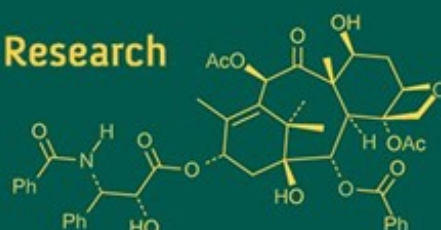


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The names and affiliations of all authors are provided below, following the references.

Emerging trends in unmanned aerial vehicles in weed management: emphasis on weed identification and control: A review

Ravi Vimalraj¹, Pasoubady Saravanane², SR Sharu³, Sreekala Sruthi⁴, Ramadoss Poonguzhalan⁵, Sujithkumar P⁶, R Praveen⁷

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ABSTRACT

Effective weed control is crucial because the growing world population has increased the demand for increased agricultural productivity. In addition to acting as habitats for pests and diseases, weeds lower crop output by competing for nutrients, water, sunshine, carbon dioxide and space. Herbicide resistance, labor scarcity, high cost, time commitment and excessive water use are some of the drawbacks of traditional weed management techniques include manual, mechanical and chemical treatments. In this context, Drones, also known as unmanned aerial vehicles (UAVs), are becoming a viable option in precision agriculture. This review emphasizes how UAV can improve herbicide application and weed detection. Site-specific weed control is made possible by UAVs with sophisticated imaging systems, such as RGB, multispectral and hyperspectral cameras, which can precisely identify weed-infested areas. Decision-making and detection are further improved by integration with artificial intelligence. UAV spraying decreases environmental effect, uses less labor and water and guarantees accurate and consistent pesticide application. Spraying efficacy is influenced by operational parameters such droplet size and spray volume. Even while there is still little research on using UAVs to apply herbicides, particularly in India, the studies that have been done so far have shown encouraging outcomes. All things considered, UAV technology provides an economical, effective and environmentally responsible substitute for traditional techniques, with great potential to enhance weed control and promote sustainable agriculture.

Keywords: Crop yield, Herbicide, Spray volume, UAV, Weed detection, Weed management

Introduction

The rising global population is driving a greater demand for food, which requires continuous increase in food production. To meet this challenge, farmers are adopting advanced technologies, such as Unmanned aerial vehicles (UAV), to enhance productivity by detecting weeds and spraying efficiently. Weeds present a major challenge to crop productivity (Storkey *et al.*, 2021) [1]. Weeds compete with crops for critical resources like nutrients (Thompson *et al.*, 2019) [2], water (Kaur *et al.*, 2019) [3], sunlight (Guglielmini *et al.*, 2017) [4], carbon dioxide (Roslim *et al.*, 2021) [5] and space (Korav *et al.*, 2018) [6], which can significantly reduce crop yields (Table 1). Weeds are engaged with different biological entities in the surrounding operating as homes for plants pests including bugs, fungi and microorganisms posing threats to close by cultivars (Srinivasan *et al.*, 2012; Abo-Habaga *et al.*, 2018; Smith *et al.*, 2018; Roshan *et al.*, 2019) [8, 7, 9, 10]. Thus, timely measures and effective weed control tactics must be applied for better crop productivity. Various methods are utilized for weed control, such as hand weeding, conventional herbicides, mechanical and machine-based weeding, environmentally friendly solutions and the utilization of artificial intelligence (AI). There are far too few workers available and the wages would be too high on labour for hand weeding. One important thing to remember when evaluating the efficacy of mechanical weed control is the limitations of weed management (Hicks *et al.*, 2018) [11]. Chemical control of weeds is a more effective measure to decrease weed density (Barbaš *et al.*, 2020) [12] relying on herbicides, which can confer resistance in weeds (Beckie, 2020) [13]. While cost-effective and versatile (Mac-Laren *et al.*, 2020) [14], herbicide use has drawbacks, such as low effectiveness with knapsack sprayers, high labor demands and time consumption. Additionally, significant water usage (250-550 l/ha) is required for this method (Chen *et al.*, 2019). These limitations make herbicide-based control less ideal in some cases.

UAVs are essential for improving agricultural productivity by standardizing chemical spraying and addressing labor shortages. This technology ensures more precise application, reducing environmental losses. UAVs can monitor small plants or weed patches that were previously hard to detect (Xiang *et al.*, 2011) [15]. Mink

Corresponding Author: Ravi Vimalraj

PhD Scholar, Department of Agronomy, College of Agriculture, Kerala Agricultural University, Vellayani, Thiruvananthapuram, Kerala India

et al. (2018) [16] demonstrated that UAV imagery can identify weed presence in row crops. This method allows for targeted herbicide application based on aerial analysis (Islam *et al.*, 2023) [17]. There is limited research on UAV-based herbicide spraying, highlighting the need for more studies on its effects on weed control. This review examines UAV technology in comparison to other sprayers to enhance weed management effectiveness. The focus is on advancing UAV usage in Indian agriculture to increase yields, alleviate labor shortages and reduce dependence on chemicals. The goal is to improve weed control.

2. UAVs in agriculture

Unmanned aerial vehicles, or UAVs, are reusable aircraft designed to fly without a pilot present. To carry out particular tasks, it can be controlled remotely, operate somewhat independently, or operate completely on its own (Van, 1999) [18]. Huang *et al.* (2008) [19] determined that integrating an autonomous UAV spray system with remotely sensed data holds significant promise for precision weed control. According to Li *et al.* (2023), the rapid adoption of agricultural UAVs across Asia is pivotal in advancing agricultural development, ensuring trade safety, protecting the agricultural environment and enhancing the quality and safety of agricultural products.

Table 1. Yield loss caused by weeds in different crops

Sl. No.	Crops	Yield loss	Reference
1	Cereals		
	Rice		
	Direct seeded rice	70-80%	Dass <i>et al.</i> (2017)
	Dry direct seeded rice	60-90%	Karthickraja <i>et al.</i> (2024), Saravanane (2020), Pooja <i>et al.</i> (2021)
	Wet direct seeded rice	40-90 %	Saravanane <i>et al.</i> (2021); Kokilam <i>et al.</i> (2023)
	Transplanted Rice	40-70 %	Bhattarai <i>et al.</i> (2023), Balaji <i>et al.</i> (2024), Yakadri <i>et al.</i> (2022)
	Wheat	60-75%	Iffat <i>et al.</i> (2010)
	Maize	50%	Landau <i>et al.</i> (2021)
	Barley	71%	Metiku <i>et al.</i> (2024)
	<i>Sorghum</i>	15-97%	Peerzada <i>et al.</i> (2017)
	Millets	15-97%	Dubey <i>et al.</i> (2023)
2	Pulses		
	Greengram	30-85%	Gupta <i>et al.</i> (2019)
	Blackgram	45-60%	Aliveni <i>et al.</i> (2016)
	Chickpeas	75%	Barla and Upasani, 2022
	Lentils	62%	Hussain, 2015
	Cowpeas	90%	Campos <i>et al.</i> (2023)
3	Oilseeds		
	Soybean	50-76%	Gharde <i>et al.</i> (2018)
	Sunflower	64%	Kanatas (2020)
	Groundnut	24-70%	Parthipan and Harisudan, 2023
	Sesame	50-70%	Kumar and Thakur, 2005
4	Cash Crops		
	Cotton	87 %	Vimalraj <i>et al.</i> (2025b)
	Sugarcane	20-40%	Tomar and Singh, 2024

Fengbo *et al.* (2017) [20] noted that China has recently implemented UAVs for crop protection. Yellappa *et al.* (2018) [21] stated that UAV with sprayers are ideal for various crops, including those in hard-to-reach areas. This technology reduces pesticide costs, minimizes environmental impact and benefits small-scale farmers. It is especially useful for orchards, rice fields and hilly terrains. China is increasingly utilizing small drones to address pest and disease issues due to a shortage of agricultural labor (He, 2018) [22]. Tsouros *et al.* (2019) [23] emphasize that UAVs provide an efficient, fast and user-friendly solution for agricultural tasks. Ahmad *et al.* (2020) [24] suggest that UAVs offer a superior approach for modern weed management. The global use of drones in agriculture is expected to rise as more countries permit their use for crop protection. Many of these nations are in East and Southeast Asia, including China, Japan, South Korea, Thailand and India (Wang *et al.*, 2023) [25].

3. Types of UAV

UAV are categorized based on type (e.g., fixed-wing, multirotor), level of autonomy, size, weight and power source (Figure 1). This classification is crucial for determining the most suitable UAV for

various agricultural tasks (Table 2). Flight height, speed, duration, payload and sensors will differ based on the specific purpose or conditions.

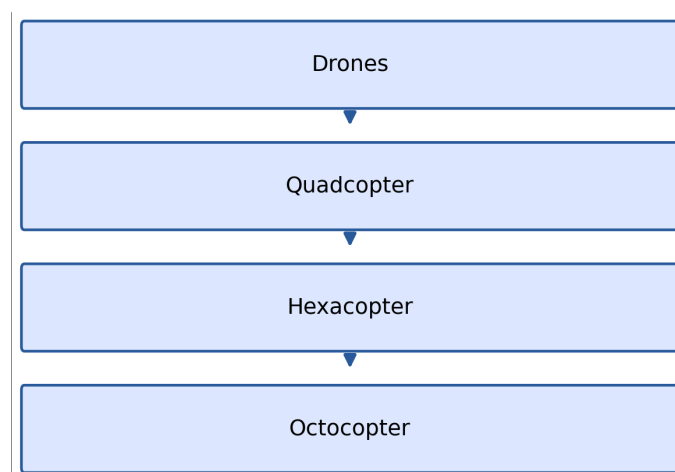




Figure 1. Types of UAVs used in agricultural applications based on rotor configuration and payload capacity.

Table 2. Features of Quadcopter, Hexacopter and Octocopter UAV

Feature	Quadcopter	Hexacopter	Octocopter
Number of Rotors	4 rotors	6 rotors	8 rotors
Wings	4	6	8
Spraying Height	1.5-3 meters above crop canopy	2-4 meters above crop canopy, adjustable	2-5 meters above crop canopy, depending on terrain
Spraying Speed	5-7 m/s (faster for small-scale fields or spot spraying)	4-6 m/s (moderate to high speed for mid-sized fields)	3-5 m/s (slower speed due to heavy payload, but ideal for large areas)
Spraying Width	2-4 meters (narrow)	4-6 meters (medium)	5-8 meters (wide)
Payload Capacity	up to 10 liters	10-15 liters	15-30 liters
Coverage Area per Flight	5-10 acres (ideal for small-scale farms or localized infestations)	10-15 acres (depending on battery life and payload)	15-25 acres (suitable for large-scale farms)
Stability in Adverse Conditions	Moderate stability, suitable for calm weather	High stability in windy conditions	Exceptional stability, ideal for challenging terrains
Weed Spraying Applications	Ideal for spot spraying, small-scale fields and localized weed infestations	Suitable for broadcast, targeted and variable-rate spraying on medium-to-large fields	Best for heavy-duty spraying, large-scale weed infestations and terrains with hills or obstacles

A hexacopter carries 6 rotors, while an octocopter has 8 rotors, meaning they are capable of heavier payloads than quadcopters. According to Reddy *et al.* (2021) [26] The evolution of hexacopter drones was fueled by their capacity for heavier lifting and extended flight, underscoring that design can greatly affect the effectiveness. The hexacopter's enhanced stability and control, along with the additional rotors, enabled precise and consistent herbicide application. This capability was crucial for efficient material use, minimizing waste and ensuring full coverage of crops or vegetation. Although octocopters had a similar payload capacity, their higher cost was due to having more motors compared to hexacopters. Consequently, the hexacopter was the preferred choice for carrying robust payloads (Shelare *et al.*, 2023) [27].

4. UAV in weed management

4.1. Using UAV to detect weeds

UAVs are highly suitable for identifying weed patches. Their key advantages over Utility Terrain Vehicles include significantly reduced monitoring or surveying time and superior maneuverability, especially when navigating around obstacles. This makes them particularly effective for operating between crop rows (Hassanein *et al.*, 2018) [28]. UAVs can cover large areas, spanning several hectares, within minutes by flying over the field, delivering photographic data essential for identifying weed patches (Krishna, 2018) [29]. Then the

images can be processed by means of deep neural networks (Crimaldi *et al.*, 2020) [30], convolutional neural networks or object-based image analysis (Maes *et al.*, 2019) [31].

A thorough analysis of the literature on weed identification using unmanned aerial vehicles revealed that three main types of cameras - RGB, multispectral and hyperspectral are employed to find weed patches (Table 3). The majority of the crops examined by these UAVs have been staple crops, such as *Zea mays*, *Hordeum vulgare*, *Beta vulgaris* and *Triticum spp.* (Franco *et al.*, 2018; Rasmussen *et al.*, 2019) [32, 33]. These crops are among the most commonly farmed in the world and they are especially vulnerable to early-life competition from weeds. Such crops, on the other hand, allow a variety of dicotyledonous weeds, e.g., *Amaranthus palmeri*, *Chenopodium album*, *Cirsium arvense* (Louargant *et al.*, 2017; Hansen *et al.*, 2013) [35, 34], as well as monocotyledonous weeds like *Phalaris spp.*, *Avena spp.* and *Lolium spp.*, (Sanders *et al.*, 2019) [36] have been successfully identified. These weed species pose a threat worldwide (Davis *et al.*, 2018) [37]. Therefore, the integration of UAVs and image processing technologies can play a crucial role in effectively managing different weed species that interfere with crops, offering notable environmental benefits (De *et al.*, 2018; Hunter *et al.*, 2020) [38, 39]. In a few minutes, UAVs can accurately monitor vast areas and detect weed patches (Sujithkumar *et al.*, 2022) [40]. (Table 4.) highlighted the identifying weed patches with various camera types.

Table 3. Features in RGB, Multispectral and Hyperspectral camera

Feature	RGB Camera	Multispectral Camera	Hyperspectral Camera
Spectral Bands	Captures 3 wide bands (Red, Green, Blue)	Captures 4-10 selected spectral bands, often including Red, Green, NIR, etc.	Captures hundreds of narrow, contiguous bands across a wide spectral range (e.g., visible to infrared).
Data Output	Produces standard color photographs.	Provides reflectance data for selected wavelengths.	Provides detailed spectral signatures for each pixel.

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Feature	RGB Camera	Multispectral Camera	Hyperspectral Camera
Spectral Resolution	Low, limited to broad visible bands.	Medium, with more detailed band selection.	High, with precise information from many narrow bands.
Spatial Resolution	High spatial resolution.	Medium to high, depending on the sensor.	Typically lower spatial resolution compared to RGB or multispectral sensors.
Advantages	Cost-effective and simple to use. Suitable for detecting visible color or shape differences in weeds.	Identifies vegetation and basic plant health by using specific spectral bands. Useful for identifying crop stress and basic crop-weed separation.	Detects small spectral differences, making it useful for species-level weed detection and biochemical analysis.
Limitations	Cannot distinguish crops and weeds with similar colors.	Fewer spectral details compared to hyperspectral systems.	Expensive, complex and generates large datasets requiring advanced processing.

4.2. UAVs used to spray various herbicides

A UAV carrying a diflufenican + isoproturon herbicide shows excellent weed control, effectively eliminating more than 98% of weeds in wheat fields, including bedstraw (*Galium aparine*) and Japanese fox-tail (Chen *et al.*, 2019) [41]. According to Zhang *et al.* (2020a) [42], the impact of weed growth and height is greatly reduced when Fluroxypyr-meptyl is applied at a rate of 20% EC using a drone at 600 ml/ha. Supriya *et al.* (2021) [43] recommended the use of pre-emergence Atrazine, early post-emergence Tembotrione and post-emergence 2,4-D for herbicide application via drones in maize to achieve effective phytotoxicity and efficient weed control. Herbicide application using a combination of a knapsack sprayer (PE) and a drone (PoE) results in a lower weed index compared to PE herbicide application with a knapsack sprayer using metribuzin 70% at a rate of 0.175 kg a.i./ha (Pranaswi *et al.*, 2022) [44].

Naveen *et al.* (2023) [45] found that the post-emergence application of penoxsulam 1.02% + cyhalofop-butyl 5.1% OD at 180 g a.i. ha⁻¹ using a drone effectively increased rice yield and reduced weed dry matter 60 days after application. Paul *et al.* (2023) [46] concluded that the drone application of pretilachlor *fb* bispyribac-Na is an effective weed management strategy for direct-seeded rice, providing benefits in terms of energy use and profitability. UAVs effectively apply the herbicide combination of tritosulfuron and florasulam to winter wheat, successfully controlling weed species such as *Shepherd's*

purse, *Lactuca serriola*, *Sinapis arvensis* and *Viola arvensis* (Bošković *et al.*, 2023) [47].

Avhale *et al.* (2024) [48] concluded that drone-based spraying of pretilachlor followed by bispyribac sodium is an effective weed management strategy for wet direct-seeded rice, resulting in superior yield, energy use efficiency and profitability. Paul *et al.* (2024) [49] found that applying pre-emergence pretilachlor through UAVs is more effective for timely weed control in the early stages of direct-seeded rice, reducing labor intensity and drudgery compared to knapsack application. Ramesh *et al.* (2024) [50] found that applying pendimethalin at 0.75 kg/ha under drone spraying to control weeds, increase grain yield and improve profit in greengram, especially considering the reduced herbicide dose and labor scarcity. Karthickraja *et al.* (2024) [51] found that using a UAV to apply pendimethalin + penoxsulam at 625 g/ha on 3 DAS, followed by bispyribac-sodium at 25 g/ha on 20 DAS, reduced total weed density and biomass, leading to better rice crop growth. Applying pendimethalin at 1.0 kg ha⁻¹ on 3 DAS using a UAV sprayer with a spray volume of 37.5 L ha⁻¹ significantly reduced overall weed density and dry biomass, according to Vimalraj *et al.* (2025b) [52]. The growth of cotton was improved by effective weed suppression, as seen by higher plant height, improved yield components such as boll weight and number per plant, increased seed cotton yield and increased profitability as measured by net returns and benefit-cost ratio.

Table 4. Identifying weed patches with various camera types

Crop	Type of camera	Weed		Main results	References
		Common name	Scientific name		
<i>Triticum sp.</i>	RGB camera	Thistle	<i>Cirsium arvense</i>	Discriminate crop vs weeds	Rasmussen <i>et al.</i> (2019)
<i>Vitis vinifera</i>	RGB camera	Bermuda grass	<i>Cynodon dactylon</i>	Discriminate crop vs weeds	De <i>et al.</i> (2017)
<i>Heliathus annuus</i>	RGB camera	Pigweed	<i>Amaranthus blitoides</i>	Discriminate crop vs weeds	López <i>et al.</i> (2016)
<i>Zea mays</i>	Multispectral camera	Common lambsquarters	<i>Chenopodium album</i>	Discriminate crop vs weeds	Louargant <i>et al.</i> (2018)
<i>Zea mays</i>	Multispectral camera	Mat amaranth	<i>Amaranthus blitoides</i>	Discriminate crop vs weeds	Peña <i>et al.</i> (2013)
<i>Beta vulgaris</i>	Multispectral camera	Thistle	<i>Cirsium arvense</i>	Discriminate crop vs weeds	Garcia <i>et al.</i> (2015)
<i>Lactuca sativa</i>	Multispectral camera	Common groundsel	<i>Senecio vulgaris</i>	Discriminate crops vs weeds	Slaughter <i>et al.</i> (2008)
<i>Triticum durum</i>	Hyperspectral camera	Wild oat	<i>Avena fatua</i>	Discriminate crop vs weeds	López <i>et al.</i> (2006)
<i>Sorghum spp.</i>	Hyperspectral camera	Amaranth	<i>Amaranthus macrocarpus</i>	Discriminate crop vs weeds	Che <i>et al.</i> (2013)
<i>Zea mays</i>	Hyperspectral camera	Marestail	<i>Conyza canadensis</i>	Discriminate herbicide-resistant weeds	Scherrer <i>et al.</i> (2019)

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Crop	Type of camera	Weed		Main results	References
		Common name	Scientific name		
<i>Triticum spp.</i>	Hyperspectral camera	Weeds		Discriminate crop vs weeds	Shapira <i>et al.</i> (2010)

5. Effect of UAV spraying

5.1. Efficiency of UAV spray

UAV-assisted aerial pesticide application offers numerous advantages, including improved efficiency, reduced crop and soil damage, water conservation, lower pesticide pollution, higher pesticide application rates and greater flexibility (Meng *et al.*, 2018; Xue and Lan, 2013; Gui *et al.*, 2013) [54, 55, 53]. Pederi *et al.* (2015) [56] reported that using drones, 40% of Japan's rice fields are treated with plant protection chemicals. Compared to traditional methods, drones consume less power, increase productivity, employ ultra-low volume spraying, prevent water waste, eliminate operator risk and reduce crop-dusting costs due to their low flying altitude.

Zhang *et al.* (2020a) [42] reported that small UAVs effectively apply herbicides to wheat fields, resulting in higher yields and better weed control compared to manual methods. Hunter *et al.* (2020) [39] found that UAV sprayers can enhance both efficiency and effectiveness in site-specific weed management and weed escape detection. Combining site-specific and time-specific weed control methods using unmanned aerial vehicles (UAVs) can significantly reduce herbicide use in maize, benefiting both the environment and on-farm variable costs (Nikolić *et al.*, 2021) [57].

Takekawa *et al.* (2023) [58] reported that spray drones effectively control invasive weeds in managed wetlands, offering high precision and lower costs compared to other aerial application methods. Allmendinger *et al.* (2024) [59] stated that spot-spraying with UAVs is a viable method that leads to a significant reduction in herbicide usage. The drone can be used in agriculture to automate fertilizer application, pesticide spraying and field monitoring, reducing human exposure risks and enhancing safety (Souvanhnakhoomman, 2024) [60]. Nobre *et al.* (2024) [61] reported that drone-based herbicide spot spraying can decrease the amount of herbicide used and minimize environmental impacts, while enhancing weed control efficiency and agility in agriculture. Drone technology in agriculture enhances crop health, streamlines farm operations and improves safety, all while minimizing risks to both operators and the environment (Singh *et al.*, 2024) [62]. Anne *et al.* (2024) [63] found that smart spot sprayers reduce herbicide use by 90%, optimize crop potential, preserve natural development and yield potential and save labor and without compromising yield. According to Vimalraj *et al.* (2025b) [52], applying herbicides with drones improves operational efficiency by lowering the need to move heavy equipment into the field and saving time, labor and water. According to Modi *et al.* (2026) [64], the UAV-based spraying system reached a field capacity of 2.6 ha h⁻¹ at an operational cost of US\$4.37 ha⁻¹, saving 81.6% on operating costs and 89.0% on water when compared to the traditional management approach.

5.2. Spray volume reduction

Chen *et al.* (2019) [41] reported that, UAV application at a spray volume of 50 l/ha enhances weed control efficiency in wheat fields, showing no crop injury for pre-emergence applications, while injury rates vary for post-emergence applications. The ideal spray fluid for herbicide application via drones in maize is 80 L/ha to ensure efficient weed control (Supriya *et al.*, 2021) [43]. Shan *et al.* (2021) [65] found that when using UAVs for wheat herbicide application, the most uniform deposition is achieved with a spray volume of 15.0 l/ha and a volume median diameter of 150 µm.

Hussain *et al.* (2022) [66] reported that the application of 22-Homobrassinolide via unmanned aerial vehicles at a spray volume of 15 l/ha during the silking stage considerably improves maize grain yield compared to manual spraying techniques. A UAV spray volume of 50 l/ha enhances deposition, coverage rate and spray deposits per cm² compared to 37.5 l/ha and 500 L/ha applied with knapsack

sprayers in rice fields (Jeevan *et al.*, 2023a) [67]. Ramesh *et al.* (2024) [50] found that applying 60 liters of spray fluid per hectare was the optimal dosage and spray fluid for drone spraying to control weeds, increase grain yield in greengram.

Jeevan *et al.* (2023b) [68] found that the optimal application of 25 l/ha using an unmanned aerial vehicle (UAV) for weed control and higher yield in transplanted rice is more efficient and cost-effective compared to the 500 l/ha used with a knapsack sprayer. A UAV spray volume of 50 l/ha enhances grain yield and improves weed control efficiency in dry direct-seeded rice (Karthickraja *et al.*, 2024) [51]. The use of a UAV sprayer operating at 37.5 L ha⁻¹ to apply 1 kg ha⁻¹ of pendimethalin produced weed control that was statistically comparable to that of a knapsack sprayer (KMS) applied at a spray volume of 500 L ha⁻¹. This shows that UAV-based application can remain effective even with a significantly reduced spray volume (Vimalraj *et al.*, 2025b) [52].

6. Effect of operating parameters on droplet parameters

The effectiveness of spraying and the uniform distribution of the spray are influenced by several application factors, including flight altitude, speed, type of UAV, application rate, nozzle design, droplet size, spray pressure, use of adjuvants and environmental conditions such as wind speed, wind direction, air temperature and humidity. Research consistently shows that herbicide application efficiency is closely linked to droplet size, concentration and the volume of spray applied.

6.1.

Droplet release speed and height

Drone speed and flighting height play a vital role in herbicide application by influencing spray coverage, droplet deposition and drift management. Excessive speed and height may lead to uneven spraying and greater drift, whereas an optimal height and speed ensure consistent coverage and effective weed control (Table 5). Zhou *et al.* (2019) [69] indicate that as the drone's flying speed increases, there is a decrease in both the coverage area and the density of droplets settling on the target surfaces. Droplet uniformity, coverage rate, deposition and drifting ability are improved when the UAV flight height is set to 2 meters (Lou *et al.*, 2018) [70].

6.2. Droplet deposition in UAV spraying

Water-sensitive paper is used to assess droplet deposition, distribution and coverage on the target surface, serving as key indicators for evaluating spray effectiveness (Cerruto *et al.*, 2019) [71]. Fritz *et al.* (2007) [72] reported that applying a lower spray rate of 18.7 l ha⁻¹ on wheat heads resulted in the highest deposition, with a D_{v0.5} of 350 µm. In contrast, higher spray volumes were associated with reduced deposition.

According to Salyani *et al.* (2013) [73], spray deposits showed a significant reduction from the upper to the lower canopy levels and decreased linearly with an increase in the leaf area index. In the later stages of development, the lower parts of the wheat canopy received considerably fewer deposits due to blade overlap and obstruction. When the UAV is operated at a height of two meters and a forward speed of two meters per second, the average spray deposition, which is measured at 2.29 µL/cm², reaches its maximum value (Al-Heidary *et al.*, 2014) [74].

At present, the droplet density in the soybean intermediate layer is 14.75% lower compared to the upper layer and 71.85% lower than in the middle layer. Interestingly, the droplet density and deposition in the middle layer are now higher than those in the upper and lower layers during spraying with the M23 electric four-rotor UAV (Zhang *et*

et al., 2019) [75]. Xiao *et al.* (2020) [76] compared droplet deposition between a UAV and an electric air pressure (EAP) knapsack sprayer in a pepper field. The UAV achieved significantly higher deposition, measuring 1.01 $\mu\text{g}/\text{cm}^2$, which was 98% greater than that of the EAP sprayer.

6.3. Uniformity of droplet distribution

For sugarcane, 15 l ha^{-1} spray volume at 4 m/s achieved higher droplet density on both upper and lower layers and optimal deposition uniformity on the upper layer. Meanwhile, 12 l ha^{-1} at 4 m/s was ideal

for uniform deposition and penetration in the lower layer (Zhang *et al.*, 2020b) [77]. The most uniform deposition was achieved with a spray volume of 15.0 l/ha and a Volume Median Diameter (VMD) of 150 μm (Shan *et al.*, 2021) [65]. Fine and medium droplet sizes lead to high deposition rates but lower distribution uniformity in *Euphorbia heterophylla*. In contrast, larger droplets exhibit reduced distribution uniformity in *Urochloa ruziziensis* (Oliveira *et al.*, 2021) [78]. UAV spraying at 37.5 L ha^{-1} (4.4 m s^{-1}) produced a reduced relative span (0.85), indicating a more uniform droplet distribution than at 25, 50 and knapsack spray of 500 L ha^{-1} (Vimalraj *et al.*, 2025a) [79].

Table 5. Droplets release speed and height of drone spray.

Flight speed (m/s)	Flight height (m)	Efficiency	Reference
2	2	The majority of deposition occurs within the target area, while off-target zones receive little to no deposition.	Ahmad <i>et al.</i> (2020)
3	1.5	Greater deposition and penetrability in both the top and lower layers. Adequate coverage of the target area.	Xinyu <i>et al.</i> (2014); Hunter <i>et al.</i> (2020)
3.7	2	Better coverage and uniform distribution	Qin <i>et al.</i> (2019)
5	1.5-2	Uniform distribution and higher efficiency	Qin <i>et al.</i> (2016)
			Huang <i>et al.</i> (2023)
4	3	Improving droplet density, uniformity and penetration.	Zhang <i>et al.</i> (2020b)
2-5	1-3	Uniform distribution and higher efficiency	Chen <i>et al.</i> (2016)
4.4	1	Better coverage and uniform distribution	Vimalraj <i>et al.</i> (2025a)

6.4. Spray volume on droplet parameters

The lower spray rate of 19 l ha^{-1} resulted in greater tracer deposits, (Fritz *et al.*, 2006) [80], evaluated the aerial application of wheat using spray rates of 19, 47 and 94 l ha^{-1} . Using spray rates of 18.7, 37.4 and 74.8 l ha^{-1} , Nuyttens *et al.* (2007) [81] evaluated aerial spraying and discovered that the largest herbicide deposits occurred at 18.7 l ha^{-1} . As demonstrated on water-sensitive paper, maximal deposition was achieved with a decreased spray volume and productivity was increased by cutting down on loading and ferrying times (Zhu *et al.*, 2010) [82]. In their evaluation of the impact of spray volume on droplet dispersion in the cotton canopy, Chen *et al.* (2018) [83] discovered that increased coverage and droplet density were associated with larger spray volumes. Cui *et al.* (2018) [84] found that variations in spray volume caused variations in droplet size, spray deposits and area coverage.

The highest spray volume (37.4 l/ha) resulted in a greater number of depositing droplets and increased deposition on Palmer amaranth and morning glory weed foliage, outperforming the spray volume of 18.7 l/ha (Martin *et al.*, 2020) [85].

6.5. Droplet size on deposition

Generating smaller droplets can improve spray coverage, which may enhance herbicide efficacy. However, it also increases the likelihood of spray drift (Ramsdale *et al.*, 2001) [86]. Smaller droplets are prone to drifting, whereas larger droplets often fail to adhere effectively to the plant canopy, primarily due to increased runoff (Boukhalfa *et al.*, 2014) [87]. Additionally, the size, quantity and concentration of droplets significantly influence the field efficacy of pesticides (Yuan *et al.*, 2015) [88]. Droplet deposition and penetration improved with increasing droplet size, with a droplet VMD of 185.09 μm achieving the highest penetration rate of 38.13% (Chen *et al.*, 2016) [89]. Droplet size is a key parameter when evaluating sprayer performance. To minimize the risk of drift during spraying, droplet size should exceed 150 μm (Foster *et al.*, 2018) [90].

Xiao *et al.* (2019) [91] observed droplet deposition on the cotton canopy sprayed by UAVs and found that the use of high molecular polymer adjuvants produced larger droplets (D_{v50} of 474.71 and 526.28 μm). These larger droplets demonstrated an *anti*-evaporation effect and, influenced by gravity, resulted in the formation of even larger defoliant droplets. Chen *et al.* (2020) [92] reported that droplet size significantly impacted both the target area (rice canopy) and the

non-target area (drift). Their findings indicated that larger droplets improved deposition on the rice canopy and were less prone to drift. Additionally, the study suggested that lower spray volumes could enhance canopy penetration, while higher volumes might provide better coverage of plant surfaces. Fine and medium droplet sizes lead to high deposition rates but lower distribution uniformity in *Euphorbia heterophylla*. In contrast, larger droplets exhibit reduced distribution uniformity in *Urochloa ruziziensis* (Oliveira *et al.*, 2021) [78]. Droplets smaller than 200 nm have a 0.4% probability of penetrating a single-wall carbon nanotube membrane (Gubarev *et al.*, 2022) [93]. In comparison to lower-volume UAV applications, Vimalraj *et al.* (2025a) [79] found that the knapsack sprayer (500 L ha^{-1}) delivered a higher droplet density. The amount of active ingredient deposited per unit area was similar even though there were fewer droplets under UAV spraying because each droplet had a higher herbicide concentration.

6.6. UAV spray drift

Gil *et al.* (2005) [94] noted that turbulence increases the likelihood of droplet dispersion, recommending a UAV flying height of 1.5 to 2 meters to ensure uniform distribution and minimize drift. However, there is a trade-off between flying height and drift potential (Ahmad *et al.*, 2018) [95]. The downward airflow from ultralow altitude UAVs aids droplet deposition in paddy fields (Xinyu *et al.*, 2014) [96]. Smaller droplets are more prone to drift, while larger droplets face challenges in penetrating plant surfaces (Wang *et al.*, 2020; Mohsan *et al.*, 2022) [92, 97]. Tiny droplets lose kinetic energy quickly or merge, making them susceptible to suspension and drift in crosswinds. Larger droplets tend to settle on surfaces or bounce off. When UAV height increases, the starting position of droplet deposition shifts by 4 meters, indicating drift (Wang *et al.*, 2020) [92].

Higher drone speeds also increase drift, potentially causing uneven pesticide distribution due to reduced kinetic energy (Wang *et al.*, 2018; Mohsan *et al.*, 2022) [97]. Slower drones, with less kinetic energy, make droplets more vulnerable to environmental influences like wind. In contrast to greater spray volumes, Vimalraj *et al.* (2025a) [79] found that UAV spraying at 25 L ha^{-1} with a flying speed of 7.4 m s^{-1} produced fewer droplets (58 droplets). At both 2 m and 5 m drift distances, droplet quantity gradually reduced as spray volume decreased, suggesting a decrease in off-target droplet deposition with lower application volumes.

7. Comparison of UAV and other sprayers

The working efficiency of UAV was 4.11 ha/h, which was roughly 1.7–20.0 times higher than the three other sprayers: self-propelled boom (SPB) sprayer; Knapsack mist-blower (KMB) sprayer; electric air-pressure knapsack (EAP) sprayer (Wang *et al.*, 2019) [98]. Hiremath *et al.* (2024) [99] indicated that UAV-based herbicide application achieved weed control equivalent to that of knapsack and boom sprayers when utilized at recommended dosages. Across all sprayer types, the combination of pre- and post-emergence herbicides successfully decreased weed density, dry biomass and weed index.

Despite comparable biological effectiveness, UAV spraying significantly increased operational efficiency by reducing labor requirements, water consumption by around 95–96% and application time (about 20 min ha⁻¹ compared to 2 h for boom and 8 h for knapsack sprayers). These results show that although the effectiveness of weed control stayed consistent, UAV technology provided definite benefits in terms of efficiency and resource use, confirming its applicability for accurate and environmentally friendly weed control methods.

7. Future scope and applications

The future of drone-based weed management lies in the integration of precision spraying, artificial intelligence (AI), machine learning, and advanced sensing technologies. Further improvements in nozzle de-

sign, droplet size, spray pattern, and real-time flight control could enhance herbicide deposition and reduce off-target losses. AI- and machine-learning-based weed detection using RGB, multispectral, hyperspectral, and thermal sensors could enable accurate discrimination between crops and weeds and facilitate site-specific herbicide application, thereby reducing overall chemical inputs.

Future UAV systems may increasingly incorporate real-time image processing, autonomous navigation, variable-rate spraying, and GPS/RTK-based positioning to improve the precision and consistency of weed control. Integration with Internet of Things (IoT) platforms, farm-management systems, and other precision-agriculture technologies could enable continuous monitoring and automated decision-making. The development of lightweight UAVs with improved battery capacity, payload efficiency, and longer flight endurance could further expand their use in large-scale agricultural operations.

Future research should also evaluate the effectiveness and economic feasibility of drone-based weed management across different crops, weed species, agroecological environments, and climatic conditions. Standardization of spray parameters, assessment of herbicide drift and environmental safety, and optimization of regulatory frameworks will be important for wider adoption. Combining UAV-based weed detection with precision application could ultimately support reduced herbicide use, improved resource-use efficiency, lower labour requirements, and more sustainable crop production (Figure 2.)

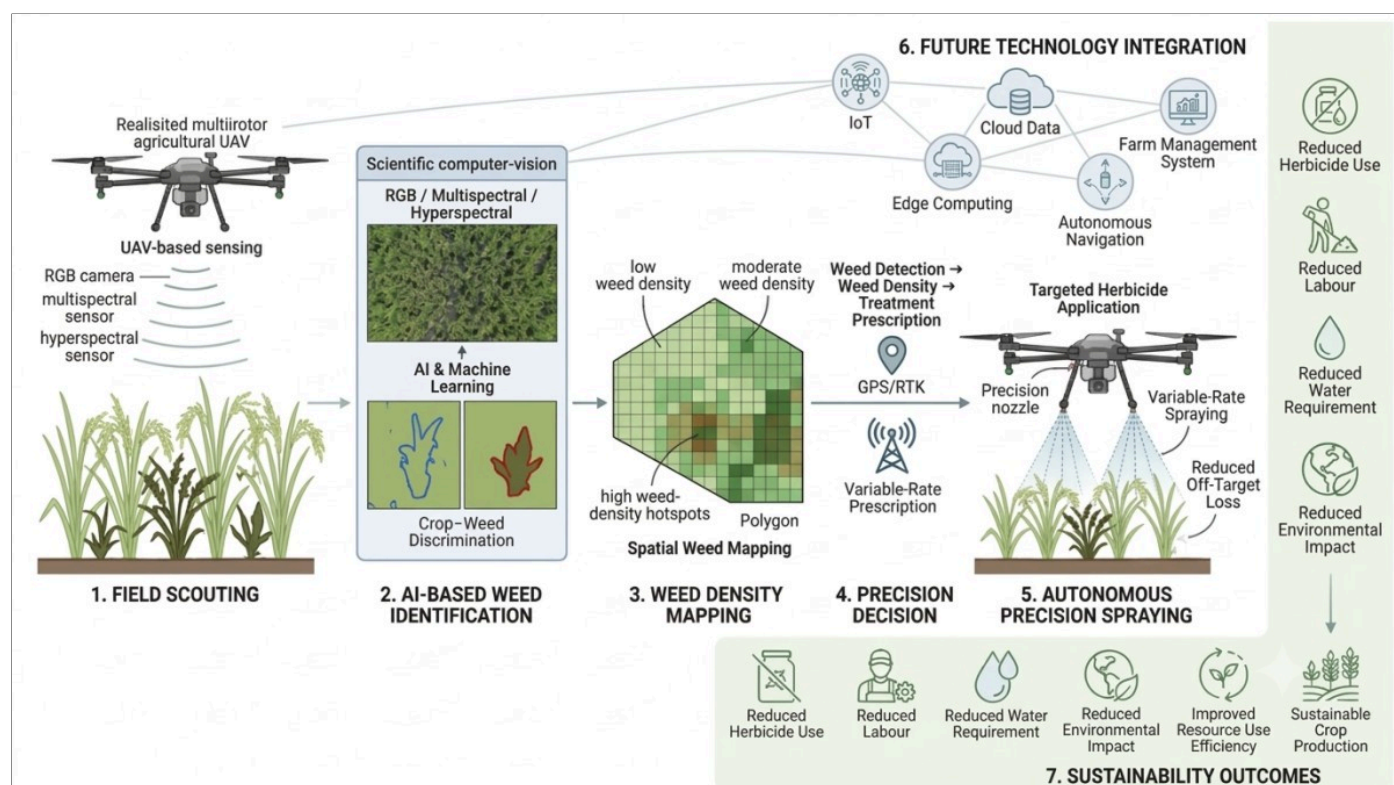


Figure 2. Future Evolution of UAV-Based Weed Detection and Autonomous Precision Spraying

8. Conclusion

This review emphasizes how important drones are to improving farming methods, particularly weed control. Compared to conventional techniques, drones provide a number of benefits, such as more accurate herbicide application, lower labor costs and increased output. Using RGB, multispectral and hyperspectral cameras and other sophisticated imaging techniques, UAVs are very good at identifying weed areas. The accuracy and effectiveness of weed detection and management are further enhanced by the combination of artificial intelligence and image processing. Numerous pesticides may be applied efficiently by UAVs; research indicates that drones can effectively manage weeds in different crops.

Drone spraying works well when the right spray quantities and application methods are used, according to operational factors. Droplet deposition is influenced by spray volume, with smaller volumes providing greater control and coverage. Along with assuring efficient weed management, UAVs also help minimize environmental effects by lowering the use of herbicides. In addition, compared to traditional techniques, drone spraying increases efficiency by using less water and manpower.

Even though there is still more study to be done, the results indicate that drones can greatly improve weed management techniques and offer an economical and ecologically beneficial alternative. Drone technology has the potential to completely transform agriculture methods, increasing crop yields and sustainability, by tackling issues like manpower shortages and excessive chemical use.

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Disclaimer

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Conflict of interest

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Ethical issues

Not applicable. This review article did not involve human participants, animals, or experimental procedures requiring ethical approval.

Artificial intelligence (AI) use statement

Artificial intelligence-based image-generation tools were used to assist in the creation and visual design of selected schematic figures in this manuscript. The authors reviewed, edited, and finalized the generated figures and remain fully responsible for their scientific accuracy, content, and presentation. AI tools were not used to generate or alter the scientific conclusions or interpretations presented in this article.

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Authors

Ravi Vimalraj

PhD Scholar, Department of Agronomy, College of Agriculture, Kerala Agricultural University, Vellayani, Thiruvananthapuram, Kerala India

Pasoubady Saravanane

Professor, Department of Agronomy, Pandit Jawaharlal Nehru College of Agriculture and Research Institute, Karaikal, UT of Puducherry, India

SR Sharu

Assistant Professor, Department of Agronomy, College of Agriculture, Kerala Agricultural University, Vellayani, Thiruvananthapuram, Kerala India

Sreekala Sruthi

PhD Scholar, Department of Soil Science and Agri. chemistry, College of Agriculture, Kerala Agricultural University, Vellayani, Thiruvananthapuram, Kerala India

Ramadoss Poonguzhalan

Professor, Department of Agronomy, Pandit Jawaharlal Nehru College of Agriculture and Research Institute, Karaikal, UT of Puducherry, India

Sujithkumar P

PhD Scholar, Department of Agronomy, College of Agriculture, Kerala Agricultural University, Vellayani, Thiruvananthapuram, Kerala India

R Praveen

PhD Scholar, Center for Plant Breeding and Genetics, Tamil Nadu Agricultural University, Coimbatore India