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Spray Drones in Agriculture: Technology, Regulation and Field Operations

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Introduction

Spray drones, also known as Unmanned Aerial Systems (UAS), are receiving increasing interest in agriculture because they may help address several practical challenges, including labor shortages, rising production costs, limited field access, and the need for timely application of crop protection products (Ozkan, 2024). Their adoption has expanded rapidly in the United States, where approved Part 137 UAS operators treated 10.4 million crop acres in 2024, and that area increased to more than 16.3 million acres in 2025 (ASDC, 2025). Modern spray drones are equipped with GPS-guided navigation, advanced sensors, and data-processing capabilities that support site-specific management. Their ability to operate in small, fragmented fields and difficult terrain makes them particularly valuable where conventional ground or aerial equipment is limited. This article provides an accessible overview of spray drone technology, operational components, regulatory frameworks, agricultural applications, environmental implications, and future prospects to support Extension audiences, practitioners, and decision-makers (Biglia *et al.*, 2022).

Design and Operational Technologies of Spray Drones

Spray drones combine advanced engineering and digital technologies to support precise, efficient field operations, and understanding their components helps operators choose and use equipment more effectively.

1. Spraying Systems

Spray drones generally rely on one of the two spraying approaches:

- Hydraulic nozzle systems: These use conventional agricultural nozzles (e.g., flat-fan or air-induction types). Nozzles such as XR11001 or TT11001 typically produce fine-to-medium droplets and are commonly used when greater surface coverage is required, such as in pre-emergence herbicide applications (Fig. 1).
- Rotary atomizer systems: These use spinning discs or cups to electronically control droplet size. Operators can often adjust droplet size settings (e.g., 200–300 µm) through the drone's control interface, allowing greater flexibility across different crops and application goals (Fig. 1).
- Droplet size classifications are determined based on the American Society of Agricultural and Biological Engineers ASABE S572.3 standard (ASABE, 2020). For example, under this framework, medium droplets correspond to a volume median diameter (VMD) of 236–340 µm, whereas very coarse droplets fall within the 404–502 µm range (Table 1).

Why do droplet size and nozzle selection matter in herbicide application?

Droplet size and nozzle selection play a critical role in achieving uniform spray coverage, which is essential for effective herbicide performance.

When the correct nozzle and droplet size are selected, the spray is distributed more evenly across the target area. This uniformity ensures that all weeds receive a consistent dose of herbicide, reducing the risk of untreated patches or over-applied zones. In contrast, poor nozzle selection or inappropriate droplet size can lead to uneven spray patterns, resulting in streaks, gaps, or excessive overlap.

Smaller droplets generally provide better coverage and more uniform distribution on leaf surfaces, especially for contact herbicides that require thorough coverage. However, they may increase the risk of drift. Larger droplets reduce drift but can lead to less uniform coverage if not properly managed.

Therefore, selecting the appropriate nozzle type and droplet size helps maintain a balance between coverage uniformity and application efficiency, ensuring that herbicides are applied consistently across the field and perform as intended.

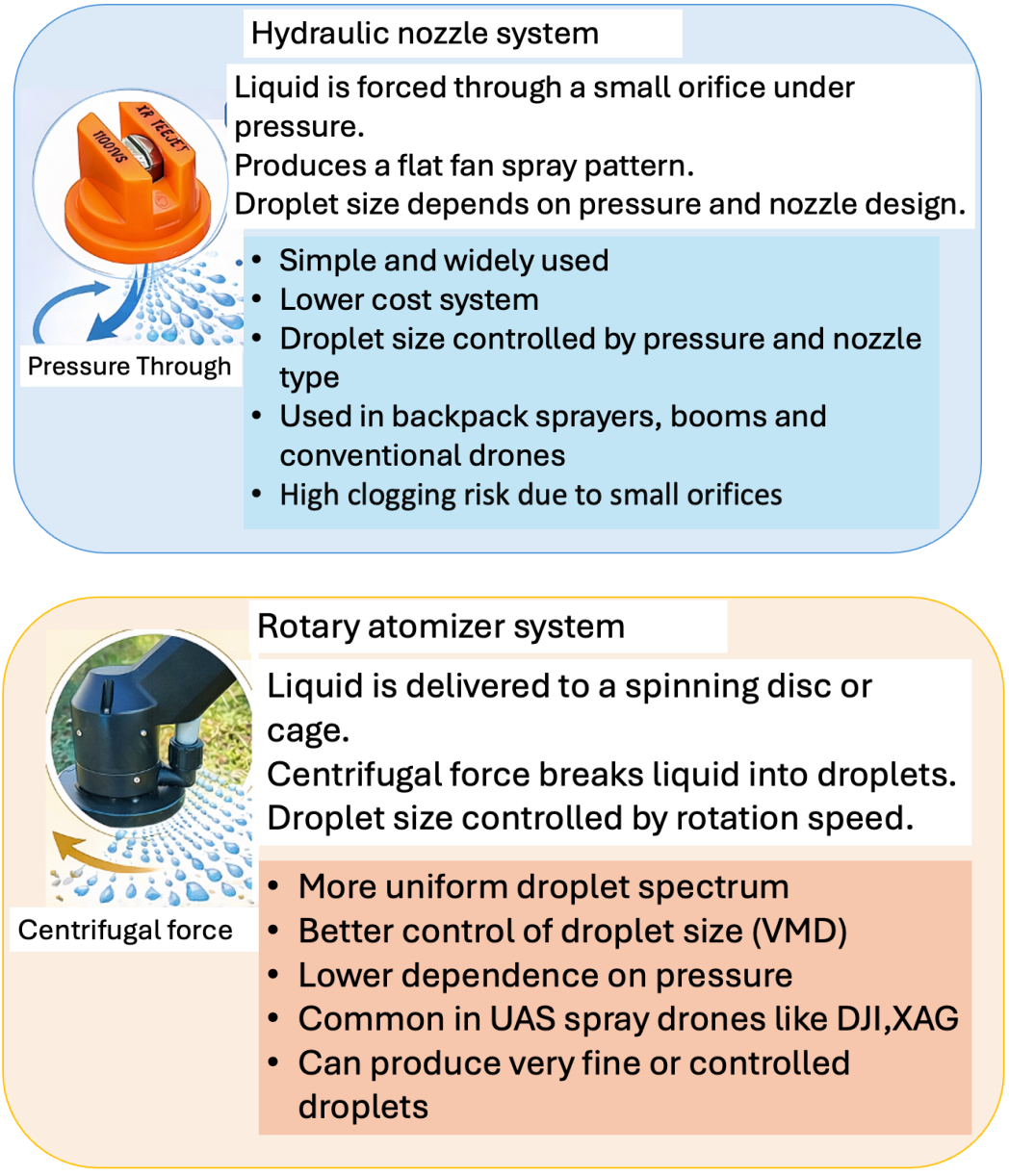

Figure 1. Comparison of spray systems in agricultural drones (Ozkan, 2024).

Table 1. Droplet size classification based on the American Society of Agricultural and Biological Engineers ASABE S572.3 standard, showing the volume median diameter (VMD) ranges for different droplet categories, with color coding used to distinguish each classification.

Spray quality	VMD range (μm)
Extremely fine	<60
Very fine	61-105
Fine	106-235
Medium	236-340
Coarse	341-403
Very coarse	404-502
Extremely coarse	503-665
Ultra coarse	>665

2. Sensors and Data Collection

Many modern spray drones are equipped with RGB, multispectral, and sometimes LiDAR sensors to assess crop vigor, detect stress, and map field variability. Multispectral data can generate vegetation indices, such as the Normalized Difference Vegetation Index (NDVI), to support variable-rate or targeted spraying. While not yet widely adopted by all commercial operators, these technologies represent a key advancement in precision agriculture (Reddy et al., 2025).

3. Artificial Intelligence and Decision Support

Artificial intelligence (AI) and machine learning are increasingly being integrated into agricultural drone systems and software platforms to support more precise and data-driven spraying decisions. These tools can help predict droplet deposition, optimize spray parameters such as speed, flow rate, height, and swath width, and generate prescription maps for site-specific applications. AI-based image analysis may also be used to detect weed patches, pest hotspots, or crop stress from aerial imagery, allowing targeted treatment rather than uniform application across the entire field. In addition, some emerging systems combine weather, canopy, and flight data to improve application timing and reduce the risk of drift. Although these capabilities are still developing, they indicate a continued shift toward more automated, precision-oriented drone spraying systems in agriculture (He *et al.*, 2022).

4. Navigation and Safety Systems

Accurate navigation is essential for effective drone spraying. Most systems rely on GNSS (Global Navigation Satellite System) for route planning and autonomous flight. Higher-end platforms may include obstacle-avoidance sensors (e.g., radar and vision-based systems) to detect trees, power lines, and other hazards. These safety features improve reliability and reduce the risk of accidents, particularly in complex landscapes (Andanaputra *et al.*, 2020).

Commercial Spray Drone Platforms

A wide range of commercial spray drones is currently available, differing in tank size, spray width, flight time, and price. Larger platforms such as the DJI Agras T40/T50 and XAG P100 Pro are designed for higher-capacity operations, while smaller systems are more accessible for small farms or custom operators. When selecting a platform, users should consider not only cost but also local service support, part availability, training resources, and regulatory compliance (Table 2, Fig. 2).

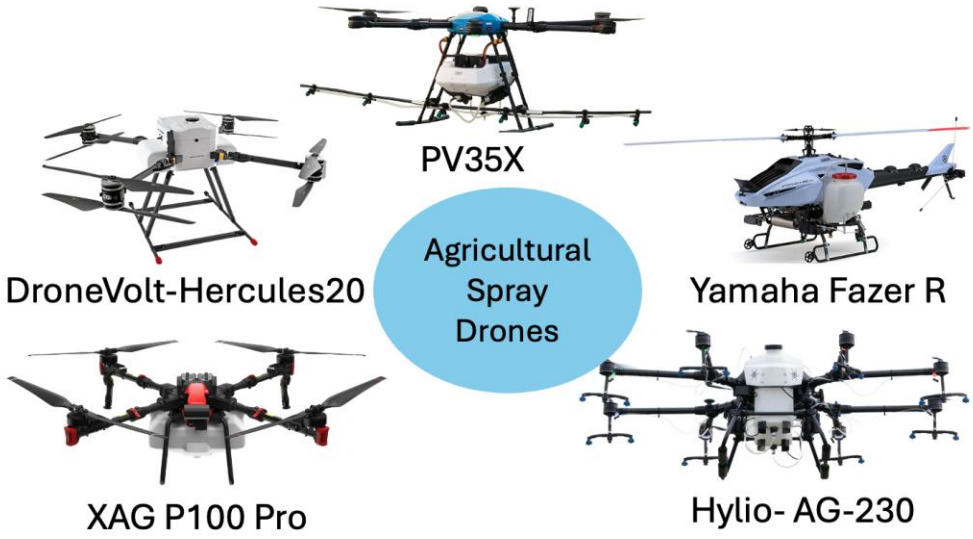

Figure 2. These platforms illustrate aerial technologies used for spraying in precision agriculture

Table 2. Different types of spray drones on the market (Magdolna, 2025). The listed price is only an estimate of the base price and may increase depending on the number of batteries, charger, or other accessories.

Drone Model	Company	Spray Tank (liters)	Spray width (meters)	Hovering flight time (minutes)	Price Range
DJI Agras T-40	SZ DJI Technology Co. LTD.	40	12	18-20	$18,000+
DJI Agras T-50	SZ DJI Technology Co. LTD.	40	11	18-20	$18,000-$32,000
XAG P100 Pro	XAG	50	7-10	18	$19,000+
XAG V40	XAG	16	5-7	15	10,000+
Yamaha FAZER R AP	Yamaha Moter Co. Ltd	32	7.5-10	60	$85,000
Hylio AG-230	Hylio Inc	30	10.7	20	$30,000+
ATLAS HYL-300	Hylio Inc	113	Up to 15	15	$64,000+
TTA M6E-X	Beijing TT Aviation Technology Co., Ltd. (TTA)	16	12	30	$10,000+
Kray Pro	Kray Technologies	16	12	30	$20,000+
DroneVolt Hercules20	Drone Volt	81	2	40	$20,000+
PV 100X	Central UAS Technologies	50	9.2 (Boom) 10.7 (Rotary atomizer)	15	$30,000+

Regulatory Framework

Spray drones are being adopted across a wide range of agricultural practices, including pesticide and herbicide application, fertilizer application, spot spraying, and seeding operations (Fig. 3).

In the U.S., agricultural drone operations are primarily governed by the Federal Aviation Administration (FAA) and the Environmental Protection Agency (EPA) (Fig. 4).

The FAA requires registration of drones weighing more than 0.55 lb (250 g) and mandates compliance with operational rules such as visual line-of-sight, altitude limits, and Remote ID requirements. Navigating these regulations can be challenging for new operators. Training programs and Extension support play an important role in helping applicators understand and comply with these requirements (Klauser and Pauschinger, 2021).

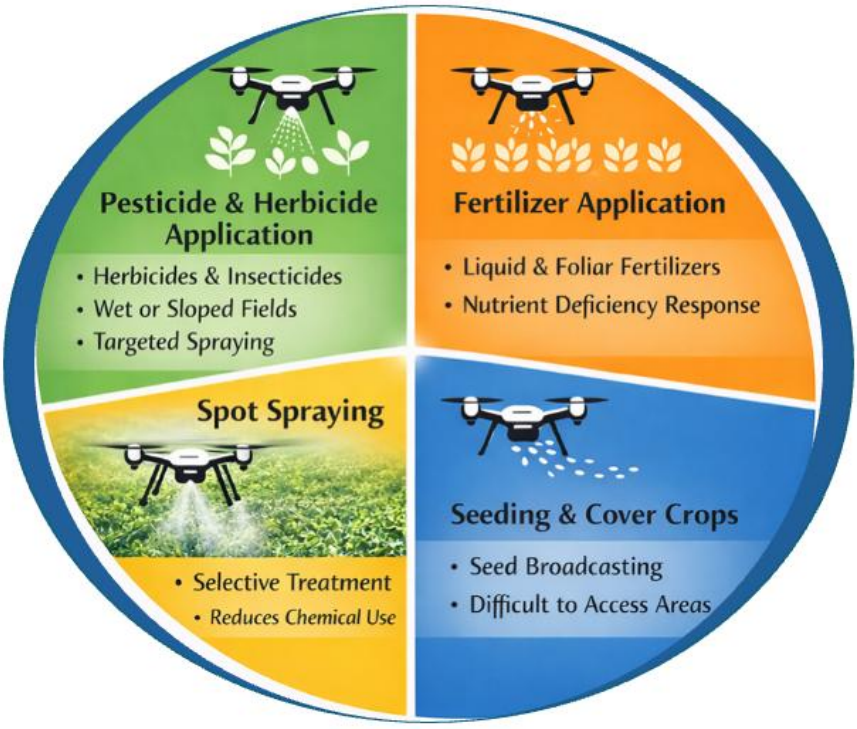

Figure 3. Advantages of spray drone applications in agriculture

Operational Considerations for Effective Use

Successful drone spraying depends on several key factors. Operators must carefully select droplet size to balance coverage and drift risk, optimize flight height and speed to improve deposition and reduce off-target movement, and monitor weather conditions, especially wind, temperature, and inversions, to ensure safe application. Efficient battery and logistics management is also essential due to limited flight times. Proper training and a strong understanding of both drone technology and agronomic spraying principles are critical for achieving effective results.

Environmental, Social, and Ethical Considerations

Spray drones provide environmental advantages, including reduced soil compaction, lower fuel use, and no greenhouse gas emissions from electric systems, and potential reductions in chemical use through targeted applications. However, challenges remain, such as spray drift under unfavorable weather conditions, possible

disturbance to livestock and wildlife from repeated low-altitude flights, and privacy concerns related to aerial imaging and data ownership. Responsible use requires both technical expertise and careful attention to environmental and community considerations.

Figure 4. Key regulatory requirements for agricultural drone spraying in the United States.

What steps should be taken prior to the main spray application?

Before the main spray application, pattern testing and effective swath width should be evaluated. This can be done using Kromekote® cards (Fig. 5A) or water-sensitive papers (WSPs) (Fig. 5B). These cards are placed on the ground across the expected spray swath before spraying. After applying a colored spray mixture or fluorescent tracer, the droplet pattern deposited on the cards becomes visible, allowing the operator to observe the spray distribution across the swath. This helps identify areas of over- or under-application and determine the effective swath width. Pattern testing also helps verify whether the selected droplet size from the rotary atomizer is being delivered as expected. The collected cards can be analyzed using scanner-based systems such as AccuStain (Version 0.35; University of Illinois, Champaign, IL), which quantifies spray coverage, droplet density, and deposition patterns. Based on the measured effective swath width, applicators can properly design field plots and accurately determine the centerline of the drone spray path for consistent and uniform application. WSP is a yellow paper that turns blue when it contacts water-based spray droplets, allowing quick field assessment of spray coverage.

In contrast, Kromekote® cards are glossy white papers typically used with fluorescent dyes for more precise laboratory analysis of spray coverage, droplet density, and deposit size. WSP is sensitive to humidity, which may cause false color change under humid conditions, whereas Kromekote® cards are not affected by humidity and provide more stable results. Additionally, WSP is a specialized agricultural product and generally more expensive than glossy paper such as Kromekote® (Fig. 5).

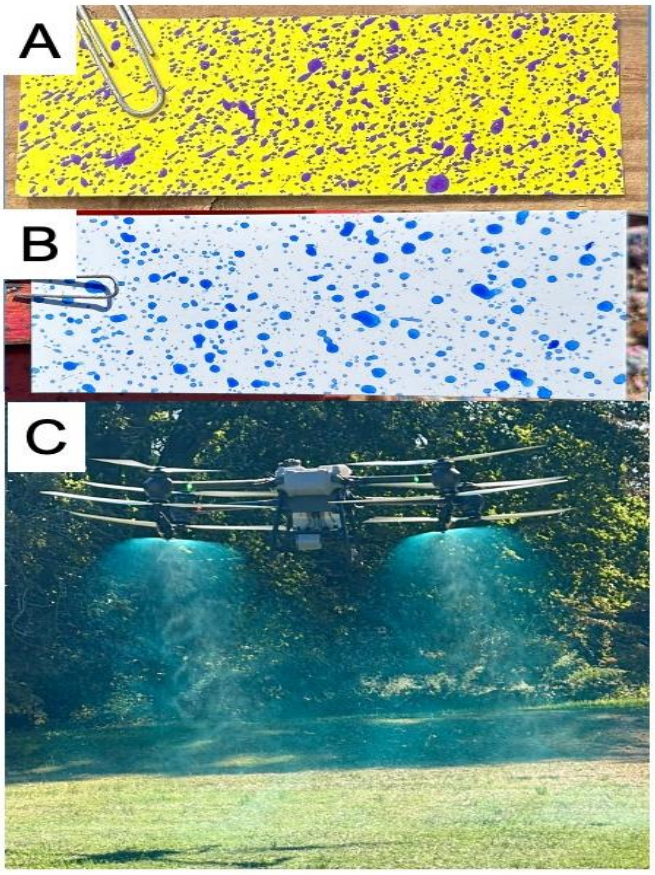

Figure 5. Kromekote® cards (A) and water-sensitive paper (B), and a DJI T50 spraying FD&C blue 1- dye for pattern testing.

The other way of determining effective swath is the use of swath paper strips (Fig. 6A), followed by scanning and analysis using the Swath Gobbler™ (Application Insight LLC, Lansing, Michigan), which provides a continuous and complete record of spray distribution across the swath (Fig. 6B). This method utilizes inexpensive 3-inch bond paper rolls mounted on simple collection boards and a visible dye to capture droplet deposition. Unlike discrete sampling methods such as cards, it produces an ordered cross-sectional profile of the entire spray pattern, reducing sampling bias and improving the accuracy of coefficient of variation (CV) estimation. In addition, the collected paper strips serve as a durable record that is not affected by humidity, allowing long-term storage and later analysis. The method is also cost-effective and efficient, as the materials are inexpensive, and the scanned rolls can be digitized rapidly to generate detailed swath reports. Find all information about Swath Gobbler™, swathing supplies, white papers, and other related products at this link.

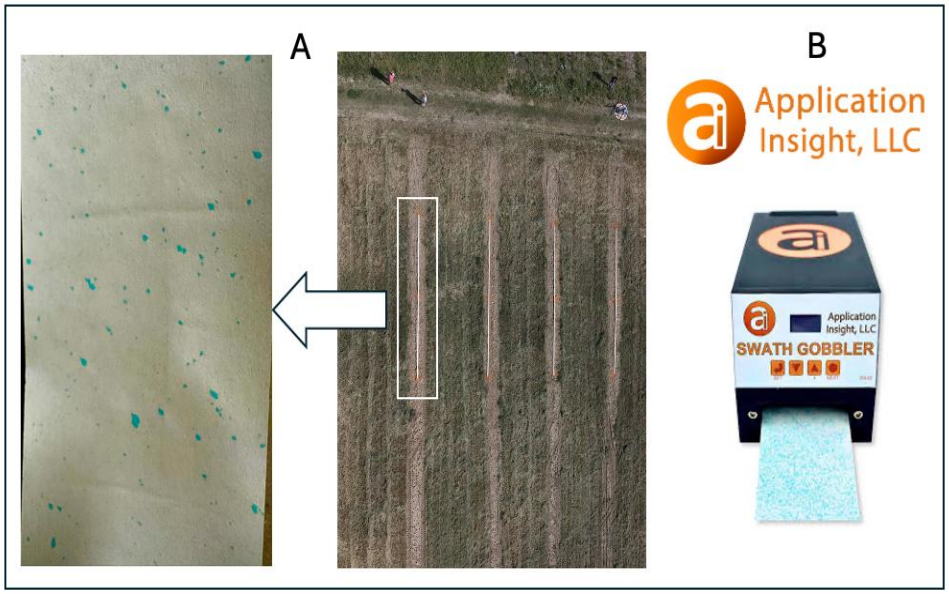

Figure 6. (A) Swath paper strips were placed in the field to determine the effective swath width (A), followed by (B) scanning and analysis using Swath Gobbler.

For example, in a study by Esmaeilbeiki *et al.* (2026), swath analysis was conducted prior to the main experiment and the distribution suggested a bell-shaped pattern, indicating uniform deposition at the center of the spray and tapering off towards the edges (Fig. 7). This trend highlights the area of optimal spray application, where coverage is more uniform, ensuring effective deposition within the intended treatment zone. Based on this deposition profile, the effective spray swath is defined as the width of the primary deposition zone corresponding to the main coverage peak. In general, the threshold is considered at 50% of the maximum coverage. For instance (Fig. 7), the maximum is around 40%, and the corresponding threshold is at 20%. The left and right boundaries of this zone were identified at approximately 4.0 and 8.0 m, respectively, where spray coverage began to decline markedly beyond the central region. Consequently, the effective spray swath was calculated as the distance between the two boundaries (8.0 – 4.0 m), resulting in an effective swath width of 4.0 m (13 feet) at 20% coverage. This swath was considered with a coefficient of variation (CV) around 15%, which indicates a more uniform pattern. However, if a CV of 25% is acceptable, the resultant effective swath will be around 4.9 m (16 feet). This effective swath was subsequently used to determine pass spacing for overlap and multi-pass applications in the field, ensuring adequate overlap between adjacent spray passes while minimizing under- or over-application.

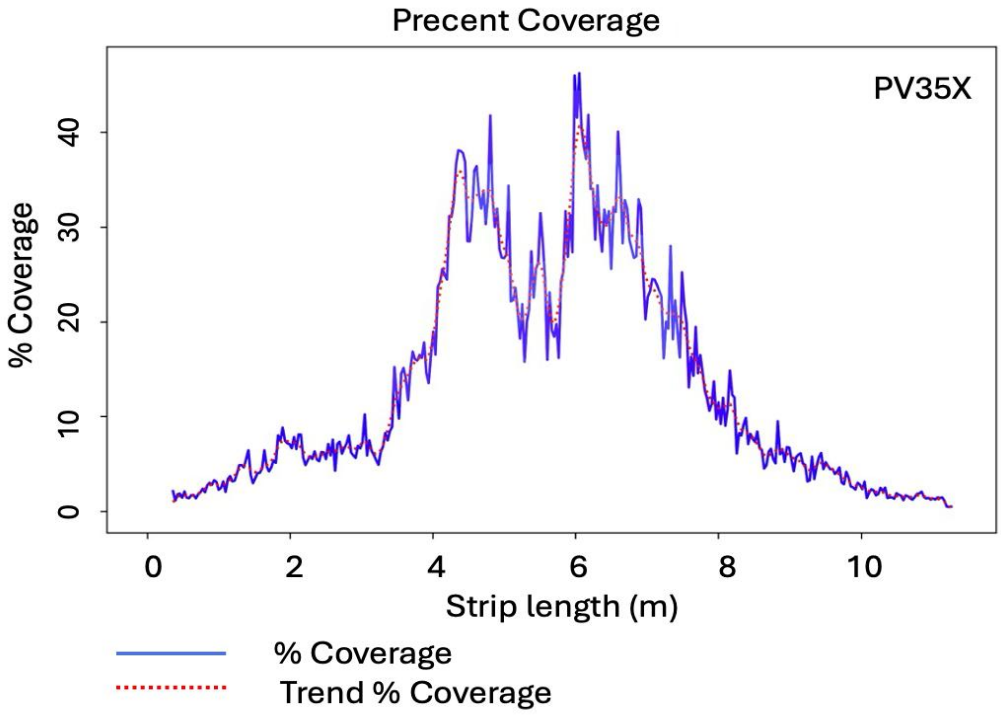

Figure 7. Swath analysis of LeadingEdge PV35X equipped with four TT11001 nozzles and spray volume 37.41 L ha^{-1} (4GPA). An effective spray swath is 4.9 m with a coefficient of variation (CV) of 25% and 4.0 m with a CV of 15% (Esmaeilbeiki et al., 2026).

How does flow rate influence droplet size and atomization performance

It has been observed that aerial drones equipped with aerial drones (e.g., two rear rotary atomizers on T50) provide an inconsistent, larger droplet size at higher flow rates or spray volumes per acre. Study showed that increasing the flow rate from 2.4 L min^{-1} (0.6 gallons per min) to 6.0 L min^{-1} (1.6 gallons per min) while keeping travel speed constant increased droplet size by about 100 μm VMD (Fig. 8). This result suggests that the rear rotary atomizers on the T50 may not consistently produce fine to medium droplets when liquid output is increased. From a practical standpoint, this matters because droplet size affects spray coverage, deposition, and drift potential. Larger droplets are generally less likely to drift, but they may not provide enough coverage for foliar-applied products, especially contact herbicides and insecticides that require good coverage on the target surface for effective control. Therefore, selecting appropriate flow rates is critical to balance drift control and adequate canopy coverage.

To address inconsistency in droplet size, DJI Inc. (China) introduced a potential solution to install two additional rotary atomizers beneath the front propeller arms of the Agras T50 platform. These supplementary atomizers are now available as an aftermarket upgrade kit through authorized DJI dealers and distributors, allowing existing users to retrofit their systems. This may provide a sufficient outlet for the liquid being pumped at higher flow rates, thereby producing the desired droplet sizes. Alternatively, spray volume can be changed by adjusting flight speed rather than flow rate. Keeping the flow rate constant can help maintain a more consistent droplet size, which may improve coverage and overall application uniformity. However, under windy conditions, greater speed may lead to non-uniform spray deposition.

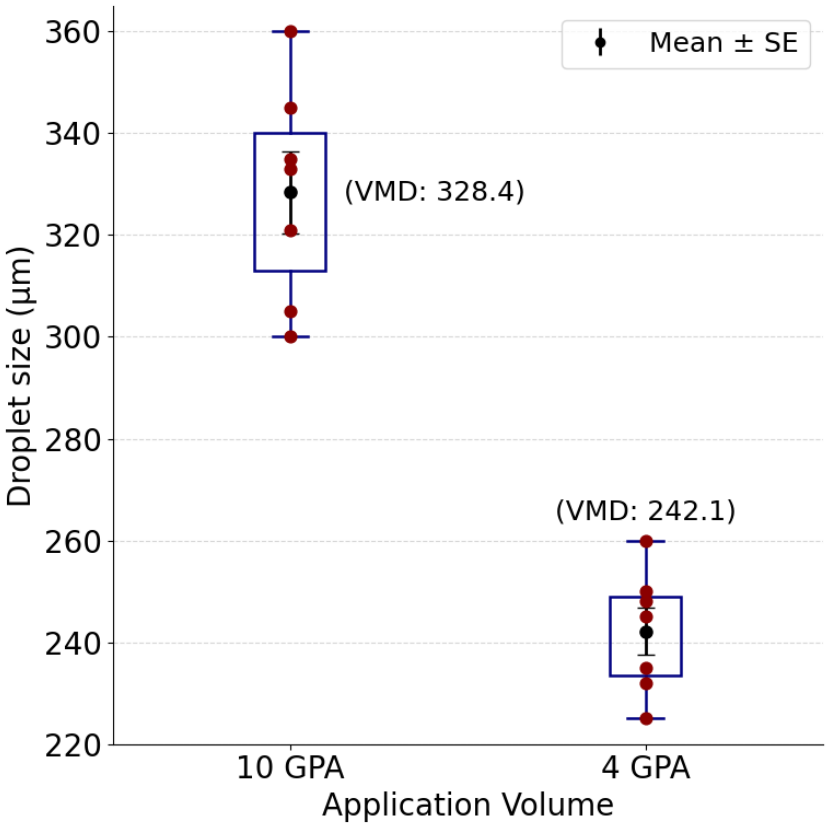

Figure 8. Box plot representation of droplet size distribution of spray application with DJI Agras T50 at lower (2.4 L min^{-1}) and higher (6.0 L min^{-1}) flow rates. These flow rates correspond to spray volumes of 4 GPA (37.41 L ha^{-1}) and 10 GPA (93.53 L ha^{-1}), respectively, where GPA = gallons per acre. Volume median diameter (VMD) for droplet size selection was 250 µm. At lower carrier volumes, Agras T50 maintains the selected droplet size, but at higher volumes it tends to increase droplet size if the flow rate is not constant (Esmaeilbeiki et al., 2026).

What is the optimal application height to use in UAS spraying?

The typical application height for UAS spraying ranges from 7 to 10 ft above the crop canopy; however, selecting the optimal flight altitude requires careful consideration of several interacting factors, including crop type and canopy structure, terrain variability, aircraft characteristics, weather conditions, and spray system configuration (Wang *et al.*, 2020). In general, spray pattern/ uniformity of spray deposition guides the optimal application height, which also depends on the aerial drone, spray mechanism, and spacing between atomizers/nozzles.

For example, when using systems equipped with rotary atomizers, such as the XAG P100 Pro, a slightly higher flight altitude is often recommended. This is because rotary atomizers generate droplets that benefit from additional travel distance, allowing the rotor downwash to distribute droplets better and improve swath uniformity and canopy penetration. A higher altitude, in this case, can help create a more even spray pattern across the effective swath width.

In contrast, UAS platforms equipped with hydraulic nozzles typically perform better at lower flight heights. Operating closer to the target reduces the distance droplets travel, which helps minimize drift and evaporation losses while improving deposition efficiency and coverage uniformity on the canopy. Lower heights also allow the spray to remain more concentrated within the intended swath, reducing variability across the field (Koo *et al.*, 2024).

Ultimately, the optimal application height should be adjusted based on site-specific conditions and application goals, balancing coverage, spray pattern/ uniformity, and drift management to achieve effective herbicide performance.

Conclusion

Spray drones are an emerging application tool that can provide real value in agricultural systems where conventional equipment is limited by field conditions, crop sensitivity, terrain, or timeliness. Their greatest strengths are in situations where reduced wheel traffic, improved access, and targeted application offer operational advantages, but these benefits must be weighed against limitations in payload, field capacity, logistics, and regulatory complexity.

Their success in the field depends on proper setup, calibration, and operator judgment. Applicators must consider droplet size, spray system selection, flow rate, flight parameters, weather conditions, and label requirements to achieve effective coverage and reduce the risk of drift. As with any pesticide application method, training, stewardship, and legal compliance are essential.

While spray drones offer environmental advantages such as reduced soil compaction, lower fuel use, and potential reductions in chemical inputs, they must be used responsibly to minimize risks related to spray drift and environmental exposure. As technology continues to advance, the integration of sensors, automation, and data-driven decision tools is expected to further enhance their performance and accessibility.

Overall, spray drones should be viewed as a complementary tool rather than a complete replacement for traditional application methods. When used appropriately and supported by sound agronomic practices and extension guidance, they have strong potential to contribute to more efficient, sustainable, and resilient agricultural systems.

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