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Precision Pest Management: Drones for Curtailing Insecticide Residues and Resistance

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INTRODUCTION

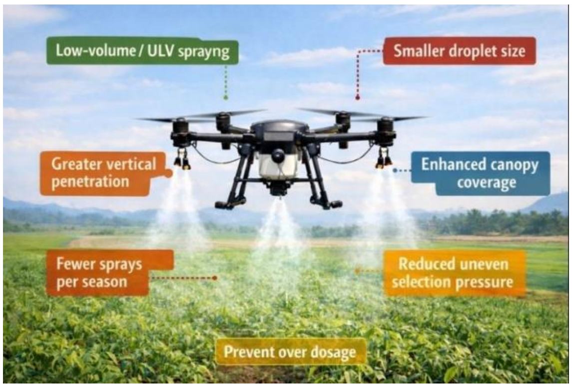
Integrated Pest Management (IPM) practices have been widely promoted as a sustainable approach to mitigate the ecological and health-related drawbacks associated with the sole reliance on chemical insecticides. IPM advocates the integration of multiple control strategies, including cultural practices, mechanical and physical practices, biological control agents and biorational insecticides, to suppress pest populations below economic injury levels. Despite these efforts, chemical insecticides continue to occupy a dominant position in most pest management programmes worldwide, particularly in intensive cropping systems (Deguine et al., 2021). The continued dependence on chemical insecticides largely stems from the need for immediate and effective pest suppression**,** especially when pest populations exceed economic threshold levels. Under such conditions, alternative IPM components often fail to provide rapid control, making chemical interventions unavoidable for protecting crop yield and quality. Consequently, insecticides remain anmajor essential component of IPM rather than a minor option. However, indiscriminate use of insecticides has resulted in several well-documented disadvantages. Given the indispensable role of chemical insecticides, the current challenge lies not in their elimination but in optimizing their use to maximize efficacy while minimizing adverse effects. Such optimization is difficult to achieve using conventional spraying equipments. Traditional spraying methods often suffer from poor spray uniformity, overdosing, larger droplet size, operator exposure and inefficient canopy penetration, all of which contribute to excessive pesticide residues and uneven selection pressure that favours resistance development (Warneke et al., 2021).

In recent years, the use of drones or unmanned aerial vehicles (UAVs) in agriculture has gained considerable attention, particularly for pesticide application under Indian farming conditions. Drone-based spraying systems are increasingly recognized for their ability to improve application precision while operating at reduced spray volumes, thereby addressing several limitations of conventional spraying methods (Safaeinejad et al., 2025).

Among the major concerns associated with conventional insecticide application, pesticide residues in agricultural produce and the rapid development of resistance in insect pests remain critical issues (Ngegba et al., 2025). Drone-assisted insecticide application is increasingly viewed as a precision-oriented approach that enables more accurate dosing and controlled exposure compared with conventional spraying methods. Such attributes are often considered supportive of sustainable pest management strategies. In this context, the present article discusses the relevance of drone-assisted insecticide application in addressing residue and resistance concerns, positioning it as an emerging tool within precision pest management rather than a substitute for chemical control.

Impact on insecticide residues-

- High insecticide residues frequently arise from excessive spray volumes used in conventional spraying methods, where a large portion of spray can wash off leaves and reach soil and water, increasing environmental contamination; drone-based application employs low- or ultra-low-volume (ULV) spraying systems that deliver the required dose with reduced carrier volume, improving retention on plant surfaces. This reduces wash-off, lowers total insecticide load, decreases soil and water contamination, and consequently results in lower residue levels on harvested crops (Safaeinejad et al., 2025).
- In conventional spraying, large and uneven droplets cause patchy coverage and localized over-deposition of insecticides on plant surfaces; drone spraying produces much finer droplets with higher coverage density, allowing efficient spreading of insecticides at lower doses. The droplet diameter produced by UAV sprayers is considerably smaller (about 40-60 µm) than that of knapsack sprayers (about 200-300 µm), while droplet coverage density is higher (40-50 droplets cm^{-2} versus 25-35 droplets cm^{-2}), resulting in uniform deposition with reduced residue accumulation on edible plant parts (Wu and Tu, 2025).
- Limited penetration of spray into the crop canopy under conventional methods often necessitates repeated applications, leading to cumulative residue build-up; drone spraying provides better vertical distribution of droplets, including improved deposition on the lower leaf surface, which enhances first-spray effectiveness and reduces the need for repeated insecticide applications, thereby lowering overall residue levels. Under dense crop canopy conditions, interception of fine droplets is more efficient, further improving spray retention and residue optimization (Wu and Tu, 2025).



Impact on insecticide resistance-

- Conventional high-volume spraying typically produces a heterogeneous deposition pattern within the crop canopy, resulting in simultaneous over-exposure in some zones and sub-lethal exposure in others. This uneven selection environment favours survival and reproduction of resistant individuals across dose ranges, thereby accelerating resistance evolution. In contrast, drone-based low- or ultra-low-volume spraying improves dose uniformity and targeting, reducing heterogeneity in insecticide exposure and moderating selection pressure on pest populations (Bantz et al., 2018).

- **Repeated spraying due to uneven canopy coverage enhances cumulative selection pressure**. Conventional sprayers often fail to cover the entire canopy uniformly, necessitating multiple applications during a season. Each additional spray further selects for resistant individuals. Drone spraying achieves more efficient initial coverage, reducing the number of applications needed per season and limiting cumulative selection pressure on the pest population (Hawkins et al., 2019).

Limitations of drone-based pesticide spraying-

- Improper optimization of drone speed and spray altitude can create spray hotspots with excessive insecticide deposition, generating higher concentrations than conventional spraying and imposing strong selection pressure on pest populations.
- **Spray drift can be higher due to UAV speed and rotor-induced airflow**, which may carry fine droplets beyond the target area. Optimization of flight height, speed, nozzle type, and spray pressure is essential to minimize off-target drift.
- **Dense canopy crops are preferred**, as sparse or irregular planting reduces droplet interception, potentially lowering application efficiency and effectiveness.
- Natural enemies population may affect potentially.
- **Limited tank capacity and battery life** restrict the area a single drone can cover per flight, requiring multiple flights for large fields.
- **Operators require training and government licensing, and the initial investment is higher than conventional spraying equipment**. Effective UAV pesticide application demands knowledge of drone handling, GPS navigation and basics of pesticide chemistry

CONCLUSION

Drone-assisted pesticide application represents a practical advancement in precision pest management by optimizing insecticide use rather than replacing chemical control within IPM frameworks. By enabling low- or ultra-low-volume, targeted and uniform application, drones significantly reduce insecticide residues on crops and minimize environmental contamination. At the same time, improved dose accuracy and reduced spray frequency lower selection pressure on pest populations, thereby slowing the development of insecticide resistance. Although challenges such as spray drift, proper optimization, operational limitations and higher initial investment remain, these can be addressed. Overall, drone-based spraying offers a promising tool for achieving effective pest control while enhancing the sustainability of chemical insecticide use in modern agriculture.

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