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Original Article

Drone-Based Pesticide Application: Efficacy, Optimisation, and Standardisation for Sustainable Crop Protection

Rittik Sarkar[1]*, Rajna S[2], Avirup Roy[3], Abithaa P[4], Yuvaraj H M[5] and Anu Gimmy[2]

[1]Department of Entomology and Agricultural Zoology, Institute of Agricultural Sciences, Banaras Hindu University, Varanasi-221005, India.

[2]Division of Entomology, ICAR-Indian Agricultural Research Institute, New Delhi-110012, New Delhi, India

[3]Department of Entomology, Jawaharlal Nehru Krishi Vishwa Vidyalaya, Jabalpur-482004, Madhya Pradesh, India

[4]Division of Agricultural Physics, ICAR-Indian Agricultural Research Institute, New Delhi-110012, New Delhi, India

[5]Department of Agricultural Entomology, University of Agricultural and Horticultural Sciences, Shimoga-577204, India.

**Corresponding author: rittikrnj197@gmail.com*

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ABSTRACT

The rapid advancement of unmanned aerial vehicles (UAVs), popularly known as spray drones, is transforming agrochemical application practices across diverse cropping systems. This review synthesises recent evidence from rice, wheat, cotton, legumes, pulses, jute, and perennial orchards to evaluate their efficacy, optimisation parameters, and potential for standardisation. Findings consistently show that UAV spraying can achieve pest and disease suppression comparable to, and in many cases exceeding, conventional knapsack and air-blast sprayers, while using substantially lower spray volumes. Critical determinants of success include flight altitude, forward speed, nozzle type, droplet spectrum, and the use of adjuvants or tank-mixes. Properly optimised UAV operations enhance canopy penetration, reduce drift, improve pesticide-use efficiency, and increase farmer profitability. Beyond pest management, UAVs have proven effective in delivering foliar nutrients and defoliants, highlighting their versatility. However, methodological inconsistencies in spray evaluation, coupled with regulatory gaps and the absence of UAV-specific pesticide labels, remain barriers to wider adoption. The integration of harmonised evaluation protocols, ISO-aligned efficiency metrics, and best management practices will be essential for regulatory acceptance. With further refinement of stage-specific optimisation, formulation science, and digital agronomy tools, UAV spraying offers a scalable, sustainable pathway for crop protection that aligns with global demands for precision agriculture and environmental stewardship.

Keywords: Unmanned aerial vehicles (UAVs); Droplet deposition and drift; Flight parameters; Pesticides use efficiency; Precision agriculture

1. INTRODUCTION

1.1. Why drones for crop protection now

Labour scarcity, timeliness constraints at pest outbreaks, and the need to reduce water and pesticide footprints are pushing applicators toward compact, rapidly deployable platforms. Multi-rotor UAVs have emerged as particularly suitable for diverse and heterogeneous cropping landscapes, including flooded rice fields, terraced systems, and perennial orchards. Their ability to navigate complex terrains, deliver high field efficiency in smallholder-dominated mosaic farming, and minimize crop damage compared to conventional tractor-mounted booms has been well documented, from the pioneering adoption in East Asia to more recent applications in Indian farmlands and U.S. orchards (Li et al., 2020; Subramanian et al., 2021). In field studies spanning cotton, rice and moong, optimised UAV settings achieved meaningful pest suppression within days, with reduced labour and operational water compared with conventional methods (Parmar et al., 2021).

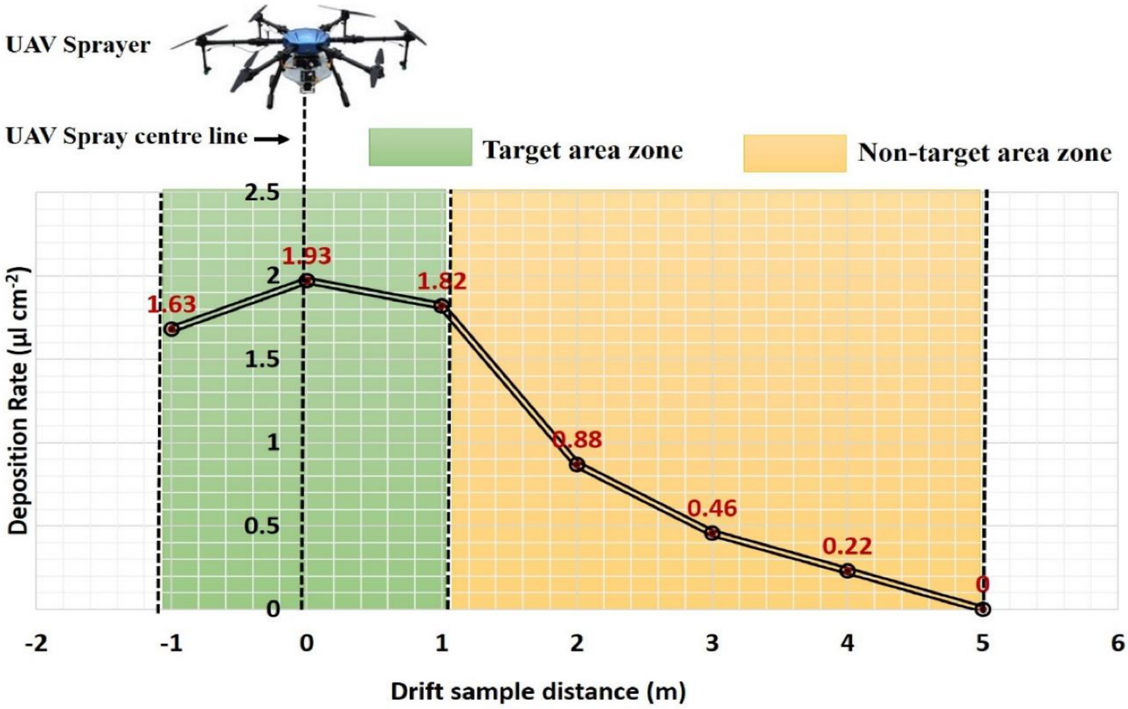
1.2. Evidence that efficacy can match conventional methods

A recurring concern is whether very low carrier volumes can deliver enough active ingredient (a.i.) to the biologically relevant strata. In almonds, UAV applications at 46.8-93.5 L ha^{-1} achieved comparable whole-nut chlorantraniliprole residues to an air-blast sprayer operating at ~935 L ha^{-1}, with measurable penetration into lower canopy layers and acceptable navel orangeworm outcomes (Li et al., 2020). In rice, small-plot and farm-scale studies show that flight height and speed tune droplet distribution and planthopper control: a 1.5 m height at ~5 m s^{-1} maximised lower-canopy deposition (CV ≈ 23%) and yielded 92-74% efficacy over 3-10 days after treatment (Qin et al., 2016). Trials from Punjab Agricultural University further demonstrated significant main effects of height and forward speed on whitefly and brown planthopper suppression across crops, with lower heights (0.5-0.75 m) and slower passes (2-3 m s^{-1}) frequently outperforming faster, higher settings (Parmar et al., 2021).

1.3. The optimisation problem: physics, formulation, and flight

UAV spraying is a coupled system: rotor downwash structures canopy airflows, nozzles and adjuvants shape droplet spectra and spreading, and meteorology gates drift and evaporation. Recent rice work quantified how tank-mix adjuvants that lower surface tension and adjust viscosity can shift droplet size distributions toward more deposition-efficient ranges, reducing drift and improving planthopper control by 20-35% versus no-adjuvant controls peaking near ~0.5% v/v (Wang et al., 2024). In parallel, growth-stage-specific parameter maps are emerging: in japonica rice, pesticide-use efficiency varied with speed (3-5 m s^{-1}) and nozzle type (e.g., F110-015 vs F110-025), with recommendations differing across tillering, jointing, and booting stages (Zhou et al., 2020).

Economically, drone-assisted tank-mix programs that pair diamide insecticides with triazole/strobilurin fungicides in paddy have delivered higher benefit–cost ratios than single-actives under Indian field conditions, even after accounting for service fees (illustrative treatments combining tetraniliprole or chlorantraniliprole with tebuconazole+trifloxystrobin) (Ragiman et al., 2024).



1.4. Measuring what matters: deposition, drift, and efficiency

Comparisons of WSP versus glass collectors under UAV passes show method-dependent absolute deposition, underscoring that trend-wise comparisons are more robust than raw magnitudes across materials (Ahmad et al., 2022). Moreover, digital stain-analysis tools (DepositScan; SprayDAT) can substantially under-estimate total volume at higher stain coverage because overlapping stains depress apparent droplet counts; cross-checking with colorant extraction and speed-based flow predictions is advised (Koo et al., 2024). For integrated performance reporting, ISO-aligned pesticide-use efficiency metrics that combine measured deposition with leaf area index (LAI) offer a path to comparable results across growth stages, provided the LAI method is standardised and non-leaf sinks (e.g., stems, panicles) are appropriately handled (Zhou et al., 2020).

Figure 1. Influence of UAV flight height and downwash airflow on spray deposition and drift distribution in crop canopies (Lan et al., 2021).

2. Cross-Crop Efficacy of UAV-Based Agrochemical Application

2.1. UAV spraying in Rice

Rice has been the proving ground for UAV pesticide application, particularly in East and South Asia. Early Chinese studies established that UAVs could provide effective control of brown planthopper (*Nilaparvata lugens*) when flown at 1.5 m altitude and 5 m s^{-1}, achieving 92-74% suppression over 10 days outperforming stretcher-mounted sprayers in both deposition uniformity and biological efficacy (Qin et al., 2016). Follow-up evaluations confirmed that UAVs could also suppress rice stem borer (*Chilo suppressalis*), with efficacy exceeding 90% when single-rotor UAVs were flown at 2-4 m altitude and 3-4 m s^{-1} (Wang et al., 2016). At the institutional level, Tamil Nadu Agricultural University validated UAV spraying under Indian smallholder conditions, reporting successful brown planthopper control with significant reductions in water use compared to knapsack methods (Subramanian et al., 2021).

Rice disease control has also been demonstrated. UAV-applied fungicides suppressed sheath blight (*Rhizoctonia solani*) by 75-77% and reduced grain discoloration by up to 78% when tetraniliprole was tank-mixed with triazole–strobilurin fungicides (Ragiman et al., 2024). Comparable levels of protection were achieved against rice blast and rice leaf roller at 18 L ha^{-1} when methylated crop oil adjuvants were included, highlighting the role of formulation optimisation (Wang et al., 2020).

2.2. Cotton and legumes: adapting UAVs to broadleaf crops

Cotton represents a contrasting challenge due to larger canopies and common reliance on whitefly management. Optimised UAV passes at 0.5-1.0 m altitude and 2 m s^{-1} reduced whitefly populations by 84.8% at 7 days after spraying (Parmar et al., 2021). In Xinjiang, UAVs were further employed for cotton defoliant application ahead of mechanised harvesting. At 48 L ha^{-1} and 1.5 m altitude, boll opening was effective, showing that drones can extend beyond pest management to harvest facilitation (Liao et al., 2019).

Pulses are emerging beneficiaries. In moong bean, UAVs applied insecticides effectively against sucking pests, while in black gram, foliar nutrient sprays delivered by drones increased grain yields to 784 kg ha^{-1} exceeding knapsack application (Nandhini et al., 2022). Nutrient UAV spraying in maize likewise boosted leaf area index and yields beyond 7 t ha^{-1}, demonstrating versatility of drones for both protection and plant nutrition (Kaniska et al., 2022).

2.3. Wheat, maize, and jute: extending to cereals and fibre crops

Wheat trials confirm UAV efficacy against both insects and diseases. Sprays at >16 L ha^{-1} with coarse nozzles-controlled aphids and powdery mildew comparably to electric knapsack sprayers (Wang et al., 2019). Disease control in wheat with triadimefon applied via UAV achieved ~55% reduction of powdery mildew at standard label rates, indicating scope for dose optimisation (Qin et al., 2018). Herbicide delivery via UAV also proved effective: drone applied post emergence metribuzin reduced weed pressure in wheat, especially when combined with pre-emergence knapsack spraying (Pranaswi et al., 2024).

Beyond cereals, Bangladesh field experiments showed UAV insecticide applications in jute effectively suppressed hairy caterpillar and semilooper populations, reducing labour requirements by 60% compared to manual methods (Alam et al., 2024).

2.4. Orchards and high-value crops

Large-canopy systems such as almonds present one of the toughest UAV challenges. Yet, UAV applications at 46-93 L ha^{-1} achieved comparable chlorantraniliprole residues to conventional air-blast spraying at 935 L ha^{-1}, penetrating lower canopy strata and effectively reducing navel orangeworm infestation (Li et al., 2020). This efficiency gain underscores UAVs' potential for perennial orchards, provided flight patterns are tuned to canopy architecture.

Figure 2. UAV-based pesticide application in orchard and perennial crop systems.

2.5. Global scope of efficacy evidence

Across crops, UAVs consistently achieve pest and disease suppression comparable to or better than conventional spraying, often with lower spray volumes, higher efficiency, and reduced operator exposure. Trials in China, India, the U.S., Pakistan, and Bangladesh collectively validate UAVs as broadly applicable tools though crop-specific calibration remains critical (Nordin et al., 2021).

Table 1. Cross-crop efficacy of UAV-based agrochemical application compared with conventional spraying systems

Crop	**Target pest/disease**	**UAV parameters**	**Main findings**	**Reference**
Rice	Brown planthopper	1.5 m height; 5 m s^{-1}	92-74% control efficacy	Qin et al. (2016)
Rice	Stem borer	2-4 m height	>90% suppression	Wang et al. (2016)
Cotton	Whitefly	0.5-1.0 m; 2 m s^{-1}	84.8% reduction	Parmar et al. (2021)
Wheat	Aphid & powdery mildew	>16 L ha^{-1}	Comparable to knapsack spraying	Wang et al. (2019)

Almond	Navel orangeworm	46-93 L ha^{-1}	Comparable residue to air-blast sprayer	Li et al. (2021)
Jute	Hairy caterpillar	UAV insecticide spraying	60% labour saving	Alam et al. (2024)
Black gram	Foliar nutrient spray	UAV foliar application	Higher yield than conventional spray	Nandhini et al. (2022)

3. Deposition Dynamics and Drift Behaviour

3.1. Fundamentals of UAV-driven deposition

Unlike tractor booms or aerial fixed-wing aircraft, UAVs rely on rotor-induced downwash to transport droplets into the canopy. This airflow redistributes spray laterally and vertically, producing distinct deposition profiles that depend on flight height, speed, rotor type, and nozzle configuration (Wang et al., 2016; Zhou et al., 2020). Studies in rice and cotton reveal that low-altitude flights (1.5-2.0 m) with moderate forward speed (3-4 m s^{-1}) enhance canopy penetration while maintaining acceptable uniformity of deposition (Qin et al., 2016; Parmar et al., 2021).

3.2. Vertical distribution within the canopy

Deposition stratification is a consistent observation in UAV trials. For instance, rice trials using water-sensitive paper (WSP) cards documented higher coverage in the upper canopy and reduced deposition in the basal layers, particularly at later crop growth stages (Weicai et al., 2023). Use of adjuvants mitigates this decline by increasing droplet adhesion and reducing bounce-off, allowing droplets to remain on erectophile leaves. In cotton, centrifugal nozzles at lower flight heights provided improved coverage of the upper and mid canopy compared with hydraulic nozzles, though sugarcane benefited more from the latter due to denser architecture (Ranabhat and Price, 2025).

3.3. Nozzle, droplet size, and formulation effects

Droplet spectrum is a key determinant of drift versus retention. Flat-fan nozzles produced finer droplets and better canopy penetration in rice compared with air-induction nozzles, though with increased drift risk (Wongsuk et al., 2024). Tank-mix adjuvants significantly improved spray deposition by lowering surface tension and increasing viscosity; in rice, 0.5% v/v adjuvant addition improved brown planthopper control efficacy by 20-35% over non-adjuvant sprays (Wang et al., 2024). Formulation optimisation has therefore become central to maximising UAV efficiency while minimising drift losses.

3.4. Rotor type and UAV design

Aircraft design influences droplet movement. Single-rotor UAVs created more uniform deposition patterns compared to multi-rotor systems, especially at 2-4 m altitudes, achieving over 90% control of stem borer in rice (Wang et al., 2016). Conversely, eight-rotor UAVs generated stronger downward airflows than quadcopters, leading to greater overall deposition, particularly when coupled with flat-fan nozzles and adjuvants (Wongsuk et al., 2024). This highlights that UAV configuration should be tailored to crop type and canopy density.

3.5. Drift and off-target movement

Drift remains a major challenge for UAV spraying. Small droplets (<100 μm) are highly susceptible to off-target transport, particularly under windy conditions (Knoche, 1994; Subramanian et al., 2021). Trials show that drift losses increase with flight height, but can be mitigated by using adjuvants, coarser nozzles, and optimised swath overlap (Wang et al., 2020).

3.6. Comparative deposition efficiency

Relative to ground knapsack sprayers, UAVs often achieve similar or superior canopy penetration with much lower water volumes. For example, almond orchards treated with UAVs at 46-93 L ha^{-1} showed comparable chlorantraniliprole residues to air-blast sprayers operating at nearly 935 L ha^{-1} (Li et al., 2020). In rice, pesticide-use efficiency ranged from 47-56% with UAVs, compared to 38-42% for knapsack sprayers, underscoring better deposition per unit of active ingredient (Zhou et al., 2020).

4. Optimisation Strategies for UAV Spraying

4.1. Flight height and forward speed

Optimal combinations of flight height and speed are critical to balance deposition uniformity and drift. In rice, 1.5 m flight height at ~5 m s^{-1} maximised droplet coverage across canopy strata, achieving superior planthopper control compared with stretcher-mounted sprayers (Qin et al., 2016). Similarly, wheat and cotton trials revealed that lower altitudes (0.5-1.5 m) combined with moderate speeds (2-3 m s^{-1}) improved spray penetration and reduced off-target losses (Parmar et al., 2021; Wang et al., 2016). Conversely, excessive heights (>3 m) increased drift and reduced lower canopy deposition, underscoring the need for fine-tuned passes aligned to crop stature and density (Weicai et al., 2023).

4.2. Nozzle selection

Nozzle choice dictates droplet spectrum and deposition efficiency. Flat-fan nozzles generate finer droplets with better canopy penetration but greater drift risk, while air-induction nozzles produce coarser droplets that reduce drift but limit penetration (Wongsuk et al., 2024). For cereals like rice and wheat, flat-fan nozzles at low altitudes were preferable; for taller or denser canopies (sugarcane, cotton), centrifugal or hydraulic nozzles at adjusted heights improved deposition uniformity (Ranabhat and Price, 2025).

4.3. Spray volume optimisation

Unlike ground sprayers applying hundreds of litres per hectare, UAVs typically operate at ultra-low volumes (10-50 L ha^{-1}). Trials in wheat showed that increasing spray volume from 9 to >16 L ha^{-1} improved control of aphids and powdery mildew, with coarse sprays enhancing leaf surface retention (Wang et al., 2019). In almonds, UAV sprays at 46-93 L ha^{-1} delivered equivalent residues to 935 L ha^{-1} via air-blast sprayers, suggesting that efficiency gains are possible without compromising efficacy (Li et al., 2020). Rice trials further demonstrated pesticide-use efficiencies of 47-56% with UAVs, significantly higher than 38-42% for knapsack sprayers (Zhou et al., 2020).

4.4. Role of adjuvants and tank-mixes

Formulation enhancement plays a decisive role in UAV spraying. Tank-mix adjuvants improved droplet spreading, adhesion, and reduced drift. For instance, in rice, 0.5% methylated vegetable oil adjuvant increased deposition uniformity and improved brown planthopper control by 20-35% compared with water-only sprays (Wang et al., 2024). Similarly, UAV-applied pesticide tank-mixes (e.g., tetraniliprole + triazole–strobilurin fungicides) provided integrated insect and disease suppression, yielding up to 7995 kg ha^{-1} of rice and benefit-cost ratios exceeding 1:5.6 (Ragiman et al., 2024).

4.5. Crop growth stage considerations

Deposition patterns shift with crop phenology. In rice, denser canopies at booting and heading reduced basal deposition; UAV efficacy was maximised when parameters were tailored to crop stage (Weicai et al., 2023). In cotton, defoliant UAV sprays ahead of harvest were optimised at 48 L ha^{-1}, 1.5 m altitude, and ~3 m s^{-1} speed (Liao et al., 2019). For legumes like black gram, drone-based foliar nutrient sprays at reproductive stages increased pod number and yield significantly over manual application (Nandhini et al., 2022).

4.6. UAV design and rotor configuration

Aircraft design dictates deposition uniformity. Single-rotor UAVs generated more consistent coverage than multi-rotor drones in rice, though the latter were easier to operate in fragmented fields (Wang et al., 2016). Eight-rotor drones produced stronger downwash than quadcopters, improving penetration and efficacy, especially when paired with adjuvants (Wongsuk et al., 2024). This suggests rotor configuration should be selected based on crop size, canopy complexity, and field conditions.

Table 2. Recommended operational parameters for UAV spraying in major crops

Crop	**Flight height (m)**	**Speed (m s^{-1})**	**Spray volume (L ha^{-1})**	**Preferred nozzle**	**Reference**
Rice	1.5-2.0	3-5	18-30	Flat-fan	Qin et al. (2016); Wang et al. (2020)
Cotton	0.5-1.5	2-3	30-48	Centrifugal	Parmar et al. (2021)
Wheat	1.5-2.0	3-4	>16	Coarse spray nozzle	Wang et al. (2019)
Almond	2-3	3-4	46-93	Hydraulic nozzle	Li et al. (2021)
Sugarcane	2-3	2-4	30-50	Hydraulic nozzle	Ranabhat & Price (2025)

5. Standardisation of UAV Spray Evaluation Methods

5.1. Challenges in evaluating UAV deposition

Assessing UAV spray performance is inherently complex because deposition patterns are less uniform than those produced by tractor-mounted booms. Traditional evaluation relies heavily on water-sensitive papers (WSPs), which register droplet density, size, and coverage. However, WSPs can overestimate deposition due to stain enlargement and fail to capture droplets <50 μm, leading to systematic errors (Ahmad et al., 2022). Glass strips and polyester collectors have been tested as alternatives, providing more accurate quantification of fine droplet residues but missing broader spatial variability. This highlights the absence of a universally accepted sampling standard.

5.2. Digital analysis tools: DepositScan vs. SprayDAT

For over a decade, DepositScan has been widely used to analyse scanned WSPs, estimating droplet size distribution and volume from stain geometry. Yet UAV-specific studies show that DepositScan underestimates spray volume by up to 2.7-fold compared with spectrophotometric extraction of tracer dyes (Koo et al., 2024). More critically, overlapping stains at high coverage led to merged droplet counts, inflating mean diameters and obscuring true droplet density.

To address these limitations, SprayDAT, a Python-based batch processing tool, was recently introduced. It improves recognition of small droplets (<100 μm), processes large datasets efficiently, and allows researchers to modify spread factors for different substrates (Koo et al., 2024). Adoption of such flexible, transparent tools will be central to harmonising UAV spray research across institutions.

5.3. Cross-validation with extraction-based methods

Deposition assessment should not rely solely on WSP imaging. Studies that paired WSP with tracer-dye extraction from Mylar or Kraft paper sheets provided more reliable absolute deposition values. For example, spectrophotometric extraction of blue dye from Kraft paper correlated strongly with SprayDAT outputs, providing a scalable means of validating digital image analysis (Koo et al., 2024).

Such hybrid protocols reduce reliance on assumptions about spread factors and allow calibration of image-based estimates.

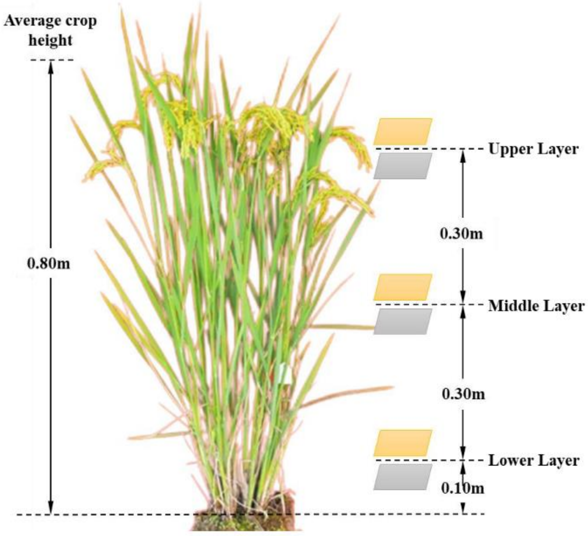


Figure 3. Proposed standardised workflow for evaluation of UAV spray deposition, drift, and pesticide-use efficiency (Jing et al., 2023).

5.4. Towards ISO-aligned efficiency metrics

Beyond deposition, performance reporting increasingly includes pesticide use efficiency (PUE), the ratio of biologically effective deposition to total a.i. applied. In rice, UAV spraying achieved PUE values of 47-56%, outperforming knapsack sprayers at 38-42% (Zhou et al., 2020). Incorporating canopy structure, e.g. leaf area index (LAI), into these calculations ensures stage-specific comparisons. The ISO 24253 framework for field efficacy and drift assessments could provide a foundation for standardised UAV evaluation protocols if adapted for low-volume aerial systems.

5.5. Need for harmonised global protocols

Current evidence highlights methodological inconsistency across studies: different collectors (WSP, glass, filter papers), image tools (DepositScan, ImageJ, SprayDAT), and tracer chemicals complicate cross-trial comparisons. Without harmonisation, results remain crop and site specific, slowing regulatory acceptance and label development for UAV applications. A minimal reporting standard (MRS) is therefore recommended:

1. Use at least two collector types (WSP for pattern, extraction-based for volume).
2. Report canopy-stratified deposition (upper, middle, lower).
3. Quantify drift at ≥2 downwind distances.
4. Specify UAV operational parameters (altitude, speed, nozzle, spray volume, adjuvant).
5. Express efficiency in ISO-aligned PUE terms.

Table 3. Comparative assessment of UAV spray deposition evaluation methods

Method	**Principle**	**Advantages**	**Limitations**	**Reference**
Water-sensitive paper (WSP)	Droplet stain analysis	Easy and inexpensive	Cannot detect very fine droplets	Ahmad et al. (2022)
Glass slides	Residue deposition measurement	Accurate quantification	Limited spatial coverage	Ahmad et al. (2022)
DepositScan	Image-based droplet analysis	Rapid processing	Underestimates volume at high coverage	Koo et al. (2024)
SprayDAT	Python-based batch analysis	Improved small droplet recognition	Requires calibration	Koo et al. (2024)
Dye extraction methods	Spectrophotometric quantification	Accurate absolute deposition	Labour-intensive	Koo et al. (2024)

6. Economic, Environmental, and Safety Implications of UAV Spraying

6.1. Cost-benefit outcomes

In India, UAV-delivered tank-mixes (tetraniliprole + fungicides) not only enhanced pest and disease suppression but also achieved an incremental cost-benefit ratio (ICBR) of 1:5.63, making them economically superior to conventional methods (Ragiman et al., 2024). For maize and pulses, drone-based nutrient sprays improved yield parameters beyond ground application, suggesting that UAVs can contribute not only to crop protection but also to productivity gains (Nandhini et al., 2022; Kaniska et al., 2022).

6.2. Labour and time efficiency

Labour savings are substantial. UAV spraying in jute reduced manual labour requirements by nearly 60% compared to traditional backpack application (Alam et al., 2024). Similarly, UAVs cover more hectares per hour than knapsack sprayers, particularly in fragmented smallholder landscapes where tractor-mounted booms are impractical. Reduced dependence on labour also mitigates seasonal shortages, a key driver of UAV adoption in both Asia and North America (Li et al., 2020).

6.3. Operator exposure and health safety

Conventional knapsack spraying exposes applicators to significant pesticide risks due to direct contact and inhalation. UAV spraying eliminates the need for human presence in the treated field during application, thereby reducing operator exposure and improving occupational safety (Subramanian et al., 2021; Pathak et al., 2020). This advantage is particularly important for hazardous chemistries and in crops grown in waterlogged or steep terrains, where manual application can be both unsafe and inefficient.

6.4. Environmental footprint and drift reduction

While UAVs often operate at low spray volumes, concerns remain regarding drift of fine droplets (<100 μm). The use of methylated vegetable oil adjuvants further reduced off-target drift by improving droplet stability and canopy retention (Wongsuk et al., 2024; Wang et al., 2024). Furthermore, the pesticide-use efficiency gains observed with UAVs (47-56% vs. 38-42% for knapsack sprayers) translate directly into reduced chemical loads per unit of effective pest control (Zhou et al., 2020).

6.5. Barriers and equity considerations

Despite these advantages, high initial costs, short battery life, limited payload capacity, and regulatory restrictions remain barriers to adoption. In developing regions, many farmers rely on service providers rather than owning UAVs, raising questions of accessibility and equitable deployment (Pathak et al., 2020). Policies that subsidise drone services, establish training programs for certified operators, and support cooperative ownership models could enhance uptake among smallholders.

Table 4. Economic and environmental advantages of UAV spraying over conventional application systems

Parameter	UAV spraying	Conventional spraying
Water use	Low	High
Labour requirement	Very low	High
Operator exposure	Minimal	High
Field capacity	High	Moderate
Pesticide-use efficiency	47-56%	38-42%
Crop trampling	Negligible	Moderate
Suitability in wet fields	Excellent	Poor

7. Policy, Regulatory, and Adoption Challenges

7.1. Regulatory gaps in UAV spraying

While UAV applications have expanded rapidly across Asia, Europe, and North America, regulatory frameworks often lag behind technological advances. In India, for example, pesticide labels are not yet standardised for low volume UAV spraying, leading to uncertainty in recommended doses and flight parameters (Pathak et al., 2020). Similarly, in the United States and the European Union, UAVs remain under strict aviation and pesticide application laws, requiring case by case exemptions for commercial use (Li et al., 2020). Without harmonised registration and label guidance, UAV applications cannot be fully integrated into national crop protection programs.

7.2. Best management practices (BMPs)

Industry stakeholders have begun developing best management practices (BMPs) to bridge these regulatory gaps. FMC Corporation, for instance, outlined BMPs for UAV spraying of chlorantraniliprole products in Asia, emphasising the timing of applications before larval boring, correct droplet size classes, and flight consistency (Li et al., 2019). These BMPs represent some of the earliest standardised operational guidelines for UAV pesticide delivery, offering a foundation for label adaptation and farmer training.

7.3. Adoption drivers and barriers

Adoption of UAV spraying is shaped by both economic and social drivers. Labour shortages in China and Japan have accelerated uptake, while in India and Bangladesh, demonstrations of yield gains, labour savings, and reduced pesticide costs are encouraging farmer cooperatives to invest (Alam et al., 2024; Ragiman et al., 2024). However, barriers include high acquisition costs, dependence on service providers, lack of trained operators, and limited awareness of safety protocols (Pathak et al., 2020). In smallholder systems, cooperative UAV ownership or pay per service business models may be essential for scaling access.

7.4. International perspectives

Japan pioneered UAV spraying with the Yamaha RMAX in the 1990s and continues to lead in UAV-specific pesticide registration (Li et al., 2020). China has scaled rapidly, integrating drones into government supported mechanisation programs, while Australia has deployed UAVs in broadacre farming for weed control. In contrast, European adoption is constrained by stricter aviation rules, though pilot trials are underway in vineyards and orchards (Cunha et al., 2021). The unevenness of these frameworks underscores the need for global harmonisation, particularly around operator licensing, aerial drift limits, and residue management.

7.5. Path forward: regulatory science and stakeholder alignment

For UAV spraying to transition from experimental to mainstream, three regulatory priorities must be addressed:

1. Establish UAV-specific pesticide labels with recommended doses, spray volumes, and adjuvant use.
2. Mandate training and licensing programs to ensure safe UAV operation, including drift management.
3. Adopt harmonised evaluation methods so efficacy, drift, and residue data are comparable across countries.

Collaborative platforms involving government agencies, research institutes, and industry are essential to accelerate regulatory acceptance and farmer adoption.

8. Future Prospects and Research Priorities

8.1. Harmonised deposition and drift standards

The most urgent need is a globally harmonised protocol for UAV spray evaluation. Current practice mixes WSP, glass/Mylar, and different imaging pipelines, which complicates cross-study comparisons. A consensus package should pair (i) pattern samplers (e.g., WSP) with (ii) extraction-based quantification (Kraft/Mylar + spectrophotometry), capped at ≤20% stain cover to avoid overlap artefacts, and (iii) batch-processable image analytics with transparent spread-factor calibration (e.g., SprayDAT). Benchmarking against known flow × speed outputs should be required for QA/QC (Ahmad et al., 2022; Koo et al., 2024).

Priority actions: There is a pressing need to establish a Minimal Reporting Standard (MRS) for UAV spraying studies, mandating the inclusion of canopy-stratified deposition data, downwind drift measurements at ≥2 distances, detailed meteorological records, nozzle and droplet classification, adjuvant use, and pesticide-use efficiency (PUE) metrics aligned with ISO guidelines (Zhou et al., 2020).

8.2. Label translation for low-volume aerial rates

Most pesticide labels were written for high-volume ground or manned-aircraft systems. We need bridging studies that translate label rates to ultra-low-volume (10-50 L ha^{-1}) UAV applications, with residue (MRL), efficacy, and phytotoxicity assurance across crops and phenophases (Li et al., 2020; Pathak et al., 2020).

Priority actions: Collaborative consortia involving regulators, industry, and academia are essential to generate crop-specific dose volume deposition reference maps, and to develop UAV-tailored label guidelines encompassing swath width, flight altitude, operating speed, and adjuvant use.

8.3. Stage-aware optimisation playbooks

Deposition declines in dense canopies late in the season; optimal settings shift with growth stage and architecture. More trials should produce stage-specific parameter tables (height, speed, nozzle, volume, overlap) tied to LAI/plant height for cereals, pulses, and orchards (Weicai et al., 2023; Liao et al., 2019).

Priority actions: Open-access datasets documenting canopy-stratified deposition across key phenological stages i.e. tillering, booting, and heading in cereals such as rice and wheat, and prebloom to harvest in orchard systems along with operator-oriented decision charts, would provide critical resources for standardising UAV spray practices and improving field-level decision-making

8.4. Formulation science for UAVs

Adjuvants that tune surface tension/viscosity consistently lift canopy deposition and biological control in rice; yet comparative data across chemistries, water qualities, and climates are sparse (Wang et al., 2024; Wongsuk et al., 2024).

Priority actions: Head-to-head evaluations of adjuvant classes including methylated seed oils (MSO), methylated vegetable oils (MVO), crop oils, polymeric stickers, and drift retardants conducted at spray volumes relevant to UAV application have provided critical insights. These trials establish mechanistic linkages between droplet size distribution, biological efficacy, and off-target drift potential (Wang et al., 2019; Zhou et al., 2020).

8.5. Aircraft and rotor–nozzle co-design

Single-rotor vs. multirotor platforms, rotor count, and downwash profiles interact with nozzle type and swath to determine patterns. Evidence suggests single-rotor aircraft can improve uniformity in cereals, while octocopters boost penetration when paired with flat-fans and adjuvants (Wang et al., 2016; Wongsuk et al., 2024).

Priority actions: A CFD informed co-design approach that simultaneously optimises rotor configuration and nozzle placement can enhance spray deposition efficiency. Field validation using continuous samplers coupled with residue extraction provides the necessary feedback to close the design performance loop.

8.6. Digital agronomy: sensing, autonomy, and IPM

Future UAV programs should be data-driven: canopy height maps, wind fields, pest hot-spot scouting (multispectral/thermal), and adaptive path planning to vary height/speed/overlap on the fly (Velusamy et al., 2022; Subramanian et al., 2021).

Priority actions: The integration of prescription maps with UAV flight controllers, combined with the coupling of scouting data to enable variable-rate spraying, offers a pathway for embedding UAV spraying within integrated pest management (IPM) frameworks. Such an approach, guided by economic thresholds and the preservation of refugia, has the potential to optimise input use while minimising ecological impacts.

8.7. Environmental safeguards and eco-metrics

Low-volume UAVs can increase PUE and reduce operator exposure, but fine-droplet drift remains a concern in windy conditions. Standard drift fences and buffer guidance should be UAV-specific; ecological endpoints (non-target arthropods, aquatic edges) require dedicated trials (Zhou et al., 2020).

Priority actions: Developing empirical drift-response curves as functions of flight height, speed, nozzle type, and adjuvant class, and concurrently reporting chemical load per unit of pest control as a sustainability metric alongside pesticide-use efficiency (PUE), would enable more holistic evaluation of UAV spray technologies

8.8. Economics and service models

Evidence from Asia shows higher net returns, labour savings, and strong ICBR for drone tank-mixes; yet service availability and operator skill constrain scale (Ragiman et al., 2024; Pathak et al., 2020).

Priority actions: Comparative assessments of ownership versus service-based economics, the feasibility of cooperative deployment models, structured training pipelines, and the logistical challenges of downtime including battery exchange and refill station requirements are critical for scaling UAV adoption in smallholder mosaic farming systems

8.9. Multi-pest, multi-objective programs

UAVs excel for tank-mix programs that jointly manage insects and diseases (higher yields, better economics) (Ragiman et al., 2024). Beyond protection, nutrient and defoliant applications are promising (Nandhini et al., 2022; Liao et al., 2019).

Priority actions: Designing season long spray programs that integrate both prophylactic and curative applications, optimising spray intervals and active ingredient rotations for resistance management, and validating downstream impacts on harvest outcomes and product quality, such as in almonds and cotton are essential for aligning UAV spraying with sustainable crop protection strategies

8.10. From trials to regulation

Technical maturity must translate to regulatory acceptance: BMPs from industry (e.g., diamide guidance) offer a scaffold, but need public-domain datasets and ISO-aligned dossiers to support label amendments (Li et al., 2019; Li et al., 2020).

Priority actions: Pre competitive collaborations are needed to generate multi-site, multi-year datasets linking UAV spray efficacy, drift, and residue dynamics for priority crops such as rice, wheat, cotton, and orchards, thereby accelerating the development of UAV-specific pesticide labels.

In sum, the research agenda pivots on standardisation, stage aware optimisation, formulation co-development, platform co-design, and data driven autonomy, all tied to regulatory-ready evidence. Addressing these priorities will convert the demonstrated field potential of UAV spraying into mainstream, sustainable crop protection.

9. CONCLUSIONS

Over the past decade, UAV-based spraying has evolved from an experimental approach into a scientifically validated crop protection tool. Studies across rice, wheat, cotton, legumes, jute, and almond production systems have demonstrated that drones can achieve pest and disease control comparable to, and in some cases better than, conventional knapsack and air-blast sprayers (Qin et al., 2016; Li et al., 2020; Parmar et al., 2021). Enhanced pesticide-use efficiency (PUE), reduced spray losses, and improved canopy penetration due to rotor-generated downwash are among the major advantages associated with UAV spraying systems (Zhou et al., 2020). However, the effectiveness of UAV application is highly dependent on operational optimisation, including flight height, forward speed, nozzle configuration, spray volume, and adjuvant selection. Several studies have shown that crop stage-specific adjustments and canopy-based calibration significantly improve spray deposition and biological efficacy (Wongsuk et al., 2024; Wang et al., 2024; Weicai et al., 2023).

Despite these advances, the absence of standardised methodologies for spray assessment remains a major challenge for regulatory acceptance and scientific comparison. Variations in collector materials, imaging software, and tracer quantification methods often generate inconsistent datasets. Recent studies suggest that combining Water Sensitive Paper (WSP)-based pattern analysis with extraction-based quantification techniques can provide more reliable evaluation of UAV spray performance (Ahmad et al., 2022; Koo et al., 2024). In addition to technical benefits, UAV spraying offers substantial economic and occupational safety advantages through reduced labour requirements, lower pesticide consumption, minimised operator exposure, and improved profitability (Alam et al., 2024; Ragiman et al., 2024). Future progress will depend on stronger policy support, including UAV-specific pesticide regulations, operator certification systems, and development of standardised best management practices. Integration of drones with digital scouting, prescription mapping, and variable-rate application technologies is expected to further strengthen their role in sustainable integrated pest management (IPM) programmes.

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