Review of UAVs for efficient agrochemical spray application

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Abstract: Insect infestation attacks in agricultural ecosystems are becoming more common because of global warming as well as farmland environmental circumstances, necessitating the development of new crop production technology. Pesticide application is one of the most common strategies for protecting the entire growing period of plants or shrubs against pests and pathogens in farms. The rapid, effective, and profitable application of plant control substances via unmanned aerial vehicle (UAV) crop spraying is anticipated to be a key new technique. When compared to ground spraying, UAV spraying saves chemicals, water, time, does not damage crop plants or balls of crop, and does not create soil compaction. When using UAV, pesticide drift and deposition must be managed in order to use pesticides safely, effectively, and efficiently. This paper focuses on agrochemical spraying by unmanned aerial vehicles and the key parameters that influence spray effectiveness, such as the operating parameters of nozzle type, flying speed, flight height, type of nozzle, and type of UAV model, for reducing drift and increasing application efficiency. The multirotor UAV is most suitable for spraying due to its fast operation, safety, not requiring a runway for takeoff and landing, and lower cost as compared to fixed-wing and VTOL. UAVs can also be used for crop disease identification, soil health monitoring, livestock monitoring, field mapping, etc. This paper aims to review the development of various UAV models, optimization of operating parameters, effect of nozzle on UAV spraying, characterization of droplet deposition, drift reduction technology, UAV-based remote sensing for plant protection, and cost comparison of UAV to conventional ground sprayer.

Keywords: deposition, drift, flight height, flying speed, nozzle, unmanned aerial vehicle (UAV)
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1 Introduction

According to the "Agriculture 2050 Project", the global population may exceed ten billion. The requirement to increase food production due to population growth will necessitate a 70% rise[1]. However, one of the key issues with changing environmental and climatic conditions is that insect outbreaks in agricultural crops pose a greater risk to crop productivity[2]. In modern agriculture, pesticide application is a necessary aspect to boost the production and quality of most agricultural goods. Increasing crop output, which is the fundamental aim of agricultural production, necessitates the development and application of pesticides as it prevents up to 45% of the world's food supply from being lost[3].

The most popular sprayers used in traditional agriculture are manual- and battery-powered knapsack sprayers. However, these result in low field capacity, significant pesticide losses, and environmental effects on human and animal health. Several negative impacts were expected when pesticides were sprayed manually on the crop[4].

Spraying methods have improved in recent years to lower liquid application rates while enhancing productivity and quality in the agriculture operation[5]. Traditional sprayers are more time-consuming as well as labor-intensive, which increases operating costs. Plant protection sprayers administer insecticides, herbicides, and fertilizers to crops to boost productivity and quality. Spraying with traditional sprayers early in the crop cycle, when weeds are small, may result in an overdose on the crop, increasing the cost of operation owing to chemical waste. Ground sprayers include crop sprayers (knapsack and boom sprayers), orchard sprayers, and ultra-low volume sprayers[5].

Aircraft spraying, both manned and unmanned, is a simple, economical, effective, and fast method for crop pest management[2]. Furthermore, as compared to ground plant-protection technology, it

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can cover a broad area without destroying the crop or soil physical structure. It can successfully handle difficulties caused by high-stalk crops, labor, and ground-based machinery used on fields, as well as by steep and mountainous topography. It is an effective method for controlling widespread infestations of pests and diseases and cutting down on labor and pesticide use[6]. To reduce pesticide use rates and eliminate pesticide residues, variable rate application-based UAVs are an example of robotic and automated spraying technology that must be used. These unmanned mechanized spraying systems may provide selective pesticide delivery at the desired time and location. Also, they lower labor costs while simultaneously protecting the environment[5].

In the United States, the aircraft manned aerial application was first used in 1921[4]. Environmental characteristics, flight parameters, and spraying parameters are the three categories of elements that determine UAV performance. Spraying width, droplet size, deposition, droplet density, uniformity, and droplet coverage rate are the most critical factors that determine UAV performance. The environmental parameters that have the greatest impact on droplet deposition and drift are wind speed and direction[7,8]. The deposition and distribution of droplets are determined by flight characteristics such as flight velocity, altitude, and downwash[9-11]. Droplet characteristics and spray effectiveness are also directly impacted by several spray factors, such as spraying flow and nozzle specifications[12].

Several authors have recently expressed interest in using UAVs for spraying operations due to their stability, maneuverability, take-off and landing capabilities, and low maintenance costs, which make them suitable for optimum operation at desired flight speed, height, swath width, nozzle type, and UAV model. A nozzle positioned beneath the propellers of a UAV is the most effective and efficient pesticide spraying method[13]. The use of UAV in agriculture will increase up to 80% in the upcoming years[4]. However, droplet drift and pesticide efficacy are still concerns with UAV-based spraying technology[4]. The new requirements for an agrarian country include those that enable agricultural production to meet its goals of increased output, high product quality, high efficiency, environmental protection, and resource conservation, in addition to natural resource preservation, ecological sustainability, and energy-saving agriculture. This paper reviewed and presented the development of UAV-based spraying techniques for protecting plants. Furthermore, drift reduction technology, droplet deposition of different plant canopies on different layers, challenges and limitations, and an economical comparison of UAV spraying with conventional spraying are discussed.

1.1 Development of unmanned aerial vehicles (UAVs)

UAVs, also known as unmanned aerial systems (UAS) and remotely piloted aircraft systems (RPAS), can take off and land without the need for a human pilot and are controlled by a radio channel. UAVs are classified based on weight (Table 1), wing type (Table 2), and number of rotors (Table 3), such as single rotor, quadcopter (four rotors), hexacopter (six rotors), octocopter (eight rotors), and so on[13]. UAVs can also be classified based on their design and maximum takeoff weight and their applications (Table 4). Fixed-wing UAVs are designed differently than multirotor UAVs, and the aerodynamic shape of the two wings allows the UAV to glide effortlessly (Figure 1a). The UAV for plant protection may operate at low altitudes and low loads while suspended in the air for highly accurate GPS location. A single rotor UAV consists of a flight controller, GPS receiver, sensor, spraying unit, and image and telemetry transmitters (Figure 1b). The ground-level controlling system consists of a remotely controlled transmitter and a telemetry receiver. High-precision vertical gyroscopes were used to detect 3D positional velocity and measure the aircraft's heeling and pitching angles.

Table 1 Classification of UAV based on weight

No.	Type	Weight
1	Nano	≤ 250 g
2	Micro	250 g to 2 kg
3	Small	2 kg to 25 kg
4	Medium	25 kg to 125 kg
5	Large	≥ 125 kg

Source: [14].

Table 2 Classification of UAV based on wing type

Particular	UAV type		
	Fixed-wing	Rotary-wing	Hybrid-wing
Hovering	No	Yes	Yes
Small size	No	Yes	Yes
Transport goods	Yes	Lower weight	Yes
Charge duration of battery/ h	>1	1	>1
Maneuver speed	High speed	Low speed	High speed
Flexible communication deployment	No	No	No
Cost-effective	Costly	Affordable	Costly
Endurance	High	Low	Medium
Landing, life	150-200	500	150
Payload/kg	1.5	15-25	10
Control range/km	5	1-2	1
Radio frequency/GHz	2.4	2.4	2.4
Cruise speed/km·h^{-1}	80	150	30

Sources: [15-17].

The tricopter consists of three rotors (Figure 1c), used to balance the UAV during the operation. In this, two rotors rotate in an anticlockwise direction while one rotor rotates in a clockwise direction. A servo method is used to even out the uneven clockwise torque by tilting the rear rotor. The three rotors are moved in different directions to create an effective pitch. Rolling can be accomplished by separating the left and right rotor thrust[18]. Quadcopter UAVs are superior in design and have four rotors (Figure 1d). The model lift is generated by these four rotors. Out of these four rotors, two rotate in a clockwise direction, while the other two rotate in the opposite direction. The hexacopter contains six arms, each of which is connected to a separate high speed BLDC motor (Figure 1e). The air frame plate serves as a support structure for other components, such as batteries and motors, as well as flight-controlled GPS antenna and high-speed capacity tube, first person view camera, electronic speed controllers (ESC), circuit board and sensor. Spray nozzles are attached to the spray motor's outlet. A spray lance contains four nozzles and UAV bottom part contains landing gears below the spraying unit so that the model can take off and land safely during and after the spray. The octocopter has eight rotors and six nozzles, and is used for agricultural spraying in a similar way as the hexacopter (Figure 1f). Nozzle location and speed of rotor are the two main parameters that affect the deposition of spray movement[19]. The hybrid vertical and take-off and landing (VTOL) UAV, which combines the features of rotor-type and fixed-wing-type UAVs, is known as the hybrid VTOL UAV (Figure 1g). VTOL UAVs are like multirotor systems in terms of takeoff efficiency. Three controllers are employed in this case: horizontal, vertical, and transition[20]. Lou et al.[11] developed a hybrid vertical

Table 3 Classification of UAV based on number of rotors

No.	Particular	Single Rotor (One rotor)	Tricopter (Three-rotor)	Quadcopter (Four-rotor)	Hexacopter (Six-rotor)
1	Weight/kg	< 5	< 5	10-12	Up to 25
2	Speed/m·s^{-1}	5	8-10	8-10	10-12
3	Flight altitude/m	500	500	90	200-500
4	Battery type/mA·h	Lithium- based (LIPO) 6000.	Lithium- based (LIPO) 7000.	Lithium- based (LIPO) 16000.	Lithium- based (LIPO) 30 000.
5	Photo capture capacity, Photos/s	1-2	1-2	3	3-5
6	Flight duration, min	15-20	20-25	45	25-30
7	Area covered in single flight/m^2	Up to 4	4 -5	2-4	4 to 6
8	Camera	-	-	Sony Alpha 600, Resolution-24	RGB
9	Max. yaw speed/(°)·s^{-1}	150	150	150	125
10	Max. tilt angle/(°)	45	40	30	20-25
11	Max. vertical speed/m·s^{-1}	6-8	6-8	6	5
12	BLDC motor rating/kV	220	250	330	435
13	Electronic speed controller	Peak current (10 s) 45/ 60 A	Peak current (10 s) 45/ 60 A	Peak current (10 s) 60/ 80 A	Peak current (10 s) 80/ 120 A
14	Receiver	2.4 GHz radio frequency range, 7 km range, sensitivity 105 dBm	2.4 GHz radio frequency range, 8-10 km range, sensitivity 115 dBm	2.4 GHz radio frequency range, 5 km range, sensitivity 121 dBm	2.4 GHz radio frequency range, 3-5 km range, sensitivity 135 dBm
15	Pump flow/L·min^{-1}	2-2.5	2-3	3.5	5.5-6
16	Nozzle type	Flat fan	Flat fan	Flat fan	Centrifugal
17	Nozzle discharge/mL	0.21-0.27	0.28-0.42	0.33-0.52	0.50-0.75

Sources: [21, 22].

take-off and landing UAV for marine application. The developed VTOL can fly at a 57.7% higher cruising speed and with 25% more endurance than other UAVs. To obtain hovering speed without having a negative incidence angle, which lowers aerodynamic efficiency, additional advancements can be made by altering the airfoil profile to better suit the application. To further increase aerodynamic efficiency, the wing may also be fitted with lateral static stability and sweep angles. For some uses, traditional aircraft are still better than VTOL. Flight control and stability are the most serious disadvantages of VTOL. Also, VTOL is used for surveying and mapping, agricultural monitoring, disaster management, traffic handling, wildlife and forest cover, and military uses.

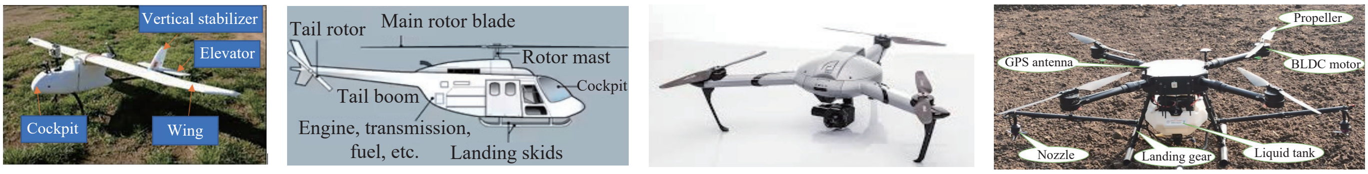
UAVs can be categorized based on their shape, size, wing configuration, and rotor count, ranging from fixed-wing to single and multirotor designs. They can be powered by either batteries or fuel. Battery-powered UAVs typically offer flight durations of 10-25 min, whereas fuel-powered UAVs can operate continuously for one or more hours, depending on the availability of fuel. Among the most prevalent multirotor UAVs in use today are those powered by batteries. These UAVs boast excellent stability in flight, efficiency, ease of maintenance, and simple structural design. Presently, UAV-based spraying has become a popular and widely adopted practice among farmers. Multirotor UAVs offer several advantages, including cost-effectiveness, flexibility, no need for a runway for takeoff and landing, increased stability at higher altitudes, and enhanced safety compared to expensive unmanned helicopters.

1.2 Operating parameters for UAV spraying

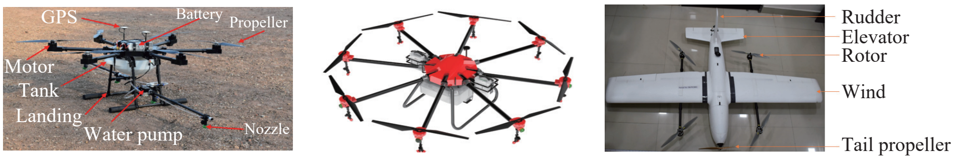
The operating parameters such as flying height, speed, swath width, type of nozzle, and UAV type (i.e., single rotor, multirotor, etc.) affect the performance of UAV spraying, i.e., droplet deposition dispersion, uniformity, drift, field efficiency, and pesticide use efficiency (Table 5). Also, weather parameters such as temperature, wind direction, wind speed, humidity, and other climatic factors have a significant effect on UAV operation[21]. Figure 2 depicts the UAV during spraying operations.

Table 4 Different types of UAV used on precision agricultural farms

UAV	Price range	Application in agriculture	Advantages	Disadvantages	Source
Piloted aircraft	Very high	• Fertilizer and pesticide spraying • Crop scouting • Drought monitoring • Security and surveillance	• High speed • High flight time • Used in rough weather conditions • Payload weight is high • Larger area covered within short period of time	• Cost of operation is high • Flight altitude is high • Small field isolation problem • Skilled pilot needed • Dangerous • Vibration and noise during spraying	[23]
Single rotor helicopter	High	• High payload capacity operation • Pesticide spraying for large area • Crop phenotyping • Soil and field analysis	• Controlled by autopilot software • High flight time • Payload capacity is more • Strong and durable • Higher speed • Petro- or gasoline- powered • Vertical takeoff and ability to land horizontally • Flies forward or backward	during spraying • Some areas cannot be covered by spraying • Heavier • Expensive • Higher flight altitude • Vibration and Noise • Stability problem • Initial and maintenance cost is high	[24]
Multi-copter	Low to medium	• Nutrition and crop stress measurement • Spot pesticide application • Soil, water stress, and field analysis	• Site-specific management. • Altitude low and flight compatibility • Better stability • Low speed flight compatibility • Ability of vertical landing and take-off • Swarm of UAV can be used for better control • Pre-programmed flight plans • Better accessibility	• Low speed • Payload capacity low • Maintenance process difficult • Limited flying time and range • Flight speed lower • Less energy • Low battery life • Problem of stability	[25]
Fixed- wing	Medium to high	• Large area monitoring • Crop phenotyping • Fertilizer and pesticide spraying	• Easier maintenance process • Long endurance and range • High flight altitude • Larger average • Greater energy efficiency • Greater ability to survive	• Limited accessibility • Less wind resistance • Difficulty in launching and landing • Harder to hover and fly • High initial and maintenance cost	[26]



a. Fixed wing type b. Single rotor c. Tri-copter UAV d. Quad-copter UAV



e. Hexa-copter UAV f. Octacopter UAV g. Hybrid vertical take off and landing

Figure 1 Different types of UAV based on number of rotors and structures

Table 5 Summary of optimal operating parameters for different types of UAV from published studies

Type of aircraft	Crop	Volume of tank/L	Flight height tested/m	Optimal flight height/m	Flight speed tested/m·s^{-1}	Optimal flight speed/m·s^{-1}	Spray swath/m	Type of nozzle	CV/%	Ref.
3WQF120-12 (Single rotor UAV)	Wheat	5-20	NA	NA	5	NA	2-20	Nozzle LU120	NA	[35]
N-3 UAV Single rotor UAV	Wheat	25	3.5, 5	3.5	4	4	7	Rotary atomizer	40	[29]
3WQF120-12, 3CD-15, WSZ-610 and HY-B-15L are four types of UAVs used.	Wheat	12, 15, 10, and 15, resp.	2, 2, 2, and 1.5, resp.	NA	5, 6, 4, and 4.5, resp.	NA	4.5, 5, 5 and 6, resp.	LU120-02, Flat-fan 01, Centrifugal atomizer and Four flat-fan-one cone	65.45, 62.58, 70.81 and 43.04, resp.	[36]
HyB-15L UAV	NA	15	0.8, 1.5, 2.0	1.5	3, 4, and 5	5	1	TeeJet110067	31.6	[37]
3WQF120-12, 3CD-15 (fuel oil- powered) and HY-B-15L (Battery- operated) are three commonly used UAVs.		15, 15, and 12, respectively, for three types of UAV	1.5, 2, and 2, respectively, for three types of UAV		5, 4, and 5, respectively, for three types of UAV		5, 5, and 4.5, respectively, for three types of UAV	TR80-015, Turbo Teejet-01, and LU120-02, respectively, for three types of UAV		[38]
3WWDZ-10A quad-rotor	Sugarcane	9, 12 and 15	2,3 and 4	3	4, 5 and 6	4	NA			[33]
JifeI p20 Quad-rotor UAV	Cotton	6, 8, 10	1.5, 2	2	1-8	NA	1.5-3	NA	50.3-178.1	[11]
V6A (Six rotor UAV)	NA	5	2, 3, 4	3	1, 3, 5, 7	7	5-7	CR80005 nozzles (Lechler)	< 25	[39]
MG-1 (Eight- rotor UAV)	NA	10	2, 3, 4	2	1, 3, 5, 7	3	5-7	XR11001 nozzles (TeeJet)	< 25	[39]
TXA-16 (Six-rotor UAV)	Citrus	16	1.5, 2, 2.5	2.5	2, 4, 6	4	NA	NA	NA	[40]
P-20 (Quad-rotor UAV)	Rice	6	1-3	2	2-6	3.7	NA	NA	NA	[41]

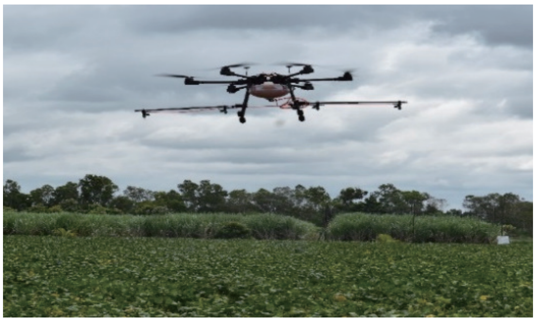


Figure 2 Hexacopter UAV during spraying operation

Pan et al.[27] evaluated the droplet penetration performance of UAV spraying on citrus trees with two distinct head forms (round and open center) and three different operating heights (0.5, 1, and 1.5 m). Water sensitive paper (WSP) was attached at the top, middle, and bottom of the plants inside and outside the tree canopy. The average droplet size and droplet deposition density were 0.30 mm and 39.97 droplets/cm^2, respectively, at the 1 m flight height. However, at 1 m height the droplet coverage (3.19%) was lower than at the height of 1.5 m (4.27%). In a similar study, Chen et al.[7] evaluated the drift of UAVs and found that the droplet deposition percentage decreased from the top to the bottom of the plant. Zheng et al.[28] studied the effect on different growth stages of various corn heights with three flying speeds (2, 4, and 6 m/s) and flight heights (1, 1.5, and 2 m). The results revealed that the droplets had a large effect on the penetration coefficient for spraying corn when the UAV was operated at 3.5-4.5 m/s and 1.0-1.2 m, respectively.

The drift percentage increases as the flying height of the UAV increases[14]. At 2 m flying height, coverage rates were higher as compared to at 1.5 m. Tang et al.[10] found that the coverage rate, droplet density, and droplet size were maximum at the top layer of the plant as compared to the middle and bottom layers, but accurate results between the middle and bottom layers of the plant could not be found due to pruning of trees. The performance of UAV spraying was better at 1.2 m flying height, as compared to 1.8 m and 0.6 m, due to the optimum amount of downwash produced by the rotors, which helps to open the canopy and penetrate the droplets deeper into the plant canopy. In other words, the size of the droplets increases as the canopy height increases. Qin et al.[29] evaluated the effect of droplet deposition and fungal growth at various operating heights and spraying concentrations of a UAV on wheat canopy. The rate of droplet coverage increased from 2.67% to 3.66% as the operation height increased from 3.5 to 5 m.

Wang et al.[30] reported that the downwash wind speed increased as the flying height and flying speed of UAV increased from 1.5 to

2 m, and from 4 to 5 m/s, respectively. Also, the average wind speed increased from 1.63 to 1.73 m/s as the operation height and speed increased from 1.5 to 2 m and from 4 to 5 m/s, respectively. As downwind distance increased, the percentage of drift decreased. The droplets that are smaller in size stay in the air and drift far away from the target zone due to wind speed. Hussain et al.[22] studied the effects of operation height (1.5 m, 2 m, 3 m), discharge rate of the spray nozzle opening (25%, 50%, 75%, 100%), and variable wind speed (1 m/s, 5.5 m/s) on uniform spraying, respectively. UAVs have more uniform spraying than conventional sprayers, particularly in thick canopies. Good uniformity and coverage area were obtained at a flying height of 1.5 m, nozzle opening of 50%, 75%, and 100%, and wind speed of 1.0-5.8 m/s.

The effect of operational parameters such as operational height (2, 3, and 4 m) and speed (1, 3, 5, and 7 m/s) on uniformity of spray pattern and droplet size spectra were evaluated by comparing the results of two UAVs (DJI model MG-1 and HSE model V6A)[31]. At the operational height of 2 m and 3 m, MG-1 produced the most effective swath width. A maximum spray droplet was found at the operational height and speed of 3 m, 5 m/s, and 2 m, 1 m/s for MG-1 and V6A, respectively. Both the aircraft generated maximum swath width at the height of 2 m. In MG-1, ground speed influenced deposited droplet size, percentage area coverage, and spray rate, but application height did not. In the case of the V6A application, the size of the deposited droplets, percentage area coverage, and spray rate were all affected by both height and ground speed. The maximum and minimum droplet spectra were MG-1 (335 m) and V6A (225 m) at the operational height and speed of 3 m, 2 m and 2 m/s, 1 m/s, respectively.

Kharim et al.[32] carried out the performance at three speeds of 2, 4, and 6 m/s and four spraying rates of 0.75, 1.5, 2.26, and 3.00 L/min at a constant height of 2 m above the plant canopy of rice.

The results revealed that the droplet deposition density and uniformity were maximum at the operational speed of 2 m/s as compared to 4 m/s and 6 m/s. In addition, at the discharge rate of 3.00 L/min, the droplet deposition density and uniformity were the highest as compared to other discharge rates during the spraying of organic liquid fertilizer. Zhang et al.[33] designed a 10 L payload capacity quad-rotor electric UAV, and the performance was evaluated at different spray volume (9, 12, and 15 L/hm^2), flight height (2, 3, and 4 m), and flight velocity (4, 5, and 6 m/s) from the ground surface heights of 1.4, 2.3, and 3.2 m in the bottom, mid, and top layers of the sugarcane plant, respectively. The highest and lowest droplet deposition densities were in the top and bottom layers, respectively. The optimized parameter combinations for flight height and flight velocity were 3 m and 4 m/s for the upper and 2 m and 4 m/s for the middle and lower layers, respectively. Furthermore, the application of pesticide by UAV was 20%-30% lower as compared to hand spray. Ahmad et al.[9] studied the effect on percentage coverage, number of droplets deposited, droplet size, and deposition of sprayed material of operational factors such as operating heights of 2 m and 3 m and operating speeds of 2 m/s and 3 m/s. The average deposition was 2.29 μL/cm^2 in the target zone when the UAV operated at a forward speed and height of 2 m/s and 2 m, respectively. The deposition of spray in the target zone was reduced as forward speed and operational height increased. In addition, increasing the aircraft speed reduced the spraying coverage. The deposition rate was generally higher in the outer layer of the plant canopy than in the inner layers.

Nordin et al.[34] evaluated the performance of the UAV at three flying speeds (2, 3, 4 m/s) and flight heights (1.5, 2.0, 2.5 m) above the canopy of the rice crop. For the spraying operation, the largest coverage area was achieved at the flying speed of 2.5 m/s and height of 2 m above the crop canopy. To avoid drift, the UAV cannot fly too fast or too high, as this results in chemical waste. The summary of studies done on optimization of operational parameters is presented in Table 5.

Several factors affect spraying operations, such as flight height, flying speed, nozzle type, arrangement of nozzles, type of chemical, crop canopy, type of crop, and UAV model, as well as meteorological parameters including temperature, wind speed, relative humidity, gust speed, etc. It is concluded from the above-discussed studies that a flight height below 2.5 m helps reduce droplet drift[38]. Flying speed also significantly influences spray drift characteristics for UAV applications. Reducing flying speed can substantially reduce possible spray drift, and a flying speed lower than 5 m/s helps for effective and efficient agrochemical application[8]. A higher spray drift was observed when UAVs operate perpendicular to wind direction. Moreover, the smaller size of droplets produced by the centrifugal nozzle (100-150 μm) leads to more spray drift as compared to those produced by the flat fan nozzle (with a droplet size of 220-300 μm).

1.3 Effect of nozzle on UAV spraying

Type of nozzle and its configuration are the most important factors that influence spray drift[42]. The type of nozzle, flow rate, and its arrangement in the lateral position have a significant effect on deposition of droplets[43]. The two types of wind speed that influence the deposition of droplets are downwash airflow generated by UAV rotors and the wind speed of the weather factor[7]. The coefficient variation of spray deposition is significantly influenced by wind speed, location of the nozzle on the UAV, flight height and flying speed of the UAV, and size of the droplets[44]. Chojnacki and Pachuta[45] reported that at 1.0 m/s speed, the twin flat nozzle deposited more droplets than the single flat nozzle. When operational speed increased, the coverage percentage of the extended flat fan nozzle decreased as compared to the air-induction nozzle[1]. Kailaskumar et al.[46] compared a flat fan and a cone nozzle at a four-operating pressure (2, 4, 6, 8 kg/cm^2), mounted at five heights (2, 3, 4, 5, 6 m) and two wind speeds (0.38 and 0.42 m/s) on a patternator. The result found that with increasing operating pressure from 2 to 8 kg/cm^2, the discharge rate increased from 352-646 mL/min and from 406-827 mL/min for the cone nozzle and the flat fan nozzle, respectively. Also, with the increasing nozzle height, discharge rate decreased and swath width changed.

Yu et al.[47] compared 18 types of nozzle performance in relation to spray angle, droplet size, pressure flow rate curve, and injection flow rate. The findings revealed that the discharge rates were approximately the same compared to the manufacturers' values, but the spray angles of the flat fan and hollow cone nozzles had a variation of 10% and 7%, respectively. The droplet size of the nozzles was significantly less than that which the manufacturer had recommended (as observed at 200 mm beneath the nozzle tip).

Selection of nozzle involves important parameters that affect the drift of UAVs[48]. The drift distance of 90% compared to Dv$_{50}$ (VMD) is listed in Table 6. The droplet size (Dv$_{50}$) of the nozzle has a significant effect on drift distances. The drift distance was less when droplet size was greater[48]. Moreover, with the increase in droplet size, drift distance was less affected by wind, operational speed, and height of the UAV (Table 6)[38,48,49].

Spraying efficacy depends on various nozzle parameters, including nozzle type, arrangement, number, and droplet size produced. Each nozzle type exhibits distinct characteristics and spray drift tendencies. Selecting the appropriate nozzle significantly mitigates spray drift. Coarse droplets tend to have lower spray drift, whereas fine droplets exhibit greater drift. Centrifugal and hollow cone nozzles produce very small droplets (VMD: 100-150 μm), resulting in heightened drift compared to flat fan nozzles (VMD: 220-300 μm). Larger droplets tend to resist upward movement, traveling shorter distances and settling at lower altitudes. Their size reduces drift distance and minimizes susceptibility to crosswind influences[8]. Droplet sizes ranging from 200 to 300 μm typically deposit directly beneath the UAV or within the target zone, while smaller droplets (50-100 μm) drift significantly farther from the intended target zones[51].

Table 6 Comparison of different nozzles of UAV for 90% drift distance

Nozzle	UAV	VMD	Wind speed, m/s	Drift distance of 90%	Source
Centrifugal nozzle (XAG company)	P20-4 rotor	100	1.16±0.06	13.2	[48]
		150	1.30±0.05	12.0	
		200	0.61±0.03	5.7	
Hollow cone nozzle (TR 80 0067)	3WQF120-12 (Helicopter)	114.9±0.07	3.31±0.17	9.99	[49]
	3WM6E-10 (6-rotor)		3.79±0.58	11.53	
	3WM8A-20 (6-rotor)		3.47±0.37	11.70	
Air injector nozzle IDK120-015	3WQF120-12 (Helicopter)	312.6±1.8	3.11±0.40	9.13	
	3WM6E-10 (6-rotor)		3.45±0.46	7.90	
	3WM8A-20 (6-rotor)		3.37±0.56	13.62	
Flat fan nozzle (LU 120-02)	3WQF120-12 (Helicopter)	268.6	2.82±0.76	10.05	[38]
Centrifugal nozzle (XAG company)	UAV	100,150,200	1.5±0.8	11.25	[50]
		100,150,200	2.3±0.3	8.90	

1.4 Characterization of droplet deposition

One of the most important factors in determining the effectiveness of a spray is the droplet coverage percentage[1], deposition on the canopy[12], droplet density (droplet density/cm^2)[52], VMD, and NMD[53]. According to Phang et al.[54], a UAV has more mobility features over conventional equipment like tractors. Compared to the typical backpack sprayer, it is 40 times quicker and reduces the amount of pesticide and water by 30%-40% and 90%, respectively. Xue et al.[55] studied the combined grid atomized droplets by using UAV, with operational parameters of flight height of 2, 3, 4 m and constant flying speed of 2 m/s with a pesticide application rate of 50 L/hm^2. The results showed that the lowest deposition rate was 34.04% for densely planted trees, while the average deposition rate on the adaxial surface of dwarfed and trellised citrus tress was 50.34% and 52.22%, respectively. The smaller canopy size had a higher deposition rate than the heavy canopy. Also, the upper surface layer had a higher deposition rate (23%-73%) as compared to the bottom layer (8.57%-22.61%). The maximum deposition rate was observed at 2 m flight height, thereafter decreasing with the increase of flight height. Fawaz[56] conducted a study on a rice canopy with four different droplet sizes and a constant rate of application by UAV. The results indicated that increased droplet size led to an increased droplet deposition rate on the upper and lower canopy of rice. This suggests that the droplet drift decreased with the increase in droplet size. Zhang et al.[57] studied the effect on deposition by using a crosswind speed of 1 m/s, 2 m/s, and 3 m/s, a flying speed of 3 m/s, and a flight height of 5 m, 6 m, and 7 m. The crosswind speed had more effect on spray drift as compared to flight height through experimental and simulation results. Additionally, spray drift occurred only in the downstream spray field. It is concluded from the above studies that the most important factors affecting deposition are flight height, flying speed, droplet size, nozzle type, and wind speed. Among all these factors, crosswind speed has the greatest effect on droplet deposition rate.

1.5 Drift reduction technology

When drift enters non-target regions, it not only wastes pesticides but may also harm sensitive crops, human and animal health, and the environment. UAVs are widely used to spray chemicals because of their speed and efficacy[58]. The factors that affect spray drift are type of nozzle, arrangement of nozzle, spray adjuvant, downward airflow, rotor, payload, flight height, flight direction, wind velocity, temperature, humidity, and droplet size[59,60]. When UAVs operate at higher speed and height, it increases crosswind influence and lowers the downward wind[7,61]. During the spraying process, droplets of a size less than 150 μm are more sensitive to drift due to wind velocity[62]. UAV chemical spray effectiveness is reduced due to drifting away from the target zone, which is the main factor hindering its use[63]. Currently, many investigators are working on the research of reduction of spray drift with the help of nozzle type, droplet size, and operation path of UAV (Table 7)[38,64].

Table 7 Comparison of characteristics of different UAV nozzles

Spraying system	Nozzle	VMD/μm	Droplet size adjustment method	Source
Hydraulic spraying system	Flat fan	110-120	Adjust nozzle pressure, nozzle type, and solution properties.	[64]
	Hollow cone	90-150		
	Air induction	220-400		
Centrifugal spraying system	Centrifugal	90-300	Change the speed of spray plate.	
Single rotor UAV (Freeman 200 model, Feirui company)	Teejet St 110 015	240-450	Adjust flying height and speed.	[9]
Centrifugal spraying system	Centrifugal	100-600	Adjust rotational speed.	[8]
Centrifugal spraying system	Centrifugal	110-300	Adjust wind speed and spray adjuvant.	[65]
Hydraulic spraying system	Flat fan	115-150	Adjust wind speed and spray adjuvant.	[65]
Hydraulic spraying system	Flat fan	< 150	Flight speed has no effect on droplet size.	[66]

Various factors influence spray drift, including operating speed, flight altitude, nozzle type, nozzle configuration, agrochemical formulation, UAV model, and operator proficiency. While it is acknowledged that spray drift is an inherent challenge, proactive measures such as implementing drift buffer zones throughout and after the spraying process are vital for its mitigation. Data from rigorous testing can significantly contribute to optimizing models and guiding the selection of operational parameters for UAVs. Additionally, ongoing advancements in UAV design and sprayer technology underscore the importance of continually collecting test data to further refine and improve the system.

2 Challenges and limitations of UAV spraying

UAV technology holds immense promise for transforming agricultural practices, particularly in crop management. However, widespread adoption of UAV spraying faces several challenges and limitations that demand attention and resolution. These include limited payload capacity, which restricts the volume of chemicals that can be sprayed in a single flight, necessitating frequent refills and reducing operational efficiency. Battery limitations further constrain flight duration and coverage area, especially in large-scale farms. UAV spraying also faces difficulties in achieving uniform coverage due to environmental factors such as wind drift and uneven terrain, leading to potential under- or over-application in certain areas. Regulatory restrictions and the high initial investment cost pose additional barriers, particularly for smallholder farmers. Another critical concern pertains to the accuracy of UAV spraying. Ensuring precise delivery of pesticides or fertilizers at the designated locations is paramount to prevent under- or over-application, thereby averting potential harm to crops and ecosystems. Lastly, safety considerations loom large in the deployment of UAVs for spraying purposes. The risk of drone accidents leading to crop damage or human injuries underscores the need for robust safety protocols. Additionally, there is a looming threat of disease or pest transmission if proper disinfection measures are not diligently followed. Addressing these challenges requires a multifaceted approach, encompassing technological innovation, regulatory frameworks, and industry collaboration. Moreover, the lack of standardized guidelines for UAV spraying operations and safety concerns related to chemical exposure and accidental crashes emphasize the need for technological advancements and farmer training programs to address these limitations effectively. Table 8 provides an overview of the major challenges faced in UAV spraying and outlines potential pathways forward to overcome these problems.

Table 8 Challenges and ways forward

No.	Challenge	Way forward
1	High cost of UAV and accessories	Provide custom hiring center within every 50 km area; provide subsidy for initial penetration in the farmer's field.
2	Adoptability by farmers	Provide facilities for large-scale demonstration at farmer's field.
3	Significant influence of operational parameters	Optimize operational, spray, and environmental parameters for spraying of target crops in different agro-climatic zones.
4	Operation and handling of UAV: lack of skills	Provide training on operation, handling, and maintenance of UAVs.
5	UAV life (limited hours)	Study multiple UAV uses such as sensor-based soil and crop health monitoring, sowing of seed, irrigation, variable rate technology, etc.
6	Availability of UAV	Develop UAV manufacturing in India.

3 Economical comparison of UAV spraying with conventional systems

Table 9 shows an economic comparison of several sprayers in terms of operation cost and area covered. The cost of operation for UAV, electrostatic sprayer, manual spraying, boom sprayer, blower sprayer, and electric air-assisted sprayer were 1000 to 1200 Rs/hm^2[67], 3230 Rs/hm^2[68], 725 Rs/hm^2[69], 220.79 Rs/hm^2[70], 1050-1200 Rs/hm^2[71], and 1500-2000 Rs/hm^2[71], respectively.

The area covered was 4.11 hm^2/h[71], 0.1 hm^2/h[68], 0.05-0.1 hm^2/h[69], 2.08 hm^2/h[70], 1.57 hm^2/h[71] , and 0.21 hm^2/h[71], respectively. The cost of operation was minimum and the area covered was maximum in the UAV sprayer as compared to the others, as listed in Table 9. The working efficiency of the UAV was nearly 1.7-20 times higher than the other three types of sprayers, i.e., self-propelled boom sprayer, knapsack mist-blower sprayer, and electric air pressure knapsack sprayer[71]. Moreover, the cost of operation of UAV was higher as compared to conventional sprayers due to the high initial cost of UAV, short battery life, skilled operator requirement, and transportation needs. The effective field capacity of UAV was also more as compared to conventional sprayers.

Table 9 Economical comparison of UAV spraying with conventional sprayer spraying

Sr. No.	Type of sprayer	Cost of operation/ ($\text{Rs}\cdot\text{hm}^{-2}$)	Area covered/ ($\text{hm}^2\cdot\text{h}^{-1}$)	References
1	UAV	1000 to 1200	4.11	[67, 71]
2	Electrostatic sprayer	3230	0.1	[68]
3	Manual spraying	725	0.05 to 0.1	[69]
4	Boom sprayer	220.79	2.08	[70]
5	Blower sprayer	1050 to 1200	1.57	[71]
6	Electric air-assisted sprayer	1500 to 2000	0.21	[71]

4 Conclusions

The use of UAVs for spraying operations is deemed safer and more precise. UAVs can save 30% of pesticide and 90% of water. The rotor-type UAV is more suitable for spraying due to its fast operation, no runway needs for takeoff and landing, safety, and lower cost as compared to fixed and VTOL UAV. Moreover, UAV is suitable for spraying of various crops such as soybean, rice, wheat, sugarcane, and orchards where ground machinery can not reach safely. Pesticide application on field crops through UAV is one of the solutions to managing crops effectively and efficiently because UAV sprays above the crop without damaging crop plants, does not damage pods or seeds of the crop or plants, saves water, and the pesticide utilization rate is higher as compared to conventional ground machines. The following conclusions were drawn from the above study:

1) Multirotor UAVs such as the quadcopter and hexacopter are most suitable for spraying as compared to fixed-wing and VTOL UAVs.

2) The factors affecting UAV operation are flight height, flying speed, type of nozzle, number of nozzles, location of nozzles, type of agrochemical, UAV model, and crop canopy. Several meteorological parameters, including wind speed, are the major factors affecting drift.

3) Based on several studies, the optimal flight height and flying speed were 1.5-2.5 m and 3-5 m/s, respectively, for effective and efficient application of agrochemicals on field crops.

4) Nozzles which produce droplets larger in size (above 200 μm) are best for spraying with UAV.

5) Spraying parallel to the wind direction reduces spray drift as compared to perpendicular to wind direction.

6) The operation cost of UAVs for spraying was higher than conventional sprayers due to high initial cost, short battery life, higher daily wages for skilled operations, etc.

The future thrust for UAV spraying may include:

1) Optimizing the operational parameters for each UAV model and for each crop, thereby ensuring effective agrochemical application and reduction in spray drift.

2) Establishing a buffer zone for each optimized UAV model for each crop for effective agrochemical application.

3) Standardizing the dosage of agrochemicals for each optimized operating parameter for each crop, thereby helping to reduce agrochemical waste.

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Authors' contribution

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