reductions in both the total volume of pesticide used and the direct human exposure that comes with manual spraying.

Several smaller agri-tech startups are advancing autonomous responses in the low-cost market segment. Farmsense, based in California, has developed an optical sensor called FlightSensor that detects and counts flying insects in real time by analyzing light and shadow patterns. This innovation addresses the delay of ten to fourteen days associated with older mechanical traps, which is problematic because many pest species only survive about five days as adults (GreyB, 2025). Meanwhile, Australian startup GoMicro has adopted a different approach by creating an affordable, clip-on magnifier for smartphones. This device transforms a standard phone camera into a simple field microscope, enabling AI-assisted pest and disease detection without the need for specialized equipment (GreyB, 2025).

AI-assisted agriculture drone performing aerial crop monitoring for early detection of pest infested areas

Limitations, Bias, and the Human Side of AI Adoption

None of these advances make artificial intelligence a complete or infallible pest management solution, and it would be misleading to suggest so. Each model described here was trained on a particular dataset collected from specific regions, under certain lighting and crop conditions. Its

ISSN: 2584-2471

accuracy often diminishes—sometimes significantly—when applied in environments with different pest species, growing conditions, or camera equipment than the original training data.

The IP102 benchmark dataset was intentionally designed to highlight this issue, as researchers observed that pest images differ greatly between classes but appear confusingly similar within a class. Additionally, some pests have many more training images than others, making consistently high accuracy across the entire pest catalog difficult, rather than just for a few well-photographed species. Explainability tools like Grad-CAM and LIME have become essential because they enable researchers to identify when a model relies on unreliable shortcuts instead of true biological features (Coulibaly *et al.,* 2022).

Questions remain about the commercial benefits for AI pest-management tools marketed as free to farmers. Some diagnostic apps make money by linking users to pesticide suppliers after identifying a pest, raising concerns about whether this aligns with the goal of reducing chemical use or simply shifting it. While this does not undermine the genuine scientific advancements discussed in this article, it highlights that AI in pest management is an evolving set of tools that still need thorough validation, careful implementation, and honest assessment, rather than being a fully solved issue.

Conclusion: Intelligence as a Tool, Not a Replacement

From convolutional neural networks quietly classifying trap images to reinforcement learning systems recommending how to allocate a season's pest control budget, artificial intelligence has given pest management a genuinely new set of capabilities in a remarkably short span of time. It can see patterns in enormous volumes of image and sensor data that no individual human scout could process, and it can put an expert-level diagnosis into the hands of a smallholder farmer through nothing more than an ordinary smartphone.

The research and real-world trials highlighted here show that this technology is still evolving. While impressive benchmark accuracy is important, it must be complemented by thorough field validation. Factors like connectivity, bias, transparency, and commercial incentives are equally crucial as raw model performance. The most successful implementations such as Plantix's farmer-driven image database and lightweight edge devices for low-connectivity areas—share a key characteristic: they are tailored to the actual challenges faced by farmers, rather than just focusing on technical achievements in a lab.

Volume-3, Issue 7
ISSN: 2584-2471

Artificial intelligence will not replace the agronomist's trained eye or the farmer's accumulated field experience anytime soon, and it should not be expected to. What it can do, and is already doing, is extend that expertise further, faster, and more cheaply than ever before, turning a single photograph into an early warning system for an entire region, one crop, one trap, and one smartphone at a time.

Volume-3, Issue 7
ISSN: 2584-2471

How Artificial Intelligence is Rewriting the Story of Indian Farming

[1]Mohit Kumar Pandey, [2]Ashmita Chauhan and [2]Vikas Chandra Gautam

[1]Project Associate-II, Centre for Aromatic Plants, Selaqui, Dehradun

[2]Ph.D. Scholar, Department of Agricultural Communication, G.B. Pant University of Agriculture and Technology, Pantnagar, U.S. Nagar, Uttarakhand 263145

Corresponding mail- chandravikas602@gmail.com

Introduction

It is five in the morning in a village in western Uttar Pradesh. A young farmer walks to his field with a phone in one hand and a torch in the other. Before he even reaches the crop, he has already checked three things on his screen: the weather forecast for the next 48 hours, a pest alert for his district, and a price update from the nearest mandi. Ten years ago, this same farmer would have relied entirely on memory, his father's advice, and the word of the local input dealer. Today, a piece of artificial intelligence sitting quietly inside an app is helping him make decisions his grandfather never had access to.

This small, everyday moment captures something larger happening across Indian agriculture. The sector still supports close to half the country's workforce, yet it faces a familiar list of pressures: shrinking and fragmented landholdings, unpredictable rainfall, rising input costs, labour shortages during peak operations, and price volatility that can wipe out a season's profit in days. Add to this the challenge of feeding a growing population from a limited and increasingly stressed natural resource base, and it becomes clear why Indian agriculture needs more than just hard work. It needs smarter decisions, made faster, with better information.

This is precisely the gap that artificial intelligence is beginning to fill. Not as a replacement for the farmer's judgement, but as an extra set of eyes, one that can read a satellite image, sense a soil's moisture, recognise a disease from a leaf, and translate all of it into a simple recommendation delivered in the farmer's own language. This article explores how AI is moving from research labs and pilot projects into everyday farming decisions across India, what technologies make it possible, which tools farmers are already using, and what still stands in the way of it reaching every field in the country.

What Exactly Is Artificial Intelligence?

Artificial Intelligence, in the simplest possible terms, is the ability of a computer system to perform tasks that would normally require human intelligence, recognizing a pattern, making a

ISSN: 2584-2471

prediction, understanding language, or making a decision based on incomplete information. AI is not a single technology but an umbrella term covering several related approaches.

1. **Machine Learning (ML):** Machine Learning is the branch of AI in which a computer learns patterns from past data rather than following a fixed set of rules written by a programmer. Feed a machine-learning model thousands of records of rainfall, soil type, and yield, and it can learn to predict yield for a new, unseen field.

2. **Deep Learning (DL):** Deep Learning is a more advanced form of machine learning that uses layered neural networks loosely inspired by the human brain. It excels at tasks involving images, sound, and complex patterns, which is exactly why it powers most crop-disease-recognition apps used by farmers today.

3. **Computer Vision:** Computer Vision allows a machine to 'see' and interpret images the way a human eye and brain would. When a farmer photographs a diseased leaf and an app instantly names the disease, computer vision, usually built using deep learning, is doing the recognition work.

4. **Robotics:** Robotics combines AI with physical machines that can sense their surroundings and act on them: a weeding robot that identifies and removes weeds without touching the crop, for instance, or an autonomous tractor that can plow a field without a driver.

5. **Generative AI:** Generative AI is the newest member of the family: systems that can produce new text, images, or even farm advisories in conversational language, rather than simply classifying or predicting. A generative AI-based farm assistant can answer a farmer's question in Hindi or Tamil the way a knowledgeable extension officer would.

AI Is Not the Same as Automation

It is worth separating two ideas that often get mixed up. Automation means a machine performing a fixed, pre-programmed task a drip-irrigation timer that switches on at 6 a.m. every day regardless of conditions is automation. AI, by contrast, adapts its decision to changing circumstances an AI-linked irrigation system decides whether to switch on at all, and for how long, based on real-time soil moisture, weather forecast, and crop growth stage. Automation follows instructions; AI learns and adjusts.

The Evolution of Smart Farming: A Short Timeline

Indian agriculture has moved through several distinct technological eras, each building on the one before it.

- **Traditional Farming (pre-1960s):** Farming guided almost entirely by inherited knowledge, manual labour, animal power, and observation of natural signs.
- **Mechanized Farming (1960s-1980s):** The Green Revolution brings tractors, tube wells, high-yielding seed varieties, and chemical fertilizers, dramatically raising output.

ISSN: 2584-2471

- **Precision Agriculture (1990s-2000s):** GPS-guided equipment and variable-rate application begin allowing input use to be matched to specific parts of a field rather than the whole farm.
- **Digital Agriculture (2010s)**: Smartphones, mobile apps, IoT sensors, and government e-governance platforms bring real-time data and connectivity to millions of farmers for the first time.
- **AI-Powered Smart Farming (2020s onward)**: Machine learning, computer vision, drones, and satellite analytics combine to turn raw data into specific, personalized, and predictive recommendations, moving from what happened to what will happen and what should be done about it.

Major Applications of AI in Agriculture

AI is not a single product a farmer buys; it is a layer of intelligence now embedded across almost every stage of the crop cycle. Here is how it is showing up on Indian farms today.

1. **Precision Farming:** Precision farming uses AI to treat every part of a field differently based on its specific soil, moisture, and crop-health conditions, rather than applying the same water, seed, or fertilizer rate uniformly. Platforms such as CropIn and Fasal combine satellite and sensor data to generate plot-level, rather than farm-level, recommendations, reportedly cutting input waste by 20 to 40 percent where adopted.

2. **Crop Health Monitoring:** Continuous monitoring using satellite indices such as NDVI (a measure of plant greenness and vigor) allows AI systems to flag stressed patches of a field days before the stress becomes visible to the naked eye, giving farmers a head start on intervention.

3. **Disease and Pest Detection:** This is one of AI's most visible successes in Indian fields. A farmer photographs an affected leaf, and a deep-learning model trained on millions of labeled images identifies the disease or pest within seconds. Plantix, built on a database of over 120 million farmer-submitted images, exemplifies this at global scale, while India's own National Pest Surveillance System, now used by more than 10,000 extension workers, recognizes 432 pests across 66 crops.

> 💡 **AI Fact**
> *India's National Pest Surveillance System, an AI and machine-learning tool used by over 10,000 extension workers, now recognizes 432 pests across 66 crops from a single photograph taken on a farmer's phone.*

4. **Smart Irrigation:** AI-linked soil-moisture sensors and weather data allow irrigation systems to water a crop only when needed and only in the quantity needed, rather than on a fixed schedule a critical advantage in a country where agriculture consumes roughly 80 percent of freshwater withdrawals.

5. **Fertilizer Recommendation:** Combining Soil Health Card data, of which over 25 crore have now been issued nationally, with AI models allows far more precise fertilizer recommendations, reducing both cost to the farmer and nutrient run-off into the environment. The rapid rise in nano-

ISSN: 2584-2471

urea and nano-DAP adoption, now exceeding 1,593 lakh bottles cumulatively, is being supported by similar data-driven application guidance.

6. **Weed Detection:** Computer-vision systems mounted on drones or ground robots can now distinguish crop seedlings from weeds row by row, enabling targeted herbicide spraying instead of blanket application a technique increasingly tested in Indian horticulture and row-crop trials.

7. **Yield Prediction:** By combining historical yield data, weather patterns, satellite imagery, and soil information, machine-learning models can forecast likely yield weeks before harvest, information valuable to farmers planning storage and sale, and to insurers assessing risk.

8. **Weather Forecasting:** Hyperlocal, AI-refined weather forecasts are increasingly reaching farmers directly. A pilot combining AI models with India Meteorological Department data, tested across parts of 13 states, found that farmers who received localized monsoon-onset forecasts through Kisan Call Centers adjusted sowing time, land preparation, or crop choice in 31 to 52 percent of cases.

💡 **AI Fact**

A pilot combining AI with India Meteorological Department monsoon forecasts, tested across 13 states, found that once farmers received localised forecasts through Kisan Call Centres, 31 to 52 percent adjusted their sowing time, land preparation, or crop choice.

9. **Soil Analysis:** AI-assisted spectral analysis of soil samples can estimate nutrient content, pH, and organic-carbon levels far faster than traditional laboratory testing, supporting the government's ambitious plan to map 142 million hectares of farmland at high resolution.

10. **Drone-Based Crop Monitoring:** Drones fitted with multispectral cameras can survey a large field in minutes, generating health maps that would take a human scout an entire day to compile. Under the Namo Drone Didi scheme, women's self-help groups are being trained and equipped to offer this as a paid rental service to farmers in their area.

💡 **AI Fact**

Under the Namo Drone Didi scheme, women's self-help groups renting out spraying drones can earn at least Rs 1 lakh in additional annual income, while ICAR field studies suggest drone-based spraying can cut pesticide use by up to 30 percent.

11. **Satellite Imagery:** Freely available satellite data, combined with AI analytics, now allows companies to monitor crop area, crop type, and crop condition across millions of acres without a single field visit. CropIn alone has used this approach to digitise more than 16 million acres of farmland.

💡 **Did You Know?**

ISSN: 2584-2471

CropIn, an Indian agri-intelligence company, has used satellite imagery and AI to digitize more than 16 million acres of farmland and now supports agribusinesses in over 50 countries.

12. **Autonomous Tractors and Farm Robots:** While still in their early stages in India compared with countries like the United States, autonomous and semi-autonomous farm machinery, self-guided tractors, robotic transplanters, and automated fruit-picking arms are being piloted by agricultural universities and larger farm enterprises.

13. **Livestock Monitoring:** AI-enabled sensors and wearables can track an animal's activity, feeding pattern, and even body temperature to flag illness or oestrus early, a technology being extended from India's dairy sector into poultry and aquaculture.

14. **Smart Greenhouse Management:** In controlled environments, AI systems continuously adjust temperature, humidity, and irrigation. Social enterprises such as Kheyti have built low-cost 'greenhouse-in-a-box' models for small farmers that increasingly draw on such automated, sensor-driven management.

15. **Supply Chain Optimization:** AI-based demand forecasting and route optimization, used by platforms such as Ninjacart, help match farm produce to buyer demand more efficiently, reducing the time between harvest and sale a critical factor for perishable fruits and vegetables.

16. **AI in Post-Harvest Management:** Post-harvest losses in India are estimated at close to Rs 90,000 crore annually. AI-based quality-assessment tools such as AgNext's Qualix use spectroscopy and computer vision to grade grain, spice, and produce quality within seconds, replacing slower manual inspection and reducing disputes between buyers and sellers.

17. **AI-Powered Farm Advisory Systems:** Perhaps the most farmer-facing application of all is the AI chatbot. Kisan e-Mitra, a voice-based assistant supporting 11 regional languages, now handles more than 8,000 queries a day on schemes such as PM-KISAN, PM Fasal Bima Yojana, and Kisan Credit Card, having answered over 93 lakh queries to date.

💡 **Did You Know?**
The voice-based AI chatbot Kisan e-Mitra works in 11 regional languages and handles more than 8,000 farmer queries every day, having answered over 93 lakh queries on schemes like PM-KISAN and PM Fasal Bima Yojana so far.

The Technologies Behind the Intelligence

Behind every farmer-facing app lies a stack of underlying technologies working together.

- **Machine Learning & Deep Learning**: The core prediction and recognition engines behind yield forecasting, disease detection, and price prediction.
- **Internet of Things (IoT)**: Networks of low-cost sensors placed in soil, water tanks, or storage units that continuously feed real-time data into AI models.

ISSN: 2584-2471

- **Remote Sensing:** The use of satellite or aerial sensors to observe crop and land conditions from a distance, without physical field visits.
- **Geographic Information Systems (GIS):** Software that maps and layers spatial data — soil type, elevation, land use to support field-level analysis.
- **GPS**: The positioning backbone that enables variable-rate machinery, drone navigation, and precise field mapping.
- **Computer Vision**: Enables cameras and drones to interpret images for disease detection, weed identification, and produce grading.
- **Drones (UAVs):** Aerial platforms carrying cameras or spray tanks for monitoring and precision input application.
- **Agricultural Robots:** Machines capable of physical farm tasks such as weeding, harvesting, or transplanting with minimal human control.
- **Cloud Computing**: Provides the storage and processing power needed to run AI models at scale and deliver results to a farmer's phone within seconds.
- **Big Data Analytics**: The ability to process enormous, varied datasets- weather, market prices, satellite images to extract patterns useful for decision-making.
- **Digital Twins**: Virtual replicas of a real farm or field used to simulate the effect of different decisions before applying them in reality.
- **Edge Computing**: Processing data directly on a device (such as a drone or sensor) rather than sending it to a distant server, useful where internet connectivity is poor.
- **Blockchain Integration**: Increasingly combined with AI to create tamper-proof records of a crop's journey from farm to consumer, supporting traceability and fair pricing.

AI Tools and Mobile Applications Used by Indian Farmers

a. **Plantix:** AI-powered crop-doctor app that diagnoses diseases, pests, and nutrient deficiencies from a photograph and suggests treatment; built on a database of over 120 million images.

b. **Microsoft FarmVibes.AI:** An open-source research toolkit from Microsoft that combines satellite, weather, and sensor data to build custom agricultural AI models, used by researchers and agritech developers.

c. **Google AI Initiatives:** Google's agricultural research collaborations, including flood-forecasting AI used across South Asia and crop-mapping projects built with partner institutions.

d. **Kisan e-Mitra:** A government-backed, voice-based AI chatbot in 11 regional languages that answers farmer queries on schemes like PM-KISAN and crop insurance.

e. **Kisan Suvidha:** A government mobile app providing weather, market price, and advisory information, increasingly integrated with AI-based recommendation layers.

f. **Agrio:** A crop-monitoring and disease-diagnosis app offering expert-backed treatment advice alongside its AI detection engine.

g. **BharatAgri:** An AI-driven advisory platform giving Indian farmers personalised crop-care schedules based on their location, soil, and crop stage.

ISSN: 2584-2471

h. **DeHaat:** A full-stack agritech platform that combines AI-based advisory with input supply, credit facilitation, and market linkages for smallholder farmers.

i. **CropIn:** A farm-intelligence platform that uses satellite data and AI to monitor crop health and predict yields across millions of acres worldwide.

j. **Fasal:** An IoT and AI platform for horticultural crops that uses in-field sensors to provide hyperlocal irrigation and pest management advice.

k. **Ninjacart:** A supply chain technology company that uses AI-based demand forecasting to move fresh produce from farms to retailers more efficiently.

l. **Pixxel:** An Indian space-tech startup building hyperspectral imaging satellites that detect crop stress and soil conditions in far greater detail than conventional satellites.

m. **AgNext:** A quality-assessment company whose AI platform, Qualix, uses computer vision and spectroscopy to instantly grade grains, spices, and other commodities.

Success Stories: AI at Work in Real Fields

Numbers and technology descriptions only tell part of the story. Here are real examples of AI creating measurable impact for Indian farmers and the systems that support them.

1. **The Chili Farmer and the Missing Diagnosis:** A chili grower in rural India noticed his plants were smaller than usual and had curled leaves. Neighbors offered a dozen different guesses about disease. When he photographed the plant with Plantix, the AI-based diagnosis instead pointed to a simple water and nutrient deficiency. Within weeks of correcting this, his crop recovered a reminder that AI's biggest value is often not exotic technology, but fast, accurate, unbiased diagnosis.

2. **Maharashtra's Rapid Disaster Relief:** When Kharif crop losses hit Maharashtra, the state used AgriStack's digitized land and farmer records to transfer more than Rs 14,000 crore in compensation to 89 lakh farmers with Aadhaar-linked accounts, dramatically compressing a process that traditionally took months of paperwork.

3. **Women Entrepreneurs Take to the Skies:** Under the Namo Drone Didi scheme, women's self-help groups have been trained as certified drone pilots, offering spraying services to neighboring farmers. Early studies of the programme found that it expanded these groups' activities beyond traditional roles and created a new, technology-based income stream for rural women.

4. **Predicting the Monsoon, Village by Village:** An AI-assisted pilot with the India Meteorological Department delivered hyperlocal monsoon forecasts to farmers across 13 states through Kisan Call Centres. Telephonic follow-up surveys in Madhya Pradesh and Bihar found that 31 to 52 percent of farmers changed their sowing time, land preparation, or crop and input choices based on the forecast.

5. **Grain Quality in Seconds, Not Hours:** AgNext's AI-based Qualix platform allows mandis, food companies, and government procurement agencies to assess grain and spice quality

ISSN: 2584-2471

using spectroscopy and computer vision within seconds, replacing manual assessments that were slower and more prone to dispute.

6. Digitising Millions of Acres: CropIn's satellite-and-AI platform has been used to digitise over 16 million acres of farmland and support agribusinesses working with roughly 7 million farmers globally, demonstrating how satellite intelligence can operate at a scale no physical survey team could match.

7. A Voice Assistant That Never Sleeps: Kisan e-Mitra, the government's multilingual voice chatbot, now answers thousands of farmer questions on welfare schemes daily extending the reach of extension advice to farmers who might otherwise never reach an officer in person.

8. Scaling Pest Surveillance Nationally: India's National Pest Surveillance System has moved AI-based pest identification from a research concept into a working tool used by over 10,000 extension workers across the country, covering 66 crops and 432 pest categories turning what was once specialist knowledge into something any trained field worker can access instantly.

> 💡 **AI Fact**
> *When Maharashtra needed to transfer Kharif crop-loss compensation quickly, AgriStack's digital records allowed the state to disburse more than Rs 14,000 crore to 89 lakh farmers with Aadhaar-linked bank accounts, a process that once took months, compressed dramatically.*

Benefits of AI in Agriculture

Taken together, these applications translate into concrete gains across the farming system.

Table 1: Key Benefits of AI Adoption in Agriculture

Benefit	**How AI Delivers It**
Higher productivity	Precision recommendations on sowing time, spacing, and inputs raise yield per hectare.
Cost reduction	Targeted input use cuts wastage of water, fertiliser, and pesticide by 20-40%.
Better decision-making	Real-time data replaces guesswork with evidence-based choices.
Efficient resource use	Sensors and satellite data ensure water and nutrients go exactly where needed.
Climate resilience	Early warnings on weather and pests help farmers act before damage occurs.
Increased profitability	Lower costs plus better yield and quality improve net farm income.
Improved food security	Better yield forecasting supports national planning and price stability.

ISSN: 2584-2471

Benefit	How AI Delivers It
Environmental sustainability	Reduced chemical overuse protects soil health and water bodies.
Better market intelligence	AI-based price and demand forecasting helps farmers time their sales.

Challenges and Limitations

For all its promise, AI adoption in Indian agriculture faces real and significant barriers that cannot be wished away.

Table 2: Benefits vs Challenges of AI in Indian Agriculture

Dimension	Benefit	Challenge
Cost	Lower input cost over time	High initial investment in sensors, drones, subscriptions
Access	Available on any smartphone	Digital divide; many farmers lack smartphones or digital literacy
Connectivity	Cloud-based, always updated	Poor or absent internet connectivity in many rural areas
Scale	Works across small and large farms	India's small, fragmented landholdings limit machinery economics
Skills	Simple, guided interfaces	Shortage of trained technical staff to support and troubleshoot
Data	Enables precise, personalised advice	Data privacy, ownership, and consent concerns around farmer data
Infrastructure	Cloud and satellite coverage nationwide	Weak rural power supply and last-mile logistics
Governance	Standardised national platforms	Policy, regulatory, and ethical questions still evolving

Government Initiatives Driving AI in Indian Agriculture

India's public sector has moved from pilot projects to a full-fledged national digital agriculture strategy over the past few years.

ISSN: 2584-2471

Digital Agriculture Mission (DAM)

Approved by the Union Cabinet in September 2024 with a total outlay of Rs 2,817 crore, the Digital Agriculture Mission is the umbrella scheme under which most of India's digital and AI-driven agriculture initiatives now sit, including the creation of Digital Public Infrastructure for farmers.

AgriStack

Often described as an 'Aadhaar for farmers,' AgriStack is built around three linked registries — a farmer registry, a farm (land) registry, and a crop-sown registry. More than 8.4 crore Farmer IDs had been generated as of early 2026, moving toward a target of 11 crore by 2026-27. Pilot projects have run in six districts across Uttar Pradesh, Gujarat, Maharashtra, Haryana, Punjab, and Tamil Nadu.

💡 **Did You Know?**

Under the Digital Agriculture Mission, more than 8.4 crore Farmer IDs had already been generated as India works toward a target of 11 crore digital farmer identities by 2026-27 — a system often described as an 'Aadhaar for farmers.'

Krishi Decision Support System (Krishi DSS)

This geospatial system integrates remote-sensing data on crops, soil, weather, and water resources, and is designed to help farmers achieve meaningfully higher yields through better resource planning.

National e-Governance Plan in Agriculture (NeGPA) and Digital Public Infrastructure (DPI)

These form the broader digital backbone connecting farmer identity, land records, and scheme delivery, drawing on the same Aadhaar, DigiLocker, eSign, and UPI-style architecture that transformed India's finance and welfare systems.

Namo Drone Didi

A Rs 1,261 crore central sector scheme to equip around 14,500-15,000 women's self-help groups with agricultural drones for spraying services, generating new rural livelihoods while extending precision-application technology to more farms.

AI Centres of Excellence and ICAR Initiatives

The Indian Council of Agricultural Research (ICAR), along with State Agricultural Universities and Krishi Vigyan Kendras, has procured hundreds of drones and conducted tens of thousands of field demonstrations under the Sub-Mission on Agricultural Mechanization, reaching hundreds of thousands of farmers with hands-on exposure to drone and precision technologies.

Bharat-VISTAAR and State-Level Projects

ISSN: 2584-2471

Bharat-VISTAAR, a multilingual AI tool for accessing agricultural resources, and various state-level programmes in Maharashtra, Telangana, and elsewhere, show how AI-based advisory is being localised to different regions and languages.

The Future of AI in Indian Agriculture

The next phase of this transformation is likely to look less like isolated apps and more like an integrated, conversational, and predictive farming ecosystem.

- **Generative AI Farm Assistants**: Conversational AI that can answer a farmer's specific question in their own language, much like talking to a knowledgeable extension officer, rather than searching through menus.
- **Advanced Robotics**: Wider deployment of autonomous weeding, harvesting, and monitoring robots as costs fall and rural service networks mature.
- **Digital Villages**: Clusters of farms connected through shared sensors, drones, and data platforms, pooling the cost of technology that no single smallholder could afford alone.
- **Smart, Transparent Supply Chains:** AI plus blockchain-based traceability connecting farm to fork, giving farmers better price discovery and consumers better assurance of quality and origin.
- **Climate-Smart and Predictive Agriculture**: Models that combine long-range climate data with field-level conditions to guide multi-season cropping and water-management strategy, not just single-season decisions.
- **AI-Powered Extension Services**: A shift from a handful of extension officers serving thousands of farmers to AI systems that can offer every farmer individual attention, with human experts stepping in for complex cases.
- **Precision Conservation Agriculture**: AI-guided practices that balance productivity with soil health, biodiversity, and water conservation over the long term.

Conclusion

Artificial intelligence is not a distant, futuristic promise for Indian agriculture; it is already present in millions of fields, in the form of a disease-diagnosis photo, a drone spraying pass, a voice chatbot answering a scheme query, or a satellite image flagging a stressed patch of crop. What began as isolated pilot projects a decade ago is now converging into a national digital agriculture infrastructure, backed by public investment through the Digital Agriculture Mission and AgriStack, and complemented by a fast-growing ecosystem of agritech startups. The road ahead is not without obstacles. Connectivity gaps, digital literacy, the cost of technology, and the realities of small and fragmented landholdings will continue to shape how quickly and how equitably these benefits reach every farmer. But the direction of travel is clear. Used wisely, AI can make Indian agriculture more productive, more resilient to climate shocks, more profitable for the farmer, and more sustainable for the land a powerful decision-support partner for the person who, even in the age of satellites and neural networks, remains the most important decision-maker in the field: the farmer.

ISSN: 2584-2471

Nano Fertilizers and Nano Agriculture: The Next Green Revolution

Monu Kumar[1], Binu Maurya[1], Shashank Pandey[2], Anurag Verma[1]

[1]Ph.D. Scholars, Department of Agricultural Extension Education, Sardar Vallabhbhai Patel University of agriculture and technology, Meerut 250110, Uttar Pradesh, India

[2]PG. Scholar, Department of Agricultural Extension Education, Sardar Vallabhbhai Patel University of Agriculture & Technology, Meerut- 250110, Uttar Pradesh, India

Corresponding author email: *monukumar22799@gmail.com*

Introduction

It is early October in a village near Meerut, and Ramesh Chaudhary is standing at the edge of his wheat field with an empty fertilizer sack in his hand. For the past fifteen years, his routine has not changed much: broadcast urea by hand, irrigate, wait, and hope the yield covers the rising cost of diesel, labor, and inputs. His father used two bags of urea per acre; Ramesh now uses four, yet the yield gain has been marginal. The soil, once dark and crumbly, now cakes and cracks faster after irrigation. A soil test at the nearest Krishi Vigyan Kendra confirms what Ramesh already suspected: organic carbon has fallen, micronutrients are deficient, and much of the nitrogen he applies is simply washing away or evaporating before his wheat can use it.

Ramesh's story is the story of Indian agriculture at large. Decades of intensive chemical fertilizer use, born out of the original Green Revolution, delivered food security but at a steadily rising ecological and economic cost. Nutrient-use efficiency for nitrogen in most cereal systems remains below 40 percent, meaning that more than half of what farmers pay for is never actually taken up by the crop. It leaches into groundwater, volatilizes into the air as greenhouse gas, or simply gets locked up in the soil in unusable forms. Costs keep climbing, subsidy burdens keep growing, and soil health keeps declining, a treadmill that has left many farmers no better off than their parents were, despite far higher input use.

> *Did You Know? Nutrient-use efficiency for nitrogen in most Indian cereal cropping systems is estimated at below 40 percent, meaning more than half of the applied fertilizer nitrogen is lost to the environment rather than absorbed by the crop.*

Balanced nutrient management, giving crops the right nutrient, in the right form, at the right time and place, has long been recognized as the answer in theory. In practice, conventional fertilizers are blunt instruments: granules or crystals that dissolve quickly, release nutrients all at once, and

ISSN: 2584-2471

depend on the farmer's judgment and the weather to decide how much of that release the plant actually captures. What Indian and global agriculture needed was a way to make nutrient delivery smarter, not just larger.

This is precisely the gap that nanotechnology is beginning to fill. By engineering nutrients at the scale of billionths of a metre, scientists have created fertilizer particles so fine and so reactive that they behave completely differently from their bulk counterparts — penetrating leaf stomata, binding more efficiently to plant tissue, and releasing nutrients gradually in step with crop demand rather than all at once. Nano fertilizers promise dramatically higher nutrient-use efficiency, lower application rates, reduced environmental leakage, and, if adopted responsibly, healthier soils over time.

This is why many scientists, policymakers, and agri-entrepreneurs are calling nanofertilizers and the wider field of nanoagriculture a potential "Next Green Revolution." Where the first Green Revolution multiplied yields through high-response seed varieties and heavy chemical inputs, this emerging revolution is about precision, efficiency and sustainability, doing more with less, and doing it in a way that protects the very soil and water that Indian farming depends on for the decades ahead. This article takes a comprehensive, practical look at what nano fertilizers and nano agriculture really are, where India stands today, and what farmers, researchers, companies and policymakers need to do to make this promise a reality.

What is Nanotechnology?

Nanotechnology is the science of designing, manufacturing and applying materials at an extremely small scale, typically between 1 and 100 nanometers. To put that in perspective, a nanometer is about 1/80,000th the width of a human hair. At this scale, familiar materials often start behaving in unfamiliar ways: they become more reactive, absorb and release energy differently, and interact with biological systems, such as plant cells, far more intimately than their everyday "bulk" form ever could.

What are Nanoparticles?

Nanoparticles are simply particles of matter engineered to be within the nanoscale size range. They can be metallic (such as zinc oxide or iron oxide nanoparticles), non-metallic (such as silica or carbon-based particles), or organic polymer-based capsules designed to carry and slowly release a nutrient or active ingredient. What unites them is scale, not chemistry: the same element, shrunk down to nanoparticle size, can show completely different behavior from its conventional form.

Why are Nanoparticles Unique?

The defining feature of a nanoparticle is its extraordinarily high surface-area-to-volume ratio. A gram of nano-scale material exposes vastly more surface area to its surroundings than the same gram of coarse material, which means more contact points for chemical reactions, more efficient binding to plant surfaces, and far greater biological activity per unit of material used. This is the central reason a few hundred milliliters of nano urea can, under proper application, substitute for a 45-kilogram bag of

ISSN: 2584-2471

conventional granular urea for certain nitrogen requirements: the nutrient is not being used in smaller amounts because it is diluted, but because it is being delivered with dramatically higher efficiency.

Conventional Materials versus Nanomaterials

Conventional fertilizer granules are relatively large, chemically inert on the outside, and depend on physical breakdown and dissolving in soil moisture before nutrients become available to roots. Much of this process is uncontrolled: a sudden monsoon shower can wash away a large fraction of applied nitrogen within hours. Nanomaterials, by contrast, can be engineered with specific coatings, particle sizes and release triggers, allowing scientists to design a much more controlled, gradual and targeted nutrient release that closely follows the crop's actual physiological demand across its growth stages.

Nano Fact: *A nanometre is roughly 1/80,000th the width of a human hair, nano fertilizer particles are engineered within the 1–100 nanometre range, small enough to pass through microscopic stomatal pores on a leaf surface.*

Evolution of Nanotechnology in Agriculture

Agricultural nanotechnology research began gathering pace globally in the early 2000s, with universities and research institutes exploring nanoparticle-based delivery of nutrients, pesticides and growth regulators. In India, the turning point came in 2020, when the Department of Biotechnology issued guidelines for evaluating nano-based agricultural inputs and food products, creating a formal regulatory pathway. This paved the way for IFFCO's world-first nano liquid urea, launched commercially in June 2021, and for the subsequent wave of nano DAP, nano zinc, nano copper, and other formulations.

What are Nano Fertilizers?

Nano fertilizers are nutrient formulations in which essential plant nutrients nitrogen, phosphorus, potassium, zinc, iron, or other elements are either reduced to nanoparticle size or encapsulated within a nanoscale carrier material. Rather than being broadcast onto soil in bulk granular form, most nano fertilizers currently available in India are applied as a foliar spray: a fine liquid mist coating the leaf surface, from where nutrients are absorbed directly through stomata and the leaf cuticle.

Characteristics

Nano fertilizers are characterised by extremely small particle size, high surface reactivity, uniform dispersion in the spray solution, and the ability to be engineered for slow, targeted release. Most commercial nano fertilizers in India are sold as liquid concentrates in compact bottles, in sharp contrast to the 45-kilogram bags associated with conventional urea and DAP.

Working Mechanism and Controlled Nutrient Release

ISSN: 2584-2471

When sprayed on leaves, nano-scale nutrient particles pass through the stomatal openings and are absorbed into the plant's vascular system, from where they are translocated to the tissues that need them most. Some formulations use a coating or encapsulation that dissolves gradually, releasing the nutrient over several days rather than instantly, this is what agronomists mean by "controlled" or "slow" release. The result is a nutrient supply that more closely tracks the crop's physiological demand curve, rather than flooding the root zone with more nutrients than the plant can absorb in one sitting.

Increased Nutrient-Use Efficiency

This is the single biggest selling point of nano fertilizers. Independent field studies compiled in a recent sustainability research report that nano fertilizers, on average, improved crop yields by roughly 20 to 23 percent across cereals, legumes and horticultural crops compared with conventional NPK applied at equivalent nutrient rates, with some individual trials on rice and wheat showing considerably higher gains alongside major reductions in the nitrogen dose applied. Because far less material is lost to leaching, run-off and volatilization, a much greater share of every rupee spent on fertilizer actually ends up inside the plant.

Table 1: Conventional Fertilizers vs Nano Fertilizers

Parameter	Conventional Fertilizers	Nano Fertilizers
Particle size	Millimetre to centimetre scale (granules/prills)	1–100 nanometre scale
Typical application	Soil broadcasting, basal/top dressing	Foliar spray, seed treatment, fertigation
Nutrient-use efficiency	Often 30–50% for nitrogen	Reported gains of 20–80% depending on crop and study
Quantity required per acre	High (bags of 45–50 kg)	Low (200–500 ml bottles)
Nutrient loss (leaching/volatilisation)	High	Substantially reduced
Transport & storage	Bulky, high logistics cost	Compact, lower logistics cost
Environmental footprint	Higher runoff, GHG emissions	Lower runoff, reduced emission potential
Cost per acre (indicative)	Higher recurring cost	Potentially lower with correct dosage
Regulatory status in India	Long-established under FCO 1985	Notified crop- and time-bound under Clause 20DA of FCO

ISSN: 2584-2471

Did You Know? A single 500 ml bottle of IFFCO Nano Urea, priced at around ₹240, is promoted as a substitute for one 45 kg bag of conventional urea for a portion of a crop's nitrogen requirement, though experts recommend using it to complement, not fully replace, basal urea application.

Types of Nano Fertilizers

Nano Nitrogen (Nano Urea)

The flagship product of India's nano fertilizer story, nano urea is a colloidal suspension of nanoscale nitrogen particles, applied as a foliar spray to supply nitrogen with far less loss than granular urea. It is typically recommended in combination with a reduced dose of conventional urea rather than as a complete replacement.

Nano Zinc

Zinc deficiency affects a large share of Indian soils, particularly in intensively cultivated tracts of Uttar Pradesh, Punjab and Haryana. Nano zinc oxide formulations correct this deficiency more efficiently than soil-applied zinc sulfate, improving both yield and the zinc content of the harvested grain, an important biofortification benefit for human nutrition.

Nano Copper

Copper is a micronutrient essential for enzyme function and lignin formation in plants. Nano copper formulations, recently notified under India's Fertilizer Control Order, supply this micronutrient in a highly bioavailable form while also showing some fungistatic properties that can support crop health.

Nano Iron

Iron deficiency chlorosis is a common problem in alkaline and calcareous soils found across parts of central and western India. Nano iron oxide particles are more mobile within plant tissue than conventional iron salts, helping correct chlorosis symptoms more quickly when applied as foliar sprays.

Nano Boron

Boron plays a crucial role in flowering, pollen viability and fruit set, making it especially valuable for oilseeds, pulses, cotton and fruit crops. Nano boron formulations are being researched as a way to reduce flower and fruit drop while using far smaller quantities than conventional borax or boric acid applications.

Nano Phosphorus

ISSN: 2584-2471

Phosphorus is notorious for being "locked" in soil, especially in calcareous and acidic soils, where it forms insoluble compounds unavailable to roots. Nano phosphorus and nano DAP formulations aim to bypass this soil fixation problem entirely by delivering phosphorus directly through the leaf.

Nano Potassium

Potassium is vital for water regulation, disease resistance and grain filling. Nano potassium formulations, still in the earlier stages of commercialization than nano urea or nano DAP, are being developed to improve potassium uptake efficiency, particularly in sandy soils where potassium is prone to leaching.

Nano Sulphur

Sulfur deficiency has become increasingly common in Indian soils as the use of sulfur-free high-analysis fertilizers has grown. Nano sulfur formulations are being explored for oilseed and pulse crops, where sulfur strongly influences oil content and protein quality.

Nano Composite Fertilizers

Rather than supplying a single nutrient, composite or nano NPK formulations combine multiple nutrients, often nitrogen, phosphorus and potassium together, sometimes with secondary and micronutrients in a single nano-engineered carrier. IFFCO's nano NPK, including a granular version under development at its Kandla facility, is a prominent example of this category moving toward commercial scale.

Nano Biofertilizers

These combine nanotechnology with beneficial micro-organisms nitrogen-fixing bacteria, phosphate-solubilizing microbes, or mycorrhizal fungi encapsulated in nano-carriers that protect the organisms and enhance their survival and colonization in the root zone, offering a more biological route to improved nutrient availability alongside chemical nano-fertilizers.

Nano Fact: Nano zinc and nano copper were formally added as distinct notified categories under the Fertilizer (Inorganic, Organic or Mixed) Control Order, 1985, through an amendment notified on April 24, 2024, expanding the number of officially recognised nano fertilizer categories in India.

Did You Know? Some published field studies report that nano urea, combined with reduced conventional nitrogen, has increased rice grain yields by over 25 percent while reducing nitrogen fertilizer inputs by roughly 40 percent, though results vary considerably by location, soil type, and management.

ISSN: 2584-2471

Nano Agriculture: A New Era of Smart Farming

Nano fertilizers are only one part of a much broader shift often described as "nano agriculture" the application of nanotechnology across the entire crop production cycle. Precision nutrient management, using nano carriers to deliver exactly the right nutrient dose at exactly the right growth stage, is being complemented by nano pesticides, nano herbicides and nano fungicides, which use similar encapsulation principles to release active ingredients gradually, reducing the frequency of spraying and the total chemical load released into the environment..

Applications in Indian Agriculture

Nano fertilizers and allied nano-agri inputs are being trialled and adopted across the full spectrum of Indian cropping systems. In rice, foliar applications of nano urea and nano zinc are being used alongside reduced basal urea doses in states such as Uttar Pradesh, Punjab and Odisha, with research trials reporting improved grain yield and reduced lodging. In wheat, particularly across the Indo-Gangetic plains, nano urea combined with conventional prilled urea under conservation tillage has been studied at ICAR's wheat research centres for its effect on nitrogen-use efficiency and profitability.

Maize growers are exploring nano zinc and nano boron to correct widespread micronutrient deficiencies, while pulses such as chickpea, pigeon pea and lentil are being targeted with nano sulphur and nano boron to improve flowering and pod set. In oilseeds like mustard and soybean, nano sulphur and nano boron applications are of particular interest given the direct link between these nutrients and oil quality. Sugarcane, a heavy nutrient consumer, is being studied for nano nitrogen and nano potassium applications aimed at improving juice quality and reducing the crop's substantial fertilizer bill.

IFFCO Nano Fertilizers: India's Success Story

No account of nano agriculture in India is complete without the story of IFFCO — the Indian Farmers Fertiliser Cooperative Limited. In June 2021, IFFCO launched the world's first commercially available Nano Liquid Urea, developed at its Nano Biotechnology Research Centre in Kalol, Gujarat. This was followed in April 2023 by Nano DAP, and subsequently by Nano Zinc and Nano Copper, with a granular Nano NPK product under development at a revamped facility in Kandla, targeted for launch by April 2027.

IFFCO has invested roughly ₹2,000 crore since 2017 in research, manufacturing capacity and farmer outreach for its nano fertilizer range, and continues to invest around ₹200 crore annually in promotion and farmer training. By late 2025, cumulative nano urea production since launch had crossed 14 crore

ISSN: 2584-2471

bottles of 500 ml each, while combined nano fertilizer sales for the 2024–25 fiscal year touched roughly 3.64 crore bottles, growing 46 percent over the previous year. In the current fiscal, IFFCO has recorded sales of over 2.18 crore bottles of Nano Urea Plus and about 64 lakh bottles of Nano DAP, alongside encouraging early sales of Nano Zinc and Nano Copper — volumes that, IFFCO notes, are equivalent to hundreds of thousands of tonnes of conventional urea and DAP in nutrient terms, translating into real savings in logistics, energy and import costs.

Field demonstrations conducted with ICAR institutions, state agricultural universities and progressive farmers across states including Uttar Pradesh, Madhya Pradesh and Gujarat have shown encouraging results on rice and wheat, though IFFCO's own leadership has candidly acknowledged that domestic adoption has grown more slowly than hoped, running well below manufacturing capacity, in part due to limited farmer awareness and the behavioural shift required to move from bag-based to spray-based fertilization. In response, the cooperative has scaled up village-level training, deployed women-led "Drone Didi" teams to demonstrate precision foliar application using drones, and launched a nationwide nano fertilizer awareness campaign in 2026 to accelerate adoption. Internationally, IFFCO is building on this momentum with a new nano-fertilizer manufacturing plant in Brazil, expected to become operational in 2026, reflecting growing global interest in India's nano-fertilizer innovations and opening a genuine export opportunity for Indian nanotechnology.**Table 2: Advantages vs Challenges of Nano Fertilizers**

Advantages	**Challenges**
Higher nutrient-use efficiency	High production cost per unit of active nutrient
Lower bulk quantity required per acre	Limited farmer awareness and training
Reduced nutrient leaching and runoff	Uncertainty on long-term soil/ecological effects
Lower logistics and storage costs	Rigorous, still-evolving regulatory trial requirements
Potential for biofortified, higher-quality produce	Manufacturing standardisation across companies
Supports climate-smart, low-emission farming	Need for correct application equipment and technique
Opens new export and manufacturing opportunities	Farmer scepticism after inconsistent early trial results

Government Initiatives

ISSN: 2584-2471

India's policy architecture for nano fertilizers has evolved rapidly. The Department of Biotechnology's 2020 guidelines for evaluating nano-based agri-inputs created the first formal evaluation pathway, enabling nano urea's notification in 2021. The Ministry of Agriculture and Farmers Welfare has since amended the Fertilizer Control Order multiple times, most notably introducing Clause 20DA, which creates a dedicated five-year notification framework for nano fertilizers subject to rigorous multi-location trials conducted by ICAR institutions, State Agricultural Universities, or NABL-accredited laboratories.

The February 2024 and April 2024 amendments to the Fertilizer Control Order further tightened batch-testing requirements, mandated crop-specific package-of-practice guidance on product labels, and formalised a recommended combination of 75 percent conventional fertilizer dose with 25 percent nano fertilizer, based on positive trial evidence. The government has also explicitly prohibited the forced or bundled sale of nano fertilizers with other agri-inputs, protecting farmer choice. ICAR institutions — including ICAR-IARI, ICAR-IISS Bhopal, ICAR-IIWBR Karnal and several State Agricultural Universities — continue to run field evaluation trials and farmer awareness campaigns on efficient and balanced fertilizer use, including nano fertilizers, while digital extension platforms are increasingly being used to disseminate application guidance directly to farmers' mobile phones.

Future of Nano Agriculture

The next phase of nano agriculture is likely to be defined by convergence nanotechnology combining with artificial intelligence, the Internet of Things, and satellite-based remote sensing to create genuinely closed-loop precision farming systems. Nano-biosensors embedded in fields could feed real-time nutrient and moisture data into AI models that then recommend, or even automatically trigger, precisely calibrated nano fertilizer sprays through drone or automated sprayer systems.

Smart fertilizers that respond to soil pH, temperature or moisture by adjusting their own release rate are an active area of global research, as are fully biodegradable nano-carriers designed to eliminate any residual environmental concern. For India specifically, the priority in the coming years will be scaling up domestic manufacturing capacity, particularly for granular nano NPK products capable of replacing a larger share of bulk fertilizer volumes, alongside sustained investment in farmer training so that adoption finally catches up with production capacity. If these pieces come together, nano agriculture could become a central pillar of India's climate-smart agriculture strategy over the next decade.

Success Stories

A growing body of field-level evidence demonstrates the practical impact of nanofertilizers when applied correctly. Below are illustrative examples drawn from published field trials and industry data.

1. ICAR-affiliated rice trials in eastern and northern India have reported that combining nano urea foliar spray with a reduced basal urea dose can raise grain yield while cutting overall nitrogen fertilizer

ISSN: 2584-2471

requirement, echoing global findings of double-digit percentage yield gains alongside major nitrogen savings in rice.

2. At ICAR-IIWBR's Karnal research farm, multi-year trials combining nano urea with prilled urea under conservation tillage in wheat found measurable improvements in nitrogen-use efficiency and profitability compared with prilled urea alone.

3. Wheat trials examining nano zinc application have reported yield increases alongside a substantial rise in grain zinc content a biofortification benefit directly relevant to combating micronutrient malnutrition in India.

4. IFFCO's own nationwide field demonstrations across Uttar Pradesh, Madhya Pradesh and Gujarat have been used to promote nano urea and nano DAP as complements to conventional fertilizer in rice and wheat systems, contributing to the cooperative's rapid sales growth in these states.

5. Research on zinc oxide nanoparticles in Zn-deficient paddy soils in China found consistent yield gains along with improved milling quality and reduced chalkiness, evidence that the underlying nanoparticle science translates across different rice-growing geographies.

6. Wheat trials in Pakistan's Punjab region using nano DAP reported higher yields than conventional DAP at equivalent phosphorus rates, meaningfully reinforcing the cross-border relevance of nano-phosphorus technology for South Asian cropping systems.

7. IFFCO's international expansion, including a new nano fertilizer manufacturing plant in Brazil expected to begin operations in 2026, reflects strong early market response abroad and positions Indian nano fertilizer technology as an export success story in its own right.

8. Studies on urea nanoparticle substitution in lowland rice fields have found that up to a quarter of the conventional urea requirement can be replaced without harming beneficial soil bacteria or fungal populations, an encouraging signal for long-term soil microbiome health.

Table 3: Conventional Agriculture vs Nano Agriculture

Feature	**Conventional Agriculture**	**Nano Agriculture**
Nutrient application method	Bulk soil broadcasting	Foliar spray, seed treatment, nano-carriers
Pest/disease management	Broad-spectrum chemical sprays	Encapsulated, targeted-release nano-pesticides
Monitoring	Manual scouting, periodic soil testing	Nano-sensors, real-time biosensing
Irrigation approach	Fixed-schedule or flood irrigation	Sensor-guided, precision-timed irrigation

ISSN: 2584-2471

Feature	Conventional Agriculture	Nano Agriculture
Post-harvest handling	Conventional storage and packaging	Nano-enabled antimicrobial/active packaging
Input efficiency	Moderate, with substantial losses	High, engineered for minimal loss
Environmental footprint	Higher due to excess/runoff	Lower due to precision and controlled release

Conclusion

From Ramesh Chaudhary's cracking wheat field near Meerut to IFFCO's research laboratories in Kalol and its new manufacturing plant taking shape in Brazil, the story of nano fertilizers is really a story about Indian agriculture trying to break free of a decades-old treadmill of ever-higher input use and ever-thinner returns. The evidence assembled so far- rising nutrient-use efficiency, meaningful yield gains in numerous field trials, reduced environmental leakage, and a rapidly maturing regulatory framework- suggests that nano fertilizers and the wider field of nano agriculture are among the most promising innovations available to Indian farming today. Full success will depend on closing the awareness and training gap that currently separates production capacity from farm-level adoption, but if that gap can be closed through sustained extension efforts, transparent science, and responsible policy support, nano-fertilizers have a genuine claim to being remembered as a defining technology of India's next Green Revolution.

ISSN: 2584-2471

Public-Private Partnerships in Agricultural Extension Services

Neha Arya, [2]Bhawika Bisht and [2]Vikas Chandra Gautam

[1]SRF- Department of Agricultural Communication, G.B. Pant University of Agriculture and Technology, Pantnagar, U.S. Nagar, Uttarakhand

[2]Ph.D Scholar, Department of Agricultural Communication, G.B. Pant University of Agriculture and Technology, Pantnagar, U.S. Nagar, Uttarakhand

Corresponding mail: chandravikas602@gmail.com

Introduction

For most of the twentieth century, the picture of agricultural extension in India was a familiar one: a lone Village Extension Worker on a bicycle, carrying a bag of pamphlets, cycling between villages to demonstrate a new seed variety or explain a fertilizer dose. That system, built on the Training and Visit approach of the 1970s and 80s, helped power the Green Revolution. But India's farming population has since grown far beyond what any government department, however well-staffed, can reach village by village. Today there is roughly one extension functionary for every few thousand farm households in many districts, and the knowledge farmers now need on climate-resilient varieties, precision nutrient management, market prices, credit access and crop insurance has become far more complex than a single pamphlet can convey.

Into this gap has stepped an increasingly diverse set of private and non-government players: seed and agrochemical companies with their own field force, cooperative federations, farmer-producer organizations, agri-tech startups with mobile apps and AI chatbots, and corporate CSR programs running model villages. None of these have replaced the public extension system, and none are meant to. What has instead emerged, gradually and somewhat unevenly, is a hybrid model, the public-private partnership, or PPP, in agricultural extension in which government infrastructure, research and legitimacy combine with private capital, technology and last-mile delivery capacity to reach farmers more effectively than either could alone.

This article examines how that hybrid model actually works in India today: the institutional architecture that enables it, the major players involved, the successes and genuine limitations of the approach so far, and what it will take to make public-private collaboration in extension a durable pillar of India's agricultural development rather than a patchwork of pilot projects.

> *Did You Know? India's public extension system has historically been estimated to reach only a fraction of farm households directly each season, which is one of the central reasons policymakers began actively courting private and non-government partners from the late 1990s onward.*

What is a Public-Private Partnership in Extension?

ISSN: 2584-2471

A public-private partnership in agricultural extension is any structured arrangement in which government agencies, whether a state Department of Agriculture, an ICAR institute, or a Krishi Vigyan Kendra, share responsibility, resources, or infrastructure with a private, cooperative, or civil-society partner to plan, deliver, or finance farmer advisory services. This can range from something as simple as a seed company being permitted to demonstrate its hybrids on a government research farm, to something as elaborate as a state-wide digital advisory platform co-built by a technology company and a state agriculture department.

Why Extension Needed to Change

Three pressures have driven this shift. First, fiscal constraints have limited the ability of state governments to keep expanding extension staff at the pace farmer numbers and information needs demand. Second, the private sector- input companies, agri-tech firms, cooperatives- already possesses field networks, retail touchpoints, and digital platforms that overlap heavily with where farmers actually seek advice, making duplication wasteful. Third, the nature of the advice farmers need has diversified far beyond what a single government department can credibly deliver alone, spanning weather-based advisories, market intelligence, credit linkages, digital record-keeping and crop-specific agronomy.

Forms that PPPs in Extension Typically Take

In practice, PPP arrangements in Indian agricultural extension take several recurring forms: co-financed institutional models such as the Agricultural Technology Management Agency, or ATMA, which formally invites private and NGO participation into a government-anchored district society; contracted service delivery, in which a private firm or agri-tech company is engaged to deliver a specific advisory or training service on behalf of government; open digital infrastructure, such as AgriStack, that government builds and private companies are invited to build applications upon; and voluntary CSR-based collaboration, in which corporate programmes run parallel advisory or demonstration activities in coordination with local government extension staff.

Table 1: Traditional Public Extension vs PPP-Based Extension Models

Parameter	Traditional Public Extension	PPP-Based Extension
Delivery agent	Government extension officers only	Government plus private firms, NGOs, FPOs, agri-tech platforms
Funding source	Entirely government budget	Shared government, private and donor funding
Reach mechanism	Village-level physical visits	Physical visits plus mobile apps, call centres, kiosks, dealers
Technology use	Limited, mostly print/verbal	AI advisory, satellite data, apps, drones, IoT sensors

ISSN: 2584-2471

Parameter	Traditional Public Extension	PPP-Based Extension
Content focus	Generic package-of-practices	Crop- and location-specific, often data-driven advisory
Speed of scale-up	Slow, constrained by staffing	Faster, constrained by digital access and last-mile trust
Accountability	Departmental hierarchy	Shared, sometimes contractually defined performance metrics

The ATMA Model: India's Founding PPP Framework

The single most important institutional vehicle for public-private collaboration in Indian extension remains the Agricultural Technology Management Agency, or ATMA, scheme. Piloted between 1998 and 2005 in seven states under the World Bank-funded National Agricultural Technology Project, ATMA was designed explicitly to decentralize extension management to the district level and to build partnerships between government line departments, Krishi Vigyan Kendras, State Agricultural Universities, NGOs, Panchayati Raj institutions and, crucially, private input and service providers.

ATMA now operates as a registered society in hundreds of districts across nearly every state and union territory, governed by a Governing Board that by design includes representation from farmer groups and, in many districts, private sector and NGO stakeholders alongside government officials. Funding follows a shared pattern in which the central government provides the bulk of the grant-in-aid and state governments contribute the remainder, with the scheme now operating under the Sub-Mission on Agricultural Extension within the broader National Mission on Agricultural Extension and Technology. Beyond its funding architecture, ATMA's real innovation was procedural: it introduced bottom-up, farmer-driven planning through Strategic Research and Extension Plans developed at the block and district levels, rather than having extension priorities set entirely from the state capital.

Krishi Vigyan Kendras and Research-Extension-Industry Linkages

India's network of Krishi Vigyan Kendras, anchored by ICAR and typically hosted by State Agricultural Universities or NGOs, has increasingly become a natural convening point for public-private collaboration. KVKs regularly host seed, fertilizer, farm equipment and agri-tech companies for field demonstrations, frontline demonstrations and training-of-trainers programmes, allowing farmers to see new technologies validated on neutral, credible institutional ground rather than relying solely on a company's own sales pitch. The government has continued to prioritize strengthening this KVK network, with substantial recent budget allocations directed specifically at expanding KVK

ISSN: 2584-2471

infrastructure and capacity, recognizing it as one of the more trusted and durable bridges between research, industry and the farmer.

The Digital Agriculture Mission: A New Generation of PPP Infrastructure

If ATMA represents the first generation of institutionalized PPP in Indian extension, the Digital Agriculture Mission represents the second. Approved by the Union Cabinet in September 2024 with an outlay of roughly ₹2,817 crore, including a central government share of about ₹1,940 crore, the mission is built around a farmer-centric Digital Public Infrastructure, commonly referred to as AgriStack, comprising a Farmer Registry, a geo-referenced Crop Sown Registry built through digital crop surveys, and a Krishi Decision Support System that integrates satellite, soil, weather and water-resource data into a single geospatial platform

Private Sector and Agri-Tech Players in Extension

A distinctive feature of India's current PPP landscape is the sheer diversity of private actors now delivering extension-like services. Full-stack agri-tech platforms such as DeHaat combine input supply, AI-driven crop advisory, credit facilitation and market linkage in a single farmer-facing app, and have scaled to serve millions of farmers across more than a dozen states while also building export markets for aggregated produce. AgroStar has built one of India's largest farmer networks around agri-input e-commerce paired with crop advisory, while platforms such as Arya.ag focus on warehouse-backed financing that reduces distress selling by smallholders, and Cropin and Stellapps apply satellite- and IoT-based analytics, respectively, to crop and dairy advisory.

Alongside these startups, established input companies seed, fertilizer, and crop-protection majors continue to run their own farmer training programs, often in explicit coordination with state agriculture departments and KVKs, so that company-led demonstrations feed into, rather than duplicate, the official extension calendar. Cooperative federations, most notably IFFCO, similarly combine input supply with farmer training in the proper use of new products such as nano-fertilizers, working through their vast network of primary cooperative societies in close coordination with government agricultural offices. On the government-support side, dedicated vehicles such as the Rs 750 crore AgriSURE fund, jointly capitalized by the central government and NABARD, with the remainder mobilized from private investors, exist specifically to finance innovative, technology-driven agri-startups, formalizing the funding side of the public-private relationship.

Table 3: Key PPP Institutional Vehicles in Indian Agricultural Extension

Institution/Scheme	Nature of Partnership	Primary Focus
ATMA (district societies)	Government-anchored, multi-stakeholder governing board	District-level extension planning and delivery

ISSN: 2584-2471

Institution/Scheme	Nature of Partnership	Primary Focus
Krishi Vigyan Kendras	ICAR/SAU-hosted, private/company demonstration partner	Technology validation and farmer training
Digital Agriculture Mission / AgriStack	Government-built infrastructure, private app layer	Farmer ID, crop registry, digital advisory
AgriSURE Fund	Government + NABARD + private investor co-financing	Financing agri-tech and rural enterprise startups
Namo Drone Didi	Government skilling/subsidy, private service delivery	Women-led drone spraying and advisory services
Cooperative networks (e.g., IFFCO)	Farmer-owned cooperative, government-aligned	Input supply combined with farmer training

Applications Across the Extension Value Chain

PPP arrangements now touch nearly every stage of the extension value chain in India. In technology demonstration, private seed and input companies co-host field days with KVKs and state departments to showcase new varieties and practices under real farming conditions. In advisory delivery, government helplines such as the Kisan Call Centre now sit alongside private AI-chatbot advisory tools and apps like Kisan Suvidha, which consolidates weather, market price, input dealer and plant protection information in one place. In market linkage, e-NAM, the government's online trading platform now covering more than 1,600 mandis, works alongside private aggregation and logistics platforms that connect smallholders directly to institutional buyers.

Did You Know? The Namo Drone Didi scheme, launched in March 2024 with an outlay of around ₹1,261 crore over three years, trains women from self-help groups as drone pilots who then offer paid spraying and advisory services to farmers in their area, a rare example of a PPP model that is simultaneously a livelihood, extension and technology-adoption program.

Applications Relevant to Uttar Pradesh and the Indo-Gangetic Plains

For Uttar Pradesh specifically, PPP-based extension has particular relevance given the state's scale and the diversity of its cropping systems, from the sugarcane belt of western districts to the paddy and wheat systems of the central plains and the Basmati rice tracts closer to the Terai region. AgriStack pilot work has already begun in Farrukhabad district, testing digital crop survey and farmer ID systems that could eventually support far more precisely targeted extension advisories for potato, wheat and other locally important crops. IFFCO's cooperative network, dense across the state, continues to

ISSN: 2584-2471

combine input supply with farmer training on both conventional and nano fertilizer products, while private agri-tech platforms including DeHaat and AgroStar have built out significant farmer bases across the state's districts, complementing the district-level ATMA societies and KVKs that remain the backbone of formal government extension.

Table 2: Advantages vs Challenges of PPP in Agricultural Extension

Advantages	Challenges
Wider and faster reach through existing private networks	Uneven rural digital and internet access
Access to advanced technology (AI, satellite, IoT)	Interoperability gaps between public and private systems
Shared financing reduces pressure on public budgets	Data privacy and ownership concerns at scale
Faster, more localised advisory content	Potential conflict of interest in company-led advisory
Neutral, credible technology validation via KVKs/ATMA	Land record and baseline data quality gaps
New livelihood models (e.g., Drone Didi)	Financial sustainability of venture-funded private partners
Encourages innovation and agri-startup ecosystem growth	Risk of favouring larger, better-connected farmers first

Government Initiatives Supporting PPP in Extension

India's policy architecture has steadily deepened its support for public-private collaboration in extension. The Sub-Mission on Agricultural Extension, operating under ATMA's institutional umbrella, continues to formally embed multi-agency and private-sector participation into district-level extension planning. The Digital Agriculture Mission, alongside its AgriStack infrastructure, has been explicitly designed with open APIs so that private agri-tech companies can build farmer-facing applications on shared public data rather than each building isolated systems. The Agriculture Accelerator Fund, announced with a Rs 500 crore allocation, and the more recently launched Bharat AgriTech Foundation are aimed specifically at incubating and scaling agri-tech startups in coordination with ICAR and NABARD.

The AgriSURE fund, with a Rs 750 crore corpus split among the government, NABARD, and private investors, exists specifically to finance high-risk, high-impact agri-technology ventures relevant to extension and the wider value chain. Continued budget allocations to strengthen Krishi Vigyan Kendras and Krishi Decision Support Systems reinforce the institutional backbone on which private

Volume-3, Issue 7
ISSN: 2584-2471

partnerships are built, while schemes like Namo Drone Didi provide a template for combining public skilling and subsidy support with private, farmer-facing service delivery.

Did You Know? The Rs 750 crore AgriSURE fund is structured as a genuine three-way public-private partnership, Rs 250 crore from the Government of India, Rs 250 crore from NABARD, and the remaining Rs 250 crore mobilized from private investors, specifically to finance high-risk, technology-driven agricultural startups.

Success Stories

1. ATMA's pilot experience in Bihar, extensively documented in agricultural extension research, demonstrated how a formally constituted, multi-stakeholder district society could bring NGOs, private input suppliers and farmer groups into a shared planning process, providing a template later replicated nationwide.

2. DeHaat's full-stack model, combining input supply, AI advisory, credit facilitation and market linkage, crossed ₹3,000 crore in revenue in FY25 while serving farmers across a dozen states and expanding into export markets — illustrating how a private extension-adjacent platform can achieve both scale and commercial sustainability.

3. AgroStar's farmer network, now exceeding five million active users, has attracted international climate-focused investment, reflecting growing confidence that private, technology-enabled advisory and input platforms can operate at genuine national scale.

4. The Digital Agriculture Mission's Kisan e-Mitra AI advisory tool has already resolved more than 93 lakh farmer queries across 11 languages, demonstrating how public digital infrastructure, opened to private technology partners, can deliver conversational advisory at a scale no physical extension network could match.

5. IFFCO's cooperative extension network, built around village-level primary societies, has been central to farmer training efforts accompanying the rollout of nano fertilizers, showing how a farmer-owned cooperative can function as a durable and trusted PPP-adjacent extension channel.

6. The Namo Drone Didi initiative has begun training thousands of women self-help group members as drone pilots, converting a public skilling and subsidy scheme into a genuinely private, farmer-facing rural enterprise offering spraying and, increasingly, advisory-linked services.

7. AgriStack's early pilot in Farrukhabad district of Uttar Pradesh, alongside five other districts nationally, is testing how a shared digital farmer and crop registry can eventually underpin far more targeted, locally relevant extension advisory for crops including potato and wheat.

ISSN: 2584-2471

Conclusion

From the World Bank-funded ATMA pilots of the late 1990s to today's AgriStack-enabled digital advisory ecosystem, India's extension system has traveled a long distance toward genuine public-private collaboration. Cooperatives like IFFCO, agri-tech platforms like DeHaat and AgroStar, and government-anchored institutions like KVKs and ATMA societies now operate as part of a single, if still imperfectly coordinated, advisory ecosystem that reaches farmers through village meetings, mobile apps, drone services, and AI chatbots alike. The evidence so far suggests this hybrid approach genuinely extends the reach, technological sophistication and responsiveness of extension services beyond what either government or the private sector could deliver alone, provided the persistent challenges of digital access, data interoperability, conflict of interest and land-record quality are addressed with the same seriousness as the technology itself. Done well, public-private partnership in agricultural extension has a strong claim to being one of the more durable institutional innovations supporting Indian agriculture's modernization in the years ahead.

ISSN: 2584-2471

Royal Jelly, Propolis, and Bee Pollen: Nature's Hidden Treasures from the Beehive

Ajita Singh[1], Shudhanshu Baliyan[3*], Nikhil Kumar[2], Vishvendra[2]

[1]Department of Plant Pathology,
Sardar Vallabhbhai Patel University of Agriculture and Technology, Meerut, U.P. 250110,
[2]Department of Entomology,
Sardar Vallabhbhai Patel University of Agriculture and Technology, Meerut, U.P. 250110,
[3]Department of Entomology,
Govind Ballabh Pant University of Agriculture and Technology, Pantnagar, Uttarakhand, 263145,

[*]Corresponding author mail: shudhanshubaliyan@gmail.com

Abstract

For thousands of years, honeybee colonies have supplied humans with far more than honey. Royal jelly, propolis, and bee pollen are three functional bee-derived products that have moved from folk remedies into the modern nutraceutical and pharmaceutical spotlight. Royal jelly, the glandular secretion that transforms an ordinary larva into a fertile queen, is rich in unique proteins, fatty acids such as 10-hydroxy-2-decenoic acid, and B-vitamins that together support antioxidant, anti-inflammatory, and anti-aging activity. Propolis, the resinous "bee glue" collected from plant buds and bark, contains a dense mixture of flavonoids and phenolic acids that give it broad antimicrobial, antioxidant, and immune-modulating properties. Bee pollen, a nutrient-packed blend of flower pollen, nectar, and bee secretions, supplies proteins, essential amino acids, lipids, vitamins, and antioxidant polyphenols and is increasingly studied as a functional food. This article synthesizes recent scientific literature on the composition, purported health benefits, and safety considerations of these three apiary treasures, while offering practical guidance for consumers who wish to explore them responsibly.

Keywords: royal jelly; propolis; bee pollen; apitherapy; functional food; antioxidant; nutraceutical; bee products

1. Introduction

Long before pharmaceuticals lined store shelves, humans looked to the beehive for medicine. Ancient Egyptian, Greek, and Chinese texts describe the use of honey, propolis, and other hive products to treat wounds, infections, and fatigue (Cornara *et al.,* 2017; Kocot *et al.,* 2018). Today, that ancient practice

ISSN: 2584-2471

has a modern name, apitherapy, and a growing body of peer-reviewed research behind it. Among the many gifts of the hive, three products stand out for their unusually rich and complex chemistry: royal jelly, propolis, and bee pollen.

These three substances are often lumped together under the umbrella of "bee products," but they are biologically distinct. Royal jelly is a glandular secretion produced by young worker bees to feed the queen and young larvae. Propolis is a resinous substance bees gather from tree buds and mix with wax and their own enzymes to seal and disinfect the hive. Bee pollen is the pellet of flower pollen that foraging bees pack onto their hind legs, moisten with nectar and salivary enzymes, and carry home as the colony's primary protein source (Kostić *et al.,* 2024). Each has its own nutrient profile, its own proposed mechanisms of action, and its own body of clinical evidence, ranging from promising to still preliminary.

This article reviews what current science says about each product, in turn, before comparing their safety profiles and offering a balanced perspective for anyone curious about adding them to a wellness routine.

2. Royal Jelly: The Food of Queens

2.1 What It Is and How It Is Made

Royal jelly is a thick, milky-white secretion produced by the hypopharyngeal and mandibular glands of young nurse bees. While all honeybee larvae receive royal jelly for the first few days of life, only the larva selected to become the next queen is fed royal jelly exclusively throughout its development. This single dietary difference is enough to turn a genetically ordinary female larva into a queen that is larger, more fertile, and many times longer-lived than her worker sisters (Bălan *et al.,* 2020). Understandably, this dramatic biological effect has fascinated scientists and made royal jelly one of the most intensively studied hive products.

2.2 Composition

Chemically, royal jelly is remarkably complex. Water accounts for roughly 50 to 60 percent of its fresh weight, while the remainder is composed of proteins (around 12 to 15 percent), carbohydrates, lipids, and trace vitamins and minerals (Botezan *et al.,* 2023). Its carbohydrate fraction is dominated by fructose and glucose, with smaller amounts of sucrose, maltose, and trehalose. Among its most studied components are the major royal jelly proteins (MRJPs), particularly MRJP1, MRJP2, and MRJP3,

ISSN: 2584-2471

which appear to support cell growth and tissue repair. Royal jelly also contains a unique fatty acid rarely found elsewhere in nature, 10-hydroxy-2-decenoic acid (10-HDA), which is considered a key marker of quality and a major contributor to its biological activity (Botezan *et al.,* 2023).

2.3 Proposed Health Benefits

Laboratory and animal research suggests that royal jelly's proteins and fatty acids give it antioxidant, anti-inflammatory, antimicrobial, antitumor, and anti-aging properties (Botezan *et al.,* 2023). Mechanistically, compounds such as 10-HDA appear to inhibit certain inflammatory enzymes and modulate cell-signaling pathways involved in immune regulation. Emerging research has also linked royal jelly intake to beneficial shifts in gut microbial populations, which may partly explain its systemic immune effects (Oršolić & Jazvinšćak Jembrek, 2024).

Human studies, while still limited in number, are encouraging. A systematic review of clinical and preclinical research concluded that royal jelly improves markers of immune function, supports wound healing, and may reduce the severity of chronic conditions such as diabetes and cardiovascular disease, likely through modulation of inflammatory signaling pathways such as NF-κB and AMPK. A separate meta-analysis of randomized controlled trials found that royal jelly supplementation measurably lowered inflammatory and oxidative stress markers, including C-reactive protein and malondialdehyde, compared with placebo. Royal jelly has also drawn particular interest as a natural option for easing menopausal symptoms and age-related conditions, with several trials reporting improvements in menopausal symptom scores and markers of skin and bone aging (Bălan *et al.,* 2020).

2.4 A Word of Caution

Despite this promise, researchers are consistent in noting that royal jelly research still lacks standardized dosing protocols and long-term safety data, and that nutrient content varies considerably depending on the bee colony, geography, and season of harvest (Balkanska *et al.,* 2012). Consumers should therefore treat commercial claims with appropriate skepticism and view royal jelly as a complementary, not curative, addition to a healthy lifestyle.

3. Propolis: The Bees' Own Antibiotic

3.1 What It Is and How It Is Made

ISSN: 2584-2471

Propolis, sometimes called "bee glue," is a sticky resin that bees produce by mixing plant resins and buds, primarily from poplar, birch, and conifer trees, with beeswax and their own salivary enzymes. Bees use propolis to seal cracks in the hive, smooth internal surfaces, and, crucially, to varnish the hive walls with an antimicrobial coating that helps protect the colony from bacteria, fungi, and viruses (Kocot *et al.,* 2018). This defensive role in nature translates directly into the therapeutic properties researchers have identified in humans.

3.2 Composition

Propolis typically consists of about 50 percent resins and balsams, 30 percent waxes, 10 percent essential and aromatic oils, 5 percent pollen, and 5 percent other organic compounds, although this ratio varies widely by region and plant source (Zulhendri *et al.,* 2024). More than 300 individual compounds have been identified in various propolis samples, with flavonoids such as quercetin, chrysin, and pinocembrin, along with phenolic acids like caffeic acid and its derivative caffeic acid phenethyl ester (CAPE), considered the primary drivers of its biological activity (Bhatti et al., 2023; Biochemical Profile and Antioxidant Properties of Propolis from Northern Spain, 2023).

3.3 Proposed Health Benefits

Propolis has one of the best-documented antimicrobial profiles among natural bee products. Extracts have shown activity against a range of Gram-positive and Gram-negative bacteria, as well as fungi such as Candida albicans, and studies have found that propolis can act synergistically with conventional antibiotics like amoxicillin and chloramphenicol (review on propolis and oral health and microbiota balance, 2023). Its antioxidant capacity, driven largely by its polyphenol content, has also been repeatedly confirmed using standard laboratory assays such as DPPH and FRAP (Pobiega *et al.,* 2024).

Clinically, propolis has been studied for oral health, where it appears to reduce dental plaque and support gum health; for metabolic conditions, where trials have reported improvements in fasting blood sugar, HbA1c, and lipid profiles among people with metabolic syndrome and diabetes (randomized controlled trial on propolis and metabolic syndrome indices, 2023); and for general inflammation, where a meta-analysis of randomized controlled trials found that propolis supplementation reduced several inflammatory and oxidative stress biomarkers in adults, though the authors cautioned that results across trials remain somewhat inconsistent (meta-analysis of propolis supplementation on inflammatory and oxidative stress biomarkers, 2024). Propolis has additionally been explored for cardiovascular health, kidney function, non-alcoholic fatty liver disease, and even as a supportive

ISSN: 2584-2471

material in dental implant procedures, where it has been shown to promote antibacterial activity and stimulate bone-forming cells around the implant site (systematic review of propolis in dental implantology, 2024).

3.4 A Word of Caution

Because propolis is derived from tree resins, people with known allergies to poplar, conifer, or related tree pollens face an elevated risk of allergic contact dermatitis or more serious hypersensitivity reactions (Bee Pollen, Propolis, and Royal Jelly: Incredible Health Benefits, n.d.). Raw propolis may also contain environmental contaminants or insect fragments, underscoring the importance of sourcing it from a reputable, quality-tested supplier (Bee Products: Beeswax, Bee Pollen, Propolis, LiverTox, 2022).

4. Bee Pollen: A Nutritional Powerhouse

4.1 What It Is and How It Is Made

Bee pollen is not simply flower pollen. It is a granule formed when foraging bees pack pollen collected from flowers onto their hind legs and moisten it with nectar and salivary secretions before carrying it back to the hive, where it serves as the colony's principal source of protein, especially for feeding developing larvae (Ares, Valverde, Bishop, Nozal, & Bernal, 2023). Beekeepers can harvest a portion of these pellets using pollen traps at the hive entrance without harming the colony.

4.2 Composition

Bee pollen's nutrient density is exceptional. On average, it contains around 22.7 percent protein, including all nine essential amino acids such as isoleucine, lysine, and leucine, alongside carbohydrates, fiber, healthy lipids, vitamins, and minerals (Bee pollen beyond nutrition: an integrated review, 2024). More than 250 distinct biologically active substances have been identified across various pollen samples, including antioxidant flavonoids and phenolic acids whose exact profile depends heavily on the plant species, geographic origin, and season of collection (12 Potential Health Benefits of Royal Jelly, cross-referenced with 10 Potential Health Benefits of Bee Pollen, 2024). One practical caveat is that bee pollen's outer wall is tough and somewhat resistant to human digestive enzymes, which can limit the bioavailability of its nutrients unless the pollen is cracked, fermented, or

ISSN: 2584-2471

otherwise processed (Bee Pollen: A Superfood with Health Benefits and Digestibility Challenges, 2023).

4.3 Proposed Health Benefits

Because of its diverse phytochemical content, bee pollen has been studied for a wide range of potential effects. In vitro and animal research indicates strong antioxidant and anti-inflammatory activity, with compounds like quercetin appearing to suppress pro-inflammatory pathways involving tumor necrosis factor and inflammatory omega-6 fatty acid derivatives (10 Potential Health Benefits of Bee Pollen, 2024). A 2024 laboratory study specifically found that pollen from acorn and hardy kiwi (darae) flowers reduced inflammatory and oxidative markers, leading researchers to suggest bee pollen as a potential complement to conventional anti-inflammatory approaches (10 Potential Health Benefits of Bee Pollen, 2024).

Beyond inflammation, bee pollen has shown antimicrobial, antiviral, neuroprotective, hepatoprotective, and immune-stimulating activity in experimental models, and researchers have proposed applications ranging from metabolic disorders to cardiovascular support and even wound healing (Frontiers review on bee pollen as a food and feed supplement, 2024). A broader scoping review of translational research concluded that while bee pollen shows genuine promise for malnutrition, digestive health, and metabolic and cardiovascular conditions, robust human clinical trials remain relatively scarce compared to the large body of laboratory and animal data (Translational Research on Bee Pollen as a Source of Nutrients, 2023). The global market for bee pollen as a stand-alone dietary supplement has grown accordingly, reflecting rising consumer interest even as the clinical evidence base continues to mature (Translational Research on Bee Pollen as a Source of Nutrients, 2023).

4.4 A Word of Caution

Bee pollen carries one of the higher allergy risks among hive products because it is, by definition, composed largely of plant pollen, a well-known allergen category. Reactions can range from mild oral itching to severe anaphylaxis in sensitized individuals. First-time users are generally advised to start with a very small amount to test tolerance before increasing intake.

5. Comparing the Three: Safety, Overlap, and Practical Guidance

ISSN: 2584-2471

Although royal jelly, propolis, and bee pollen differ in origin and composition, they share a few important themes. First, all three owe much of their biological activity to polyphenols, flavonoids, and other antioxidant compounds that neutralize oxidative stress at the cellular level (Bhatti *et al.,* 2024). Second, all three are, in principle, produced from the same colony and can therefore trigger cross-reactive allergic responses in individuals who are sensitive to bee stings, bee venom, or other hive products. Third, none of the three should be viewed as a replacement for prescribed medical treatment; rather, current evidence positions them as complementary, food-based sources of antioxidant and anti-inflammatory compounds.

From a practical standpoint, a few precautions are worth highlighting:

- Anyone with known allergies to bees, bee stings, or bee products, or with asthma, should avoid these supplements or use them only under medical supervision, since severe allergic reactions, including anaphylaxis, have been documented.
- People with pollen or tree-resin allergies (for example, to poplar or birch) should be especially cautious with propolis and bee pollen.
- Royal jelly may interact with blood-thinning medications such as warfarin and with blood-pressure-lowering drugs, so anyone on such medication should consult a physician first.
- Pregnant and breastfeeding individuals should seek medical advice before use, as safety data in these populations remain limited.
- Because product quality and nutrient content vary by source, geography, and processing method, consumers should choose reputable, quality-tested brands (Balkanska *et al.,* 2012).

Taken together, the picture that emerges from recent research is one of cautious optimism. Royal jelly, propolis, and bee pollen each contain genuinely bioactive compounds capable of measurable effects on inflammation, oxidative stress, and microbial activity in laboratory and clinical settings. At the same time, researchers across multiple recent reviews converge on a common conclusion: more large-scale, standardized human trials are needed before these products can be confidently recommended for specific medical conditions.

6. Conclusion

Royal jelly, propolis, and bee pollen represent three of the beehive's most chemically sophisticated products, each shaped by millions of years of insect evolution to serve a very specific biological purpose: nourishing a queen, defending a colony, or feeding a brood. That same chemistry, it turns out, has real relevance to human health. Modern analytical techniques have confirmed that these products are packed with proteins, fatty acids, vitamins, and polyphenols capable of antioxidant, anti-inflammatory, and antimicrobial activity in laboratory and animal studies, with a growing, though still developing, body of human clinical evidence behind them.

For consumers, the most sensible approach is one of informed curiosity rather than blind enthusiasm. These bee products can be a reasonable addition to a varied, balanced diet for most healthy adults, but they are not miracle cures, and individuals with bee, pollen, or tree-resin allergies should approach them with real caution. As research continues to mature, particularly through larger and more standardized clinical trials, science may yet validate many of the traditional uses that beekeepers and healers have championed for centuries. Until then, nature's hidden treasures from the hive remain a fascinating, evidence-informed complement to, rather than a substitute for, modern healthcare.