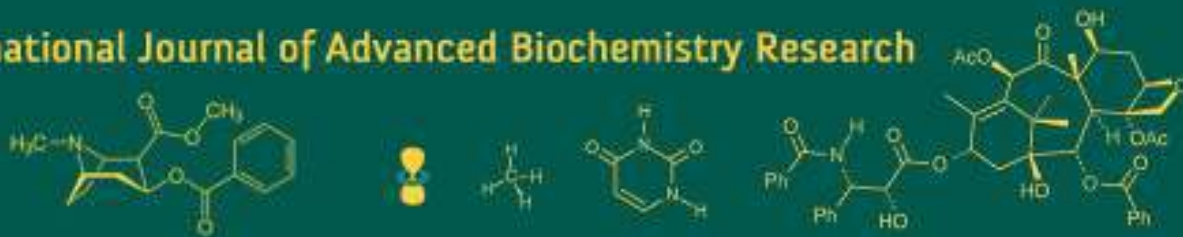


International Journal of Advanced Biochemistry Research



ISSN Print: 2617-4693
 ISSN Online: 2617-4707
 IJABR 2024; 8(2): 742-749
www.biochemjournal.com
 Received: 05-01-2024
 Accepted: 13-02-2024

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Application of drones in pesticide spraying: A review

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DOI: <https://www.doi.org/10.33545/26174693.2024.v8.i2i.4164>

Abstract

The use of unmanned aerial vehicles (UAVs), commonly referred to as drones, for pesticide spraying in agriculture has garnered significant interest in recent years due to their potential to enhance productivity, reduce costs, and mitigate environmental impact. In this review paper, we aim to provide a comprehensive analysis of the current state of research on the application of drones in pesticide spraying, focusing on their advantages, limitations, and future prospects. The paper commences by discussing the salient benefits of using drones for pesticide spraying, including their ability to cover large areas of land quickly and efficiently, reduce labour costs, and minimize environmental damage. We then examine some of the significant challenges and limitations associated with this technology, such as the need for accurate sensor data, optimizing spraying techniques and formulations, and navigating regulatory hurdles. Subsequently, the review paper presents an in-depth analysis of recent studies on drone-based pesticide spraying, encompassing both laboratory and field experiments. We scrutinize the various types of drones, sensors, and spraying techniques employed, as well as their efficacy in diverse crop types and environmental conditions. Moreover, we discuss the potential for integrating advanced technologies such as artificial intelligence and machine learning algorithms to optimize spraying efficiency and enhance environmental sustainability. Our findings highlight the potential of drones as a viable and sustainable solution for pesticide spraying in agriculture while identifying avenues for future research and development. Overall, this review paper presents a critical appraisal of the current state of research on the application of drones in pesticide spraying, illuminating its significance and its implications for agricultural productivity and environmental sustainability.

Keywords: UAV, pesticides, drones, sustainability

Introduction

Pest management is a crucial factor in crop health and productivity, and agricultural chemicals such as fertilizers and pesticides are often required for specific conditions. Pesticides are widely used in most sectors of the agricultural production to prevent or reduce losses by pests and thus can improve yield as well as quality of the produce (Oerke *et al.*, 2004; Cooper *et al.*, 2007). Population growth and climate change contribute mainly to the increasing use of pesticides (Tirado *et al.*, 2010; Hailu *et al.*, 2016; Miraglia *et al.*, 2009) and a higher global pesticide production is estimated in the future. In 2020, the worldwide agricultural sector maintained a stable level of pesticide usage, totaling 2.7 MT of active chemicals. This general trend, however, masks divergent patterns seen across countries (FAO. 2022a, b & c). Notably, India experienced a notable increase in pesticide application, reflecting the growing demands of its expanding agricultural industry. With a strong reliance on pesticides for pest management and crop protection, Indian farmers contributed to the rising consumption of these chemicals within the country. Moreover, the global pesticide trade also witnessed a significant boost, with a remarkable 30% surge in the overall volume of pesticides traded during the same year. This increase in trade activity underscores the escalating global demand for pesticides, as agriculture sectors worldwide seek effective solutions for sustainable and efficient farming practices (WTO, 2020).

Although pesticides play a significant role in improving crop yields and the production of affordable and good quality food, the increasing use of pesticides also brings a number of negative effects to the environment and human health (Miraglia *et al.*, 2009).

Moreover, pesticide contamination moves away from the target plants, resulting in environmental pollution. Pesticides move in several ways, including to the air, through wind currents, to water, through runoff or leaching, and to plants, animals, and humans (Singh *et al.*, 2012; Fang *et al.*, 2017). However, prolonged exposure to these chemicals can cause health complications, and conventional methods of chemical application can be inefficient for small plot production systems. Scientists and researchers are working towards making the chemical application process more efficient to prevent diseases and pests effectively on a large scale (Zhu *et al.*, 2010). Concurrent with the evolving UAV technology are the demands for correct and safe application of pesticides under challenged environmental and biological conditions (Li *et al.*, 2019).

The modernization of agriculture is imperative for increasing production and food supply (Rahman *et al.*, 2021) [6]. Adoption of modern technologies such as unmanned aerial vehicles (UAVs) or drones can significantly enhance risk and damage assessments and revolutionize the way we prepare for and respond to disasters that affect vulnerable farmers and the country's food security (FAO, 2018). UAVs can receive and distribute data accurately, allowing producers to take steps based on individual soil circumstances. Precision farming, crop monitoring, geographical tracking, and field mapping are a few sectors where UAVs play a massive role (European Commission, 2018; Hunt and Daughtry, 2018; Mogili and Deepak, 2018; Colwell, 1956; Cisternas *et al.*, 2020; Wang *et al.*, 2016; Patel *et al.*, 2013; Swain, 2010; Xue, 2020). Unmanned Aerial Vehicles (UAVs) are an inevitable trend of modern aerial equipment based on developments in the direction of intelligence. They can be controlled autonomously via preprogrammed flight paths in many situations where human intervention is considered difficult or dangerous (Zhu *et al.*, 2010).

The use of UAVs for pesticide spraying can be beneficial for reducing human contact with chemicals, improving the performance of spraying operations, and avoiding the presence of chemicals outside designated areas. Drones can be integrated with computing capabilities and on-board sensors to support crop management, disaster reduction, early warning systems, wildlife and forestry conservation, and more (Negash *et al.*, 2019; H. Huang *et al.*, 2021). They can also be leveraged for crop and growth monitoring, yield estimation, water stress assessment, and weed, pest, and disease detection (Inoue, 2020; Panday, Pratihast, *et al.*, 2020).

A drone is an unmanned aircraft or more formally known as unmanned aerial vehicles (UAVs). Drones are increasingly being used for pesticide spraying in agriculture, offering several advantages over traditional ground-based methods (Rolle *et al.*, 2020; FAO, 2018). Essentially, a drone is a flying robot that can be remotely controlled or fly autonomously through software-controlled flight plans in their embedded systems, working in conjunction with on-board sensors and GPS. In recent years, drones have gained significant attention due to their ability to perform a wide range of tasks, including aerial photography, delivery, inspection, and surveying. One such application is in pesticide spraying (Wang *et al.*, 2022), where drones have been found to be more efficient and effective than traditional methods. Drones are able to cover large areas of farmland quickly and accurately, while minimizing the risks

associated with human exposure to pesticides. Furthermore, the use of drones in pesticide spraying has been found to reduce the amount of pesticide needed, resulting in cost savings and decreased environmental impact.

Drones can spray chemicals like fertilizers and pesticides based on the spatial variability of crops and fields, and the amount of chemicals can be adjusted depending on the crop conditions or the severity of the pest attack. Heavy lift UAVs are required for large-scale spraying, providing accurate, site-specific application for crop fields (Gopal Dutta and Purba Goswami, 2020). By detecting pest hotspots and enabling variable rate application of pesticides, drones can potentially reduce the amount of pesticide lost to drift and minimize its impact on neighbouring ecosystems and human health.

Methodology

A number of reviewers discuss the application of drones in agriculture, focusing on various applications such as crop monitoring, livestock monitoring, spraying, and seeding (Colwell, 1956; Cisternas *et al.*, 2020; Wang *et al.*, 2016; Patel *et al.*, 2013; Swain, 2010; Xue, 2020). In this review, we use rigorous bibliometric techniques and quantitative methodology to assess the present status of research at the nexus between drones and pest management. We argue that the current study makes several contributions to the existing literature by examining an emerging drone technology that is highly needed in agriculture as it provides tremendous potential to alter several aspects of this sector. Considering the transformational potential of the technology, we posit that an in-depth network analysis yields novel insights by determining influential works and revealing themes concerning drones' potential for pesticide spraying.

We performed a comprehensive search of journal articles to cover the entire research domain of drone applications in pesticide spraying. The first step was data collection, we selected several search engines such as Science Direct, Wiley, MDPI and PubMed these are the most comprehensive and trustworthy databases with standardized results. We searched the related work publications (research papers) for 22 years (2000-2023) by applying several keywords and the meta-data of publications related to drone applications in pesticide spraying was retrieved. Further, we analysed the selected articles, by removing off-topic articles from the analysis and identified the most important keywords used in the research area. We applied keyword like "Unmanned aerial vehicle", "UAV", "UAS", "Unmanned aircraft system" or "Drone" and "Pesticide" or "Pest Management" and "UAV sprayer" or "UAV Variable precession sprayer" or "Drone pesticide sprayer" or "Drone pesticide deposition".

To start, we analysed the developments in publication output in the current literature on drones in pesticide spraying. The temporal distribution of scholarly research is shown in Fig.1. We see a rapid increase in publications from 2019 onward. We refer to the period between 2018 and 2019 as the build-up stage, which had roughly twenty papers published annually. The post-2019 period has been called the growth stage since research on drone applications in pest spraying witnessed an exponential surge during this period. After 2019, the increasing number of publications confirms the growing interest among researchers, which also reflects that drones have been applied in precision agriculture (Deng *et al.*, 2018; Maes & Steppe, 2019; Messina & Modica, 2020). Specifically, the number of publications rose from 64 in 2019 to 88 in 2021 and peaked at 138 in 2020. A total of 498 articles were published between 2017 and 2022.

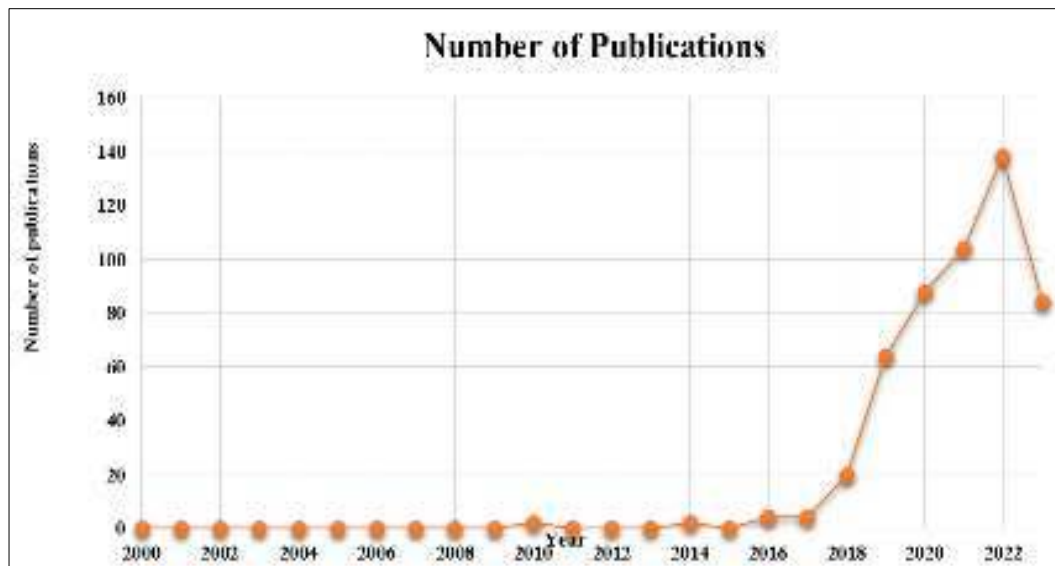


Fig 1: Temporal distribution of publications

Types of drones

Drones are classified in different ways based on purpose (Watts *et al.* 2012). Currently we distinguish two major types of small drones: rotary wing and fixed wing. Each of these has its own advantages and limitations (Hogan *et al.* 2017;). Multi-rotor and single-rotor (helicopter) drones do not require specific structures for take-off and landing. Moreover, they can hover and perform agile maneuvering, making them suitable for pesticide applications (Wang *et al.*, 2021) ^[12], where precise maneuvering or the ability to

maintain a visual of a target for an extended period of time is required (Shuping *et al.*, 2023) ^[8]. Especially multirotor drones tend to be easy to use, and relatively cheap to obtain and achieved good plant protection results in the field due to their high efficiency and high flexibility (Lan *et al.*, 2017; Zhang *et al.*, 2014; Yang *et al.*, 2018; Zhang *et al.*, 2020) ^[15]. Fixed-wing systems are usually faster than rotor-based systems (Refrence), and generally larger in size, allowing for higher payloads (Stark *et al.* 2013b, Dalamagkidis 2015).

Table 1: Type of drones

Type of drone	Description	Figure	References
Fixed Wing	Fixed wing has stationary wings in the shape of an aerofoil which creates the lift needed when the vehicle reaches a certain speed		Li <i>et al.</i> , 2021 ^[5] ; Spootyhi <i>et al.</i> 2010; Herwitz <i>et al.</i> 2004; Maurya (2015); Herwitz <i>et al.</i> , 2002;
Single rotor / Helicopter	It consists of a single set of horizontally rotating blades attached to a central mast to produce lift and thrust. It is capable of taking take-off vertically and landing, flying forward and backward and hovering at a particular place. These features allow the use of helicopters in jammed and remote areas where fixed-wing aircraft are unable to operate.		Wang <i>et al.</i> , 2021 ^[12] ; Mayeed and Darveau, 2016; Huang <i>et al.</i> , 2009; Huang <i>et al.</i> , 2014; 2016; Cai <i>et al.</i> , 2010; Zhu <i>et al.</i> , 2010; Maurya (2015); Shilin, <i>et al.</i> , 2017;
Quadcopter	The quadcopter model consists of a central mast supporting a set of four horizontally rotating blades. This configuration enables vertical take-off and landing, precise maneuverability for forward and backward flight, and the ability to hover in position. In four rotors, the two opposite rotors are turn in clockwise direction and the other two turn in counter clockwise direction. The quad copter movement around the axis includes pitch, roll and yaw. Basically, the configuration of a quad copter is divided into either plus (+) model or		Wang <i>et al.</i> , 2020 ^[13] ; Spoothi, 2019 ^[9] ; Kale <i>et al.</i> , 2015; Morey <i>et al.</i> , 2017; Patel <i>et al.</i> , 2013; Vardhan <i>et al.</i> , 2014; Meivel <i>et al.</i> , 2016; Vanitha <i>et al.</i> , 2016; Sohail <i>et al.</i> , 2016; Gupte <i>et al.</i> , 2012; Achtelik <i>et al.</i> , 2011; Mallick <i>et al.</i> , 2016.

	cross (X) model		
Hexacopter	The hexacopter featuring a central body frame with six horizontally rotating blades. This configuration provides increased stability, payload capacity, and redundancy compared to quadcopters. The hexacopter is capable of vertical take-off and landing, precise maneuverability in various directions, and the ability to hover at specific locations.		Wang <i>et al.</i> , 2021 ^[12] ; Wang <i>et al.</i> , 2022; Biglia <i>et al.</i> , 2022 ^[1] ; Yallappa <i>et al.</i> , 2017; Primicerio <i>et al.</i> , 2017;
Octacopter	The octacopter distinguished by a central body frame supplemented by eight horizontally rotating blades. This distinctive configuration imparts exceptional stability, augmented payload capacity, and heightened redundancy, surpassing the capabilities of both quadcopters and hexacopters. With its vertical take-off and landing proficiency, precise maneuverability across various axes, and the capacity to maintain a stable hover, the octacopter epitomizes versatility and reliability.		Wang <i>et al.</i> , 2021 ^[12] ; Sarghin <i>et al.</i> , 2017; Bendig <i>et al.</i> , 2012; Sarghin <i>et al.</i> , 2017;

The pesticide application using drones offers a new high-tech tool for crop protection (Giles, 2016; Li *et al.*, 2021) ^[5]. Drone sprayers featured with autonomous flight control to deliver pesticides to an array of crops is now a common substitute for traditional aysack application. The drone pesticide spraying has become increasingly popular due to their higher work efficiency, lower operator exposure, and

improved ability to apply chemicals in a timely and highly spatially resolved manner (Wang *et al.*, 2018). The process typically involves several steps as shown in Fig. 3

Working of drone in pesticide spraying application

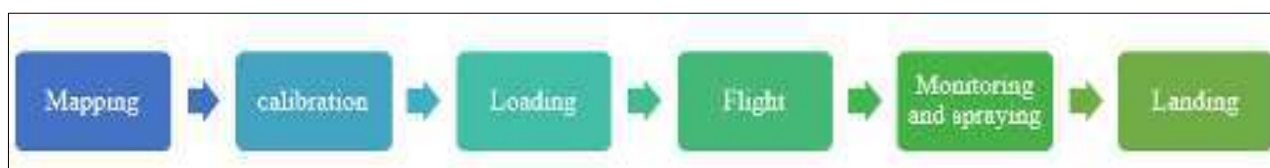


Fig 3: Flow chart of working of drone in pesticide application

The first step is mapping the area to be sprayed. This is done using GPS, and software generates a flight path based on the field's size and shape. The drone is programmed to fly autonomously, covering the entire field in a predetermined pattern. This ensures that the entire field is covered evenly, and no areas are missed (Faical *et al.*, 2014; Wang *et al.*, 2020) ^[13]. Once the field is mapped, the sprayer is calibrated to ensure that the correct amount of chemical is applied per unit area. Calibration involves adjusting the spray volume and flow rate to ensure that the desired coverage and droplet size are achieved. Over or under-application can lead to crop damage or reduced efficacy of the chemicals (Guanter *et al.*, 2019; Ali *et al.*, 2019). The drone is then loaded with the chemical to be sprayed. The amount of chemical loaded onto the drone depends on the size of the field to be sprayed and the desired coverage. The chemicals can be stored in tanks on the drone itself or in a separate ground station, which is connected to the drone through hoses (Zhan *et al.*, 2019). Once the drone is loaded and calibrated, it takes off

and flies over the field, spraying the chemical in a controlled manner. The drone follows the predetermined flight path, which is set up to ensure that the entire field is covered evenly (Shuping *et al.*, 2023) ^[8]. The drone's speed, altitude, and spraying rate are all predetermined and can be adjusted by the operator if necessary. During the flight, the drone's sensors and cameras monitor the spraying process to ensure that the correct amount of chemical is being applied and that the spray is evenly distributed. The drone's sensors can detect changes in wind speed and direction, as well as changes in terrain, and can adjust the spraying accordingly to ensure that the chemicals are applied accurately (Ali *et al.*, 2019). Once the spraying is complete, the drone lands and the operator can inspect the results. The operator can review data collected by the drone's sensors and cameras to evaluate the effectiveness of the spraying and make any necessary adjustments for future flights. The flowchart of pesticide spraying is given in Fig.4.



Fig 4: Flowchart for pesticide spraying

The components of a drone used for pesticide application consist of various essential elements. The fundamental components include Brushless Direct Current Motors (BLDC), Electronic Speed Control (ESC), Flight controller, Camera, Transmitter, and Receiver. These components enable the drone to perform necessary flight maneuvers, capture aerial footage, and establish communication with the ground station (Hafeez *et al.*, 2021). In addition to the basic drone components, the spraying system is a crucial part of pesticide application. It comprises the pump and its controlling system, tank and nozzle. The pump is responsible for delivering the pesticide or fertilizer from the tank to the nozzle, while the controlling system ensures precise control and regulation of the spraying process (Rahman *et al.*, 2021) ^[6]. To design a drone specifically for pesticide application, several factors need to be considered. The first step is to estimate the payload, which determines the weight and capacity requirements of the drone. Based on

this estimation, appropriate components are selected. The selection of batteries depends on the current and voltage requirements of the drone's modules. Finally, the drone frame is designed, taking into account the number of arms and the payload it needs to carry (Hafeez *et al.*, 2021). When it comes to spraying pesticides or fertilizers, a sprayer is connected to the tank of the UAV. The substance to be sprayed is dispensed through a nozzle, which is controlled by the flight controller. The sprayer incorporates a pump-driven spray motor that generates the necessary pressure to effectively distribute the fluid (Rahman *et al.*, 2021) ^[6]. These components and systems work in conjunction to ensure accurate and efficient pesticide application from the drone, allowing for targeted and controlled distribution of pesticides or fertilizers on agricultural fields. The algorithm for spraying is given in Fig.5. The summary of various research work on pesticide application using drone is given in Table. 2.

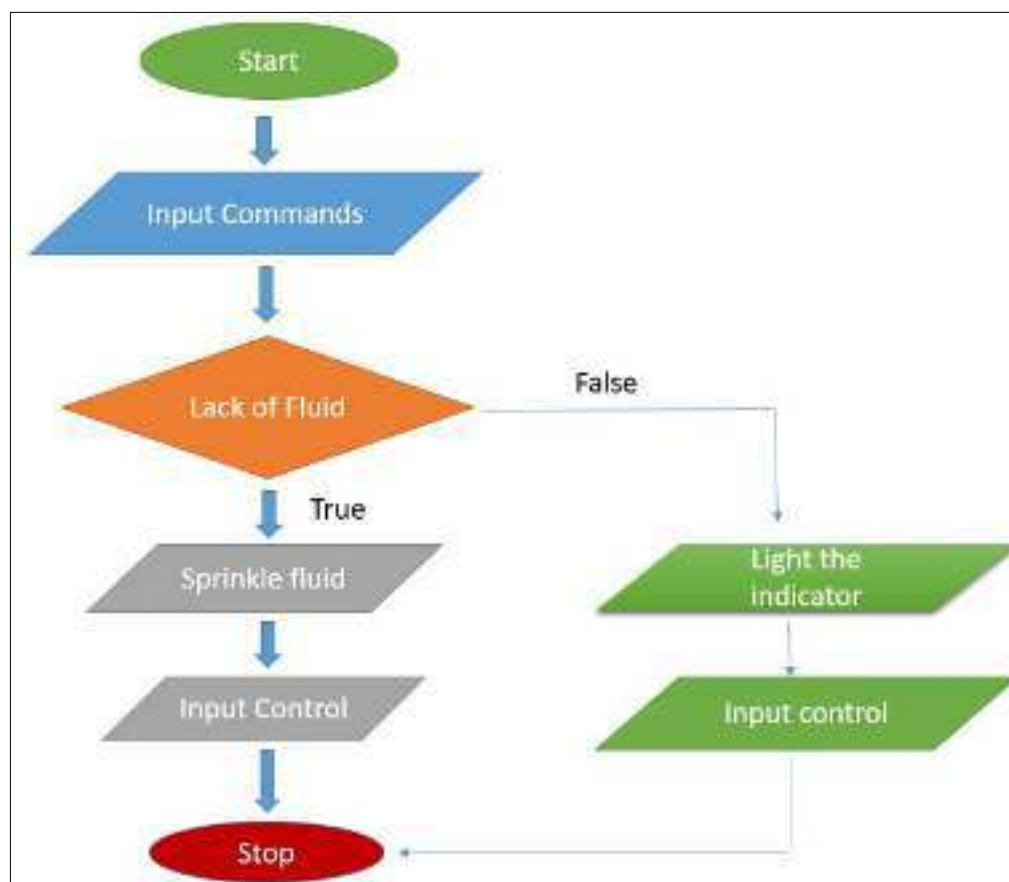


Fig 5: Algorithm for Spraying

Table 2: Summary of research work related to pesticide application using drones

Crops	Crop scientific name	Spray	Spray Volume, l/ha	Crop Height, m	Flying Height Above Crop In, m	Nozzle	Nozzle Angle And Pressure	Droplet Size	Location of Nozzle	Swath Width	Wind Speed	References
Rice	Oryza sativa	Tracer (Allura Red) 1% methylated vegetable oil adjuvant, Dupont Exirel Insect control	15	1.2	1.5 above the canopy	Flat fan nozzles		2, 0.2mm		2 m 2.5m 3 m 5 m 3.5 m		Zhao <i>et al.</i> , 2022 Yallappa <i>et al.</i> , 2017. Chen <i>et al.</i> , 2020.
Wheat	Triticum	430 g L ⁻¹ Tebuconazole SC (Horizon®) 0 g L ⁻¹ Tebuconazole SC (Horizon®) + 33% Lambda-cyhalothrin·imidacloprid SC (JinYong®) (26.4% Imidacloprid; 6.6% Lambda-cyhalothrin, 25 g a.i. ha ⁻¹) Pesticides (20% imidacloprid SL and 40% tebuconazole SC) 20% cyanophoxim, 41% methiazol and 60% oxystrobin Pesticides	9.0, 16.8, and 28 0.379 l/min 12 12 9.6-13.4 & 237.6-472.1		2 1.5 1-4 1.5-2.5	LU120-01, -02, -03 LU120-02 Flat-fan 01 Centrifugal atomizer Four flat-fan and one cone Flat fan nozzles LU120-01 Centrifugal nozzles Flat fan	The installation angle of the spraying nozzles was vertically downward to the spraying direction		Three nozzles symmetrically arranged on both sides of the UAV at intervals of 625 m. The installation angle of the spraying nozzles was vertically downward to the spraying direction	5m 4.5 6 4.5 m	5 m/s 6 m/s 4 m/s 4.5 m/s 12 m/s	Sun <i>et al.</i> , 2022 Wang <i>et al.</i> , 2022 Shilin <i>et al.</i> , 2017 Rahman <i>et al.</i> , 2021 ^[6] Wang <i>et al.</i> , 2019
Nanguo Pear	Pyrus ussuriensis Maxim.		45-90		4.5	Flat fan and hallow cone nozzle, 110 and 80 degree respectively		≤100 μm-600μm		4-7 m		Guo <i>et al.</i> , 2022
Mown Grass	Poaceae				2.5, 3.5 and 5.0	Twinjet nozzles	200 kPa pressure	fine (VMD) of 145-225 μm] and extra-coarse (VMD of 501-650 μm).	standard nozzle configuration is two pairs of nozzles positioned with one behind another in relation to the direction of flight			Richardson <i>et al.</i> , 2020
Flat Grassland	Pampas	Rhodamine-B, 5g/l	12		4 m above ground	Centrifugal nozzle	Spray angle - Horizontal direction	100 or 150 μm		3 m		Wang <i>et al.</i> , 2020 ^[13]
Olive Tree And Citrus Tree	Olea europaea		0.25 to 0.5		0.5, 1 and 2 above the tree canopy	Flat fan, hallow cone and anti-drift nozzle		100-130μm				Martinez <i>et al.</i> , 2020
Cotton	Gossypium	pesticide Topping agent	18 12-22.5		2 1-3	SX11001VS (16)				3 to 5 3 to 5	1.03 m·s ⁻¹	Azfar <i>et al.</i> , 2023 Dou <i>et al.</i> , 2022

		Defoliant (80% thidiazuron, 40% ethephon, 37% thidiazuron+17% diuron) Insecticide (Acetamiprid, Spirodiclofen, Avermectin, Allura red)			2 (from plant canopy) 1-10	UAV 1 (Hollow cone) & UAV 2 (Flat fan) Centrifugal nozzles (4)				UAV 1(6 m) & UAV 2 (4 m) 1.5-3 m		Meng <i>et al.</i> ,2022 Xin <i>et al.</i> ,2018 Lou <i>et al.</i> ,2018
Coffee	Coffea	fungicide	15.		2.5	flat fan	Below 4 rotors in sequence			3 to 5	<1 m/s	Vitória <i>et al.</i> ,2023
Pepper	Piper nigrum	insecticide	15		2	XR11001VS		50-100 µm		3 to 5		Xiao <i>et al.</i> ,2020
Sugarcane	Saccharum	Pesticide	15 l/ha, 8 l/min		2.5		Below 4 rotors in sequence					
Pear Orchard	Pyrus communis	Pesticide	60-90		4.5 2-10 4.5-5.5	Flat-fan, Lu120-015 Extended range flat fan nozzles types				4 to 7 4		Qi <i>et al.</i> ,2023 Li <i>et al.</i> ,2022
Apple Orchard	Malus domestica		20		3.5 m above the trees	Eight extended-range flat-fan nozzles		200 µm	equipped below the corresponding rotors of the UAV	4-7m		Wang <i>et al.</i> , 2022
Redgram Crop	Cajanus cajan	Insecticide			1-20	Flat fan	Below 4 rotors in sequence			3 to 5		Dengeru <i>et al.</i> ,2022
Ground Nut	Arachis hypogaea				1	flat fan					3.6 km h ⁻¹	Yallappa <i>et al.</i> , 2017
Pine Tree			15			CP02, CP03 and CP04 Nozzles with a spray fan angle of 80°, with orifice sizes of 1.0, 1.3 and 1.4 mm,		<100 µm, 101-200 µm, 201-300 µm, 301-400 µm, 401-500 µm, 501-600 µm and >600 µm.600 µm		45	7.2 to 187.2 2-52	(wileyonlinelibrary.com) DOI 10.1002/ps.6959
Maize	Zea mays	Brassinolides (28-Homobrassinolide) Pesticide	15 and 30	2.25	2 from plant canopy 1, 2 and 3	Flat fan nozzles				<3		Hussain <i>et al.</i> ,2022 Yang <i>et al.</i> , 2022
Almond		Altacor® insect control (active ingredient: chlorantraniliprole and anthranilic diamide) at 111 g a.i./hectare		6.1-7.5	1.84-2.43	hollow cone nozzles	1.2 m (40) fixed boom with four flat fan nozzles			6.1		(wileyonlinelibrary.com) DOI 10.1002/ps.6052

Conclusions

In conclusion, the use of drones for pesticide application offers significant advantages for modern agriculture. By providing more precise and targeted spraying, drones help reduce pesticide usage, minimize environmental impact, and improve overall efficiency. This technology allows farmers to address pest issues with greater accuracy, ensuring that only the necessary areas are treated, which also reduces the risk of chemical runoff and exposure. Additionally, drones can lead to cost savings and improve safety by reducing direct contact with pesticides. While there are still challenges, such as regulatory concerns and the need for proper training, the continued development of drone technology holds great potential to enhance the sustainability and productivity of farming practices, making them more efficient and environmentally friendly in the long term.

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