Precision Crop Protection through Drone Technologies - Emerging Approaches in Insect Pest Management with Reference to Indian Context

Rittik Sarkar, Rajna S, Yuvaraj H M, Sneha Sharma, Tanusree Ghosh

The increasing need for sustainable crop protection, along with labour shortages, rising production costs, and concerns about pesticide misuse, has sparked interest in drone technologies for agriculture. Unmanned aerial vehicles (UAVs) or drones now a days have gained attention for its ability to improve pest monitoring, plant observation, and pesticide application. Especially in India, where fragmented landholdings, recurrent pest outbreaks, changing climates, and dependence on labour-intensive practices most of the times limit the effectiveness of conventional spraying methods. Changing role of drones in managing insect pests, focusing on Indian agriculture is highlighted in this chapter. It examines how the developments in remote sensing, thermal and multispectral imaging, artificial intelligence, geographic information systems (GIS) and autonomous flying technologies are transforming drones from basic aerial sprayers to important decision-support tools. It highlights UAV-based pest detection, precise insecticide application, spray deposition dynamics, and how drones fit into Integrated Pest Management (IPM) programs. Drones offer many benefits, including improved accuracy, timely application, and reduction in risk for the operators while being more efficient with resources. However various challenges such as technological barriers, regulatory issues, high costs and ecological safety may continue to affect the comprehensive use of drones.

Keywords: *Precision agriculture, Drones, GIS, Crop protection, IPM, Artificial intelligence*

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Introduction

Agriculture is facing a tough challenge now a days, meeting the rising food demand while minimising environmental harm and boosting resource efficiency. Despite significant progress in pesticide development, mechanization, and crop management, insect pests still cause notable losses in agricultural output, especially in tropical and subtropical areas where climate changes and intensive farming lead to pest outbreaks (Subramanian et al., 2021). In India, pest-related losses are a major issue across cereals, pulses, oilseeds, cotton, vegetables, and plantation crops. At the same time, the ecological costs of traditional pesticide-heavy farming have become clearer. Regular preventative spraying, poor application, lack of surveillance, and careless insecticide use have led to resistance, loss of natural predators, environmental pollution, and rising concerns about food safety and ecosystem health (Qin et al., 2016; García-Munguía et al., 2024).

Traditional pesticide uses in India which includes the use of knapsack sprayers still is the norm. Although these may be low cost and easy to access, we see that they do have issues with respect to variable coverage, large scale spray loss, and high health risk for the operators. Also in large scale rice fields, in dense crop growth, in plantations and very tough terrain which require timely and efficient spraying we see that these systems' performance breaks down (Meng et al., 2018). Also, at the same time we see an increase in the use of external inputs which is a result of the growth of intensive agriculture which in turn is putting more stress on the eco system (Guebsi et al., 2024). Also, we see an increase in the incidence of what we may term as pest out breaks which include fall army worm in maize, rugose spiralling white fly in coconut, and brown planthopper in rice which in turn is a reflection of the fragile state of our present-day production systems (Sorahia et al., 2025).

To combat this challenge, precision agriculture has emerged as a consortium of technologies: remote sensing and geospatial analytics, automated sensing platforms for soil moisture stress detection, variable-rate irrigation technologies including the real-time decision-support systems to increase management efficiency, by utilizing data-processing tools that use computerized algorithms (Subramanian et al., 2021 Saini et al., 2024). In relation to pest management this is important for the reason that insect numbers rarely are even across fields. In fact, pests rarely infect entire forests meaning widespread pesticide use is both economically inefficient and unsustainable. And, thus precision pest management targets interventions based on spatial and ecological information (Saini et al., 2024).

Among the technologies driving this transition, drones have attracted considerable attention. Equipped with advanced imaging systems, GPS-enabled navigation, artificial intelligence, and automated spraying mechanisms, drones now serve as valuable tools for crop surveillance, precision spraying, and digital farm management (Guebsi et al., 2024). Their adoption has gained momentum in India through regulatory reforms by the Directorate General of Civil Aviation (DGCA), the Kisan Drone initiative, government subsidy programmes, and increasing participation of private technology companies (Singh & Singh, 2025). Research institutions such as ICAR, Tamil Nadu Agricultural University, Punjab Agricultural University, PJTSAU, and ICAR-IARI have also contributed significantly to evaluating drone performance, spray optimization, and operational protocols. Even so, drone-enabled crop protection is still evolving. Challenges related to battery life, payload capacity, spray drift, operational standardization, cost, technical expertise, and smallholder accessibility continue to influence adoption. In addition, the long-term ecological implications of UAV-assisted pesticide application require further investigation before these technologies can achieve their full potential in sustainable crop protection systems.

Types of Agricultural Drones and Components

There are several types and configurations of agricultural UAVs (Table 1). They usually fall into three categories: multi rotor, fixed wing, or hybrid. The most common ones for spraying are multi-rotor drones, which typically have 4 to 8 rotors and can hover and manoeuvre over dense crops. Fixed-wing drones look like small airplanes; they have a longer range and endurance but need space for take-off and landing. Hybrid VTOL systems combine both features. According to the Indian Drone Rules, 2021, UAVs used in agriculture are classified by weight: nano (<2 kg), micro/small (2-25 kg), and medium (25-150 kg). Light drones under 25 kg usually have smaller payloads, making them useful for scouting and spot spraying. Medium class drones are weighing 25-50 kg when empty and holding up to about 100 kg when loaded can support 10-40L tanks and allow for higher acceleration.

Each drone has several important components like an airframe, propulsion system (electric motors or petrol engines), power source (batteries or fuel tanks) and a flight controller or GPS for stabilisation, along with payload systems. For spraying, the payload includes a chemical tank, pump, plumbing and nozzles or atomizers. Sensors like cameras, LiDAR, thermal/IR, and multispectral devices, are mounted for monitoring. Communication links and ground control stations allow for remote operation (Rathore, 2026).

Table 1. Classification, operational characteristics, and major components of agricultural UAV systems used in precision crop protection

UAV category	Structural characteristics	Typical payload capacity	Major agricultural applications	Advantages	Operational limitations
Multi-rotor UAVs (Quadcopter, Hexacopter, Octocopter)	Vertical take-off and landing (VTOL); multiple rotors, high manoeuvrability and hover stability	~5-40 L spray payload depending on configuration	Precision spraying, spot application, crop scouting, multispectral imaging, pest surveillance	Excellent manoeuvrability, suitable for fragmented farms and dense canopies and effective in rice ecosystems	Limited flight endurance, shorter operational range, battery constraints
Fixed-wing UAVs	Airplane like aerodynamic structure, requires runway or launch mechanism	Lower spraying suitability, higher surveillance range	Large scale mapping, crop monitoring, NDVI analysis, field surveying	Long flight duration, larger coverage area, energy efficient	Limited hovering capability, unsuitable for localized precision spraying
Hybrid VTOL UAVs	Combines fixed-wing endurance with VTOL	Moderate to high payload capacity	Precision agriculture, large-area	Combines flexibility and long-range operation	Complex operational systems; relatively

	capability		surveillance, variable-rate application		expensive
Nano UAVs (<2 kg)	Lightweight compact systems; highly portable	Very low payload	Educational use, localized scouting, experimental imaging	Low cost and easy operation	Minimal payload and operational range
Micro and small UAVs (2-25 kg)	Medium sized operational UAVs commonly used in agriculture	Small to medium payloads	Precision spraying, crop monitoring, spot application	Operational flexibility and suitable for smallholder agriculture	Moderate flight time limitations
Medium agricultural UAVs (25-150 kg)	Heavy duty agricultural platforms with large tanks and high endurance	~10-40 L or higher spray capacity	Large scale pesticide application and precision crop protection	High operational efficiency and field capacity	Higher cost and regulatory requirements

Drone Technology and the Changing Landscape of Precision Agriculture

The increased use of drones in farming is a part of a wider move towards digital and data-led farming systems. Improvements in remote sensing, embedded electronics, autonomous navigation, artificial intelligence, and miniaturized imaging technologies have broadened the use of unmanned aerial vehicles (UAVs) well beyond their initial military applications (Sarkar et al., 2024). For decades, aerial pesticide application has been carried out using manned aircraft. However, such systems remained impractical for many developing countries, including India, due to high operational costs, fragmented landholdings and limited infrastructure. The advent of lightweight UAVs changed this scenario, making precision aerial operations feasible at farm-level scales (Morales-Rodríguez et al., 2022). The agricultural use of drones in Japan received early momentum, especially in rice-based production systems where labour shortages and small field sizes stimulated the use of unmanned helicopters for crop protection (Avhale et al., 2024). India is a particularly fertile environment for drone adoption. Conventional spraying methods often face problems in flooded rice fields, pesticide-intensive cotton ecosystems, tea plantations, horticultural crops on difficult terrain, and densely planted vegetable systems. At the same time, reduced availability of agricultural labour has stimulated interest in technologies that can improve timeliness and reduce reliance on manual operations (Matre et al., 2024).

Agricultural drones are usually classified into three types that is fixed-wing, rotary-wing, and hybrid systems. Fixed-wing drones work well for large area surveillance and mapping because they can fly longer distances. In contrast, rotary-wing drones, such as quadcopters and hexacopters, are better for spraying operations. They can hover, manoeuvre precisely, and handle fragmented fields and waterlogged conditions often found in India (García-Munguía et al., 2024; Beriya, 2022). Hybrid systems aim to combine the flight endurance of fixed-wing drones with the flexibility of rotary-wing ones (Brito et al., 2019).

Modern agricultural UAVs include a mix of hardware and software components. These consist of flight controllers like GPS or RTK-GPS units, onboard processors, spray systems and imaging sensors. RGB cameras mainly help with timely crop monitoring. Multispectral, hyperspectral and thermal sensors allow for early detection of crop stress due to pests, diseases, or lack of water (Guebsi et al., 2024). The use of RTK-GPS navigation and GIS-based mapping has also improved precision. This lets farmers apply pesticides only in targeted areas instead of across entire fields (Guebsi et al., 2024). Consequently, drones are shifting from being simple aerial tools to smart decision-support resources in modern precision agriculture.

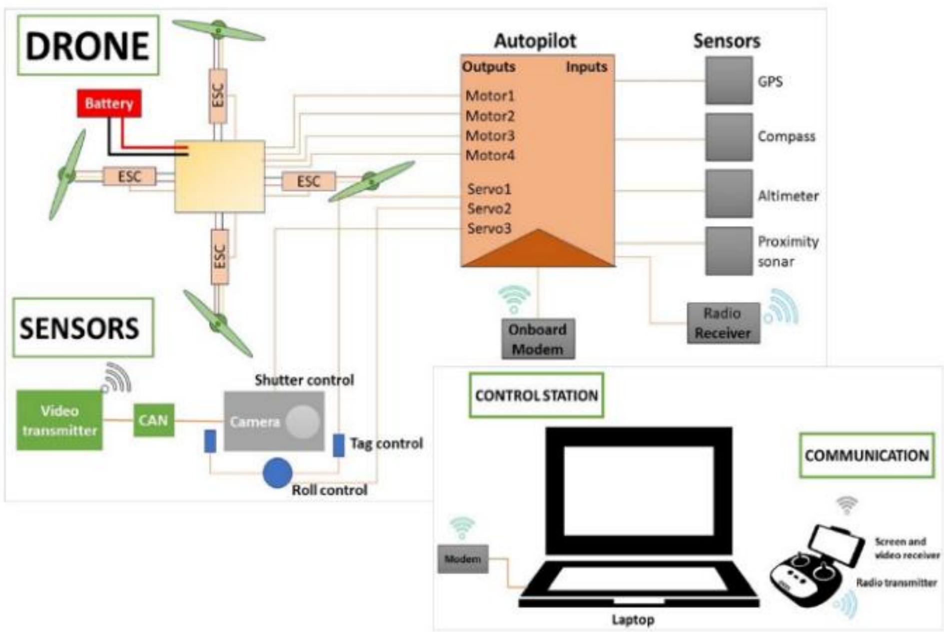

Figure 1. Structural components and operational architecture of agricultural UAV systems used in precision agriculture and crop protection (Guebsi et al., 2024)

Precision Pest Management and Drone-Assisted Surveillance

Precision pest management is based on a simple ecological fact, that is, insect pests do not spread evenly across a field. Their distribution is often influenced by differences in crop growth, soil conditions, irrigation methods, and local microclimates leading to specific hotspots for infestations. However, traditional pesticide applications usually treat entire fields as if pest problems were uniform. This generally results in unnecessary chemical usage and extra costs (Saini et al., 2024; Subramanian et al., 2021).

Drones are changing this method by delivering quick, detailed information on crop health and pest distribution. With real-time monitoring and spatial analysis, UAVs allow management decisions to be grounded in actual field conditions instead of assumptions (Awais et al., 2023). Drones equipped with multispectral and thermal sensors can pick up subtle physiological changes related to pest attacks. These changes include variations in chlorophyll levels, canopy reflectance, transpiration patterns and leaf temperature before visible symptoms appear (Aziz et al., 2025). Vegetation indices like NDVI and thermal stress indicators enhance the ability to spot localised infestations and emerging trouble spots (Ahmed et al., 2018).

The benefits of drone-based monitoring become especially clear for pests that appear in small patches rather than throughout the fields. Aphids, whiteflies and brown planthoppers generally show grouped population patterns (Table 2). This makes targeted interventions both economically and environmentally sensible (Saini et al., 2024). Progress in artificial intelligence has further boosted detection accuracy by allowing automated analysis of multispectral images and crop stress signals (Aziz et al., 2025). In rice ecosystems, UAV imaging has proven useful for spotting stress linked to brown planthopper infestations, which are often hard to detect through traditional ground scouting since populations are usually concentrated near the lower stem region (Qin et al., 2016). Scientists have looked into similar methods for identifying fall armyworm damage in maize and whitefly outbreaks in cotton and vegetable crops. Canopy-level stress signs can be captured effectively from aerial platforms (Ishengoma et al., 2022; Toscano-Miranda et al., 2022). In orchards and plantation systems, where accessing the canopy can be difficult, drones offer the added benefit of allowing quick and non-destructive field monitoring.

Table 2. Major Indian crops, target pests, and potential drone applications

Crop	Major insect pests	Drone application focus
Rice	Brown planthopper, leaf folder, stem borer	Precision spraying and surveillance
Cotton	Whitefly, pink bollworm	Spot spraying and canopy monitoring
Maize	Fall armyworm	Early detection and hotspot spraying
Pulses	Pod borers and sucking pests	Localized pesticide application
Vegetables	Whiteflies, aphids, thrips	Multispectral surveillance and precision spraying
Tea plantations	Tea mosquito bug and looper pests	Terrain accessible aerial spraying

Artificial intelligence has greatly improved the value of drone-based surveillance by turning large amounts of imagery into useful information. The combination of remote sensing and AI-assisted analysis allows for a quick interpretation of crop stress patterns. This supports more informed, real-time pest management decisions (Aziz et al., 2025). Modern machine learning methods especially deep learning and computer vision models can tell the difference between pest related damage and symptoms from nutrient deficiencies, diseases, or water stress with more accuracy. This capability decreases the need for manual scouting and speeds up pest detection over large agricultural areas.

Drone-Based Precision Spraying: Spray Physics, Operational Dynamics, and Biological Efficacy

Among the various agricultural uses of drones, pesticide application has gained the most scientific and commercial interest due to its potential to improve timeliness, precision, and efficiency in fields where traditional spraying is often challenging (Meng et al., 2018). Unlike knapsack or tractor-mounted sprayers that require large amounts of liquid, UAVs usually work with low or ultra-low-volume systems. They deliver concentrated solutions with much less water. Often, spray volumes range from 10 to 30 L ha^{-1}, compared to the hundreds of litres needed by standard ground equipment (Safaeinejad et al., 2025). This reduction is especially important in Indian agriculture, where labour and water availability (Table 3) often limit crop protection efforts. Research shows that UAV spraying can keep biological effectiveness while using less liquid and improving efficiency during pest outbreaks (Qin et al., 2016; Parmar et al., 2021).

Table 3. Comparison of UAV spraying and conventional spraying systems in insect pest management

Parameter	UAV spraying	Conventional knapsack spraying
Water requirement	Low-volume/ultra-low-volume application	High carrier volume requirement
Labour dependency	Low	High
Operator exposure	Minimal direct exposure	High pesticide exposure risk
Field accessibility	Suitable for flooded and inaccessible fields	Difficult in dense or waterlogged crops
Operational speed	Rapid coverage	Relatively slow
Spray precision	Site specific and GPS guided	Mostly uniform blanket application
Drift management	Requires careful calibration	Generally lower aerial drift
Initial investment	High	Relatively low

The success of drone spraying depends on a combination of spray characteristics, flight parameters, crop structure and environmental conditions (Mahasneh, 2024). Droplet size is important because it mainly affects the coverage, canopy penetration, evaporation and drift. Smaller droplets typically provide better coverage but are more prone to evaporation and drifting while larger droplets reduce drift risk but may lead to uneven coverage (Qin et al., 2016; García-Munguía et al., 2024). Finding the right balance between these factors are key for effective spraying. A unique aspect of multi-rotor UAVs is the downwash airflow generated by the rotors, which affects droplet movement and canopy penetration. This downward air stream can enhance deposition in dense crop canopies, an important benefit in rice crops where pests like the brown planthopper concentrate in the lower parts of plants.

Despite many advantages, spray drift continues to be a major environmental concern related to UAV use. Factors like wind speed, temperature, humidity, nozzle design, droplet size, and flight altitude affect off-target movement and overall efficiency (Zhang et al., 2015; Qin et al., 2014; Zheng et al., 2021). Therefore, standardised procedures and environmental monitoring are crucial for safe and effective use. To address these challenges, several Indian institutions have created guidelines for using agricultural drones. The standard operating protocols (SOPs) developed by Professor Jayashankar Telangana State Agricultural University represent one of the first systematic efforts to standardize UAV pesticide application in rice.

These guidelines mainly cover the calibration, nozzle selection, flight parameters, safety measures and environmental precautions (Varma et al., 2022). Similar works at Punjab Agricultural University further highlighted the importance of optimising the flight height and speed to improve deposition efficiency as well as biological effectiveness (Parmar et al., 2021). In addition to better spray precision, the drone systems provide practical benefits that are especially relevant to the Indian agriculture. It allows for quick coverage during pest outbreaks, reduce the direct exposure of operators to pesticides, minimising crop damage from ground equipments and enable spraying in flooded fields, orchards, plantations and other areas where traditional methods are tough to implement (Dengeru et al., 2022).

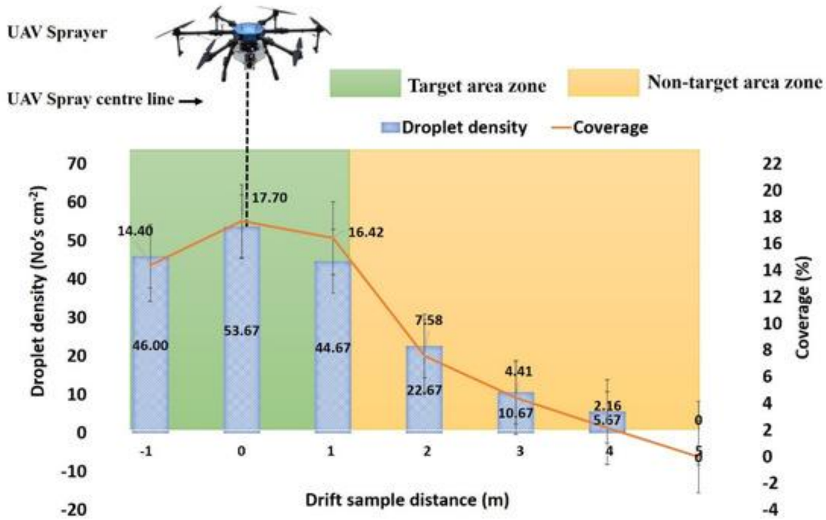

Figure 2. Schematic representation of UAV spray deposition dynamics, canopy penetration, and spray drift behaviour under different operational parameters (Dengeru et al., 2022)

Drones within Integrated Pest Management Frameworks

Integrated Pest Management (IPM) offers a helpful framework because it combines biological, cultural, mechanical, behavioural and chemical methods to keep pest populations below damaging levels while minimising harm to the environment (Karuppuchamy & Venugopal, 2016). IPM mainly focuses on making informed decisions based on pest monitoring, economic thresholds and an understanding of the ecosystems (Mitchell & Hutchison, 2009).

Drone technologies enhance several parts of IPM at the same time. High-resolution aerial monitoring speeds up and improves the accuracy of pest surveillance. Multispectral and thermal imaging can show crop stress before visible damage spreads (Maslekar et al., 2020). When paired with GIS-based analysis, these systems enable more precise mapping and management of infestation hotspots. This improves the effectiveness of threshold-based actions and cuts down on unnecessary pesticide use (Rajabpour & Yarahmadi, 2024; Venegas et al., 2018). Targeted applications may help preserve natural predators and lessen the environmental impact linked with blanket pesticide spraying (Zeeshan et al., 2026). Another promising area is using drones for biological control. The use of UAVs to deliver parasitoids, predators, microbial biopesticides, and pheromone-based products is being researched to improve the efficiency of biological interventions, especially in crops where manual release is hard or labour-intensive (Vincze, 2022). At the same time, advances in nano-formulations, controlled-release products, and microbial pesticides may enhance the effectiveness of aerial applications by improving adhesion, stability, and deposition efficiency during low-volume spraying (Rahman et al., 2026; Vishnu et al., 2024; Anjaneyulu et al., 2024).

Indian Experience: Institutional Initiatives, Policy Support, and Emerging Adoption

The growth of agricultural drones in India has come from a mix of research, government support, new technology, and more involvement from the private sector. In recent years, various institutions have tested UAV performance in Indian farming. This work helps to connect technological potential with real world use. Tamil Nadu Agricultural University did significant research on drone assisted precision agriculture and crop protection. Meanwhile, Punjab Agricultural University carried out key studies on aerial spraying for rice, cotton and moong crops (Jebalin et al., 2024; Parmar et al., 2021). These studies found that factors like flight height and speed can greatly affect spray distribution and pest control effectiveness.

Rice ecosystems are under the scanner because of flooded fields, thick canopies and persisting pest outbreaks that make the traditional spraying really hard. Research works showed positive results for drone-based pest management for insects like brown planthopper, rice leaf folder, and earhead bug. These findings stress the importance of optimising spray methods in real field conditions (Parmar et al., 2021). Another significant achievement was the creation of standard operating protocols (SOPs) by Professor Jayashankar Telangana State Agricultural University. These protocols guide drone spray calibration, nozzle selection, deposition assessment, operational safety and environmental protection for pesticide use (Varma et al., 2022). Government support has been crucial in speeding up adoption. Reforms introduced by the Directorate General of Civil Aviation made drone registration and operation easier. Initiatives like the Kisan Drone programme promoted the use of UAVs for pesticide spraying, crop monitoring, nutrient management, and digital agriculture (Mukherjee, 2025; Beriya, 2022; Joshi & Pandey, 2024). Additionally various subsidy programs, custom hiring centres, farmer-producer organisations and a fast-growing network of agri-tech startups have increased access to drone services and encouraged the development of drone technologies (Pathak et al., 2020).

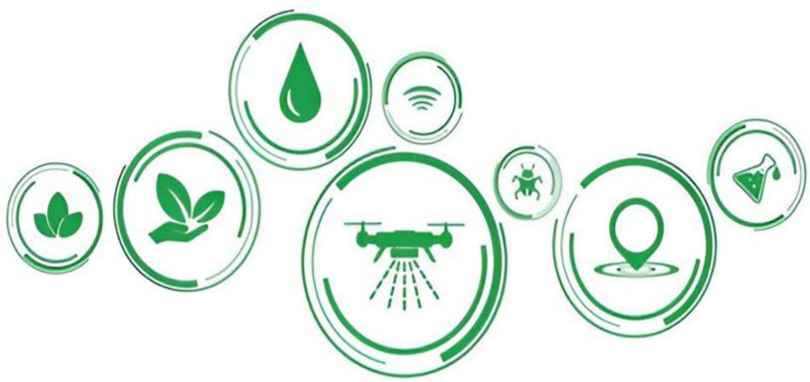

Figure 3. Conceptual framework illustrating integration of drones into precision Integrated Pest Management (IPM) systems

Ecological, Economic, and Operational Challenges

Regardless of the growing interest in agricultural drones, several scientific, technical and socio-economic challenges still affect their wider use especially in India. The Indian agricultural landscape features fragmented landholdings with varied cropping systems and changing climate conditions. Spray drift is a major environmental concern with UAV-based pesticide application. Drones often use low or ultra-low-volume formulations and fine to very fine droplets. Bad weather can increase the chances of pesticides drifting to off-target that leading to unwanted exposure of nearby crops, water sources, pollinator habitats and even human settlements. Factors like wind speed, temperature, humidity, atmospheric stability, crop canopy structure and operational details all interact to influence deposition efficiency. This makes it essential to have region specific guidelines for safe use (Carvalho et al., 2020; Semenišin et al., 2025). Additionally, battery life and payload limits impede the efficiency during large scale applications. Drones often need to be recharged and refilled multiple times which disrupts field work (Avhale et al., 2025). Another challenge is the absence of widely applicable spraying protocols. Methods that work well for rice might not yield the same results for cotton, vegetables, orchards or plantation crops as the structure of canopies, pest locations and field conditions can vary greatly among these systems (Pathak et al., 2020; Dutta et al., 2024).

The socio-economic and ecological aspects of drone use are equally important. Many small and fragmented farms in India make individual ownership less practical. This situation makes custom hiring centres, cooperative arrangements, and service-based business models more viable for large scale use (Singh & Singh, 2025; Upadhyaya et al., 2022). Effective operation of drones also requires specialised skills. Operators need to manage flights, calibrate sprays, maintain equipment, interpret data and comply with regulations. This highlights the need for ongoing training and capacity-building efforts (Sangode, 2025; Pathak et al., 2020). While precision spraying can help cut down on unnecessary pesticide use, the long-term ecological effects are not fully understood. There are still questions about the impacts on pollinators, natural enemies, soil organisms, aquatic ecosystems and other non-target species. These issues need careful evaluation within Indian agroecosystems (García-Munguía et al., 2024; Subramanian et al., 2021). More research is also necessary to improve economic analyses for smallholder situations. Factors such as crop type, availability of labour, farm size, and service delivery methods all play significant roles in operational feasibility and adoption potential (Beriya, 2022; Parmar et al., 2021). These challenges do not lessen the potential of drone technology. Instead, they highlight the need for informed implementation and ongoing innovation to ensure that UAVs make a meaningful contribution to sustainable crop protection.

Conclusion

Drone technologies are changing how crop protection is carried out in modern agriculture. UAVs are not just aerial spraying devices; they are becoming key parts of precision agriculture systems that include surveillance, spatial analysis, and targeted intervention strategies (García-Munguía et al., 2024). Their importance is particularly clear in Indian agriculture, where issues like labour shortages, fragmented landholdings, recurring pest outbreaks, and environmental concerns challenge traditional pest management practices. By improving pesticide efficiency, reducing operator exposure, and allowing for site-specific solutions, drones provide a practical way to achieve more precise and resource-efficient crop protection. However, their long-term success depends on more than just technology. Factors such as affordability, farmer training, ecological safety, standard operating procedures, and institutional support are crucial, too. As artificial intelligence, remote sensing, GIS, and IoT technologies become more integrated with UAV platforms, pest management will likely shift further toward predictive and data-driven decision-making. If backed by the right research, policy, and training efforts, drones could become valuable tools for sustainable and climate-resilient agricultural systems, aiding not just in pest management but also in the broader goal of responsible food production.

References

Anjaneyulu, B., Chauhan, V., Mittal, C., & Afshari, M. (2024). Innovative nanocarrier systems: A comprehensive exploration of recent developments in nano-biopesticide formulations. *Journal of Environmental Chemical Engineering*, *12*(5), 113693.

Avhale, V. R., Senthil Kumar, G., Kumaraperumal, R., Prabukumar, G., Bharathi, C., Sathya Priya, R., Yuvaraj, M., Muthumanickam, D., Parasuraman, P., & Pazhanivelan, S. (2025). AgriDrones: A holistic review on the integration of drones in Indian agriculture. *Agricultural Research*, *14*(1), 34–46.

Awais, M., Li, W., Cheema, M. J. M., Zaman, Q. U., Shaheen, A., Aslam, B., Zhu, W., Ajmal, M., Faheem, M., Hussain, S., & Nadeem, A. A. (2023). UAV-based remote sensing in plant stress imaging using high-resolution thermal sensor for digital agriculture practices: A meta-review. *International Journal of Environmental Science and Technology*, *20*(1), 1135–1152.

Aziz, D., Rafiq, S., Saini, P., Ahad, I., Gonal, B., Rehman, S. A., Rashid, S., Saini, P., Rohela, G. K., Aalum, K., Singh, G., Gnanesh, B. N., & Iliya, M. N. (2025). Remote sensing and artificial intelligence: Revolutionizing pest management in agriculture. *Frontiers in Sustainable Food Systems, 9*, 1551460.

Beriya, A. (2022). *Application of drones in Indian agriculture* (ICT India Working Paper No. 73). Columbia University.

Borikar, G. P., et al. (2022). Application of drone systems for spraying pesticides in advanced agriculture: A review. *IOP Conference Series: Materials Science and Engineering, 1259*, 012015.

Brito, R. C., Lorencena, M. C., Loureiro, J. F., Favarim, F., & Todt, E. (2019). A comparative approach on the use of unmanned aerial vehicles kind of fixed-wing and rotative wing applied to the precision agriculture scenario. In *2019 IEEE 43rd Annual Computer Software and Applications Conference (COMPSAC)* (Vol. 2, pp. 522–526). IEEE.

Calderone, G., Ferro, M. V., & Catania, P. (2025). A systematic literature review on recent unmanned aerial spraying systems applications in orchards. *Smart Agricultural Technology, 10*, 100708.

Carvalho, F. K., Chechetto, R. G., Mota, A. A., & Antuniassi, U. R. (2020). Challenges of aircraft and drone spray applications. *Outlooks on Pest Management, 31*(2), 83–88.

Dengeru, Y., Ramasamy, K., Allimuthu, S., Balakrishnan, S., Kumar, A. P. M., Kannan, B., & Karuppasami, K. M. (2022). Study on spray deposition and drift characteristics of UAV agricultural sprayer for application of insecticide in redgram crop (*Cajanus cajan* L. Millsp.). *Agronomy, 12*(12), 3196.

Dutta, H., Dutta, S., Yadav, H., Prabhu, I. G., Roy, A., Chowdary, N. B., & Das, S. (2024). A promising and forward-looking advancement using drones: Perspectives from Indian sericulture. *Rural and Regional Development, 2*(3), 10014.

García-Munguía, A., Guerra-Ávila, P. L., Islas-Ojeda, E., Flores-Sánchez, J. L., Vázquez-Martínez, O., García-Munguía, A. M., & García-Munguía, O. (2024). A review of drone technology and operation processes in agricultural crop spraying. *Drones, 8*, 674.

Guebsi, R., Mami, S., & Chokmani, K. (2024). Drones in precision agriculture: A comprehensive review of applications, technologies, and challenges. *Drones, 8*(11), 686.

Ishengoma, F. S., Rai, I. A., & Ngoga, S. R. (2022). Hybrid convolution neural network model for a quicker detection of infested maize plants with fall armyworms using UAV-based images. *Ecological Informatics, 67*, 101502.

Jebalin, V., Rathika, S., Ragavan, T., Baskar, M., Jeyaprakash, P., Ramesh, T., Kannan, S. V., & Sakthivel, K. (2024). Effects of drone-assisted precision weed management on irrigated barnyard millet. *Plant Science Today, 11*.

Joshi, R., & Pandey, K. (2024). IoT-enabled UAV: A comprehensive review of technological change in Indian farming. In *Unmanned Aircraft Systems* (pp. 93–135).

Karuppuchamy, P., & Venugopal, S. (2016). Integrated pest management. In *Ecofriendly pest management for food security* (pp. 651–684). Academic Press.

Kumar, K., Aruna, T. N., Anand, B. A., Singh, A. K., Krishnan, S. V., Gupta, A. K., Dwivedi, U., & Bhojyareddy, G. R. (2024). Application of drones in pesticide spraying: A review. *International Journal of Advanced Biochemistry Research, 8*(2), 742–749.

Mahasneh, H. (2024). Drones in agriculture: Real-world applications and impactful case studies. *Journal of Natural Science Review, 2*(Special Issue), 643–656.

Maslekar, N. V., Kulkarni, K. P., & Chakravarthy, A. K. (2020). Application of unmanned aerial vehicles (UAVs) for pest surveillance, monitoring and management. In *Innovative pest management approaches for the 21st century: Harnessing automated unmanned technologies* (pp. 27–45). Springer.

Matre, Y. B., Lad, A. G., Neharkar, P. S., & Sonkamble, M. M. (2024). Drone technology in precision agriculture for insect pest management: A short review. *Journal of Entomological Research, 48*(3), 360–365.

Meng, Y., Lan, Y., Mei, G., Guo, Y., Song, J., & Wang, Z. (2018). Effect of aerial spray adjuvant applying on the efficiency of small unmanned aerial vehicle for wheat aphids control. *International Journal of Agricultural and Biological Engineering, 11*(5), 46–53.

Mitchell, P. D., & Hutchison, W. D. (2009). Decision making and economic risk in IPM. In R. Peshin & A. K. Dhawan (Eds.), *Integrated pest management: Concepts, tactics, strategies and case studies* (pp. 33–50). Cambridge University Press.

Morales-Rodríguez, P. A., Cano Cano, E., Villena, J., & López-Perales, J. A. (2022). A comparison between conventional sprayers and new UAV sprayers: A study case of vineyards and olives in Extremadura (Spain). *Agronomy, 12*(6), 1307.

Mukherjee, S. (2025). *Applications of modern technologies, drones, and IoT in Indian agriculture.*

Naveen, S., Patil, R. S., Kambekar, D. N., & Kulkarni, S. (2025). Evaluation of drone technology in paddy ecosystem against key insect pests. *Journal of Farm Sciences, 38*(4), 407–412.

Parmar, R. P., Singh, S. K., & Singh, M. (2021). Bio-efficacy of unmanned aerial vehicle-based spraying to manage pests. *Indian Journal of Agricultural Sciences, 91*(9), 1373–1377.

Pathak, H., Kumar, G., Mohapatra, S. D., Gaikwad, B. B., & Rane, J. (2020). *Use of drones in agriculture: Potentials, problems and policy needs.* ICAR–National Institute of Abiotic Stress Management.

Qin, W. C., Qiu, B. J., Xue, X. Y., Chen, C., Xu, Z. F., & Zhou, Q. Q. (2016). Droplet deposition and control effect of insecticides sprayed with an unmanned aerial vehicle against plant hoppers. *Crop Protection, 85*, 79–88.

Qin, W., Xue, X., Zhou, L., Zhang, S., Sun, Z., Kong, W., & Wang, B. (2014). Effects of spraying parameters of unmanned aerial vehicle on droplets deposition distribution of maize canopies. *Transactions of the Chinese Society of Agricultural Engineering, 30*(5), 50–56.

Ragiman, R., Talluri, K. B., & Varma, N. R. G. (2024). Unmanned aerial vehicle (UAV)-assisted pesticide application for pest and disease prevention and control in rice. *International Journal of Agricultural and Biological Engineering, 17*(5), 88–95.

Rahman, M. T., Bakibillah, A. S. M., Hossain, A., Ahasan, A., Basher, M. N., Oyshe, K. U., & Mariam, A. (2026). The role of AI-integrated drone systems in agricultural productivity and sustainable pest management. *AgriEngineering, 8*(4), 142.

Rajabpour, A., & Yarahmadi, F. (2024). Remote sensing, geographic information system (GIS), and machine learning in the pest status monitoring. In *Decision system in agricultural pest management* (pp. 247–353). Springer Nature.

Rathore, B. (2026). *Drones in agriculture in India: The operator's regulation and economics guide.* Kodainya. Retrieved May 10, 2026, from https://www.kodainya.com/blogs/drones-in-agriculture

Safaeinejad, M., Ghasemi-Nejad-Raeini, M., & Taki, M. (2025). Reducing energy and environmental footprint in agriculture: A study on drone spraying vs. conventional methods. *PLoS ONE, 20*(6), e0323779. https://doi.org/10.1371/journal.pone.0323779

Saini, N., Singh, H., & Gouda, M. N. R. (2024). Use of drones in precision pest management. *International Journal of Research in Agronomy, 7*(8), 854–858.

Sangode, P. B. (2025). Modelling the barriers to the implementation of drone technology in Indian agriculture. *Indian Journal of Agricultural Research, 59*(3), 502–513.

Sarkar, R., Yuvaraj, H. M., & Rajna, S. (2024). Unmanned aerial vehicle (UAV)-assisted insecticide application in crop management. *Indian Entomologist, 5*(2), 44–48.

Semenišin, M., Steponavičius, D., Kemzūraitė, A., & Savickas, D. (2025). Optimizing UAV spraying for sustainability: Different system spray drift control and adjuvant performance. *Sustainability, 17*(5), 2083.

Singh, R., & Singh, S. (2025). A review of Indian-based drones in the agriculture sector: Issues, challenges, and solutions. *Sensors, 25*(15), 4876.

Sorahia, D., Lokesh, M., Das, A., Kumari, N., Roy, T., Singh, V., Gawaria, J., & Mehla, S. (2025). Examining the emergence of insect pests under changing climate: A comprehensive review. *Journal of Advances in Biology & Biotechnology, 28*(9), 1750–1765.

Subramanian, K. S., Pazhanivelan, S., Srinivasan, G., Santhi, R., & Sathiah, N. (2021). Drones in insect pest management. *Frontiers in Agronomy, 3*, 640885.

Toscano-Miranda, R., Toro, M., Aguilar, J., Caro, M., Marulanda, A., & Trebilcok, A. (2022). Artificial intelligence and sensing techniques for the management of insect pests and diseases in cotton: A systematic literature review. *The Journal of Agricultural Science, 160*(1–2), 16–31.

Upadhyaya, A., Jeet, P., Sundaram, P. K., Singh, A. K., Saurabh, K., & Deo, M. (2022). Efficacy of drone technology in agriculture: A review.

Vanegas, F., Bratanov, D., Powell, K., Weiss, J., & Gonzalez, F. (2018). A novel methodology for improving plant pest surveillance in vineyards and crops using UAV-based hyperspectral and spatial data. *Sensors*, *18*(1), 260.

Varma, N. R. G., Babu, T. K., Ramakrishna, A., Sunitha, V., Kavitha, K., Reddy, P. R. R., Ramana, M. V., Sridevi, G., Ramulu, V., Rahman, S. J., Umadevi, G., Rao, V. V., Jagadeeshwar, R., & Rao, V. P. (2022). *Standard operating protocols (SOPs) for drone-based pesticide application in rice* (Publication No. 41/MG/PJTSAU/2022).

Verma, S. K. (2025). Exploring the role of AI in autonomous drone technology for precision pest control in agriculture. *International Research Journal of Engineering & Applied Sciences, 13*(1), 19–28.

Vincze, H. R. (2022). *A flying start for insects: Incorporating drones in the distribution of insects used as biological control agents* (Master's thesis). New Mexico State University.

Vishnu, M., Kannan, M., Soundararajan, R. P., Suganthi, A., Subramanian, A., Senthilkumar, M., Rameash, K., Madesh, K., & Govindaraju, K. (2024). Nano-bioformulations: Emerging trends and potential applications in next generation crop protection. *Environmental Science: Nano*, *11*(7), 2831–2860.

Zeeshan, M., Li, H., Li, Y., Zhang, G., Zhang, Y., & Han, X. (2026). Role of UAVs in precision pesticide spraying and environmental safety by combating pesticide resistance and safety of natural enemies. *Pest Management Science.*

Zhang, S., Xue, X., Qin, W., Sun, Z., Ding, S., & Zhou, L. (2015). Simulation and experimental verification of aerial spraying drift on N-3 unmanned spraying helicopter. *Transactions of the Chinese Society of Agricultural Engineering*, *31*(3), 87–93.

Zheng, L., Cao, C., Chen, Z., Cao, L., Huang, Q., & Song, B. (2021). Efficient pesticide formulation and regulation mechanism for improving the deposition of droplets on the leaves of rice (*Oryza sativa* L.). *Pest Management Science, 77*(7), 3198–3207.