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Drones in Insect Pest Management

K. S. Subramanian[1]*, S. Pazhanivelan[2], G. Srinivasan[3], R. Santhi[4] and N. Sathiah[5]

[1] Directorate of Research, Tamil Nadu Agricultural University, Coimbatore, India, [2] Remote Sensing and GIS, Tamil Nadu Agricultural University, Coimbatore, India, [3] Department of Agronomy, Tamil Nadu Agricultural University, Coimbatore, India, [4] Directorate of Natural Resource Management, Tamil Nadu Agricultural University Coimbatore, India, [5] Agricultural Entomology, Tamil Nadu Agricultural University, Coimbatore, India

One of the major components in precision agriculture is crop health monitoring, which includes irrigation, fertilization, pesticide sprays, and timely harvest of the crop. Further, the progressive change in growth and development is critical in crop monitoring and taking suitable decisions to maintain health status. In order to accomplish the task, drones are highly useful for on site detection of problems so as to undertake corrective measures instantly. Although it is expensive to build algorithms and establish relationships between ground truth and spectral signatures, it is a user-friendly technique once the basics studies are done. As labor availability and technical manpower are extremely limited, particularly in India, drones are gaining popularity in the context of smart farming. Insect pests are known to cause catastrophe and drastic reduction in food grain production across the globe. The losses that have been predicted by FAO is over 37% due to pests and diseases. Recently, crops cultivated in India have been threatened by invasive pests like fall army worm (*Spodoptera frugiperda*) in corn and Rugose spiraling whitefly in coconut (*Aleurodicus rugiperculatous* Martin); these pests caused extensive damage during the years 2018 and 2019. The plant protection measures are to be taken on a community basis so as to ensure effective management of pests. In India, more than 80% of farmlands are in the category of small and marginal (<1 ha), so it is very difficult to manage the invasive pests. If one field is sprayed, the pests simply shift their feeding to the neighboring fields. To address this, drones become essential. Drones are unmanned aerial vehicles exploited in a wide array of disciplines such as defense, monitoring systems, and disaster management but are only beginning to be utilized in agricultural sciences. There are three major types of drones, namely fixed wing, multi-rotor, and hybrid type, and the usage depends on specific applications. The other types depend on degree of automation, size, weight, and power source. The set operational parameters such as flight speed, height, and endurance need to be optimized to use drones appropriately in agriculture and allied sectors. In addition, parameters related to drone-based spraying such as droplet size, spread, density, uniformity, deposition, and penetrability should also be factored in when implementing drone-based mitigation strategies. Despite the fact that drone technology is highly relevant and appropriate for pest management, the adoption of the technology is restricted. Regulatory guidelines have been set across the globe to perform site-specific farm management with higher precision at a very high resolution. Overall, drones can be employed in almost all agricultural field operations and are considered excellent

tools for rapid, reliable, and non-destructive detection of field problems. This review provides panoramic views of drone technology and its application in the management of pests in a digital agriculture era.

Keywords: unmanned aerial vehicle, drone technology, pest management, sensors, precision agriculture

INTRODUCTION

The biotic stresses caused by pests and diseases are well-known to cause devastation that results in reductions in global food grain production. The FAO has predicted that the losses due to pests and diseases are over 37% (Cao, 2015). They are also severely affecting the crop growth, yield, and quality of produce (Gossen et al., 2008; Berger-Neto et al., 2017). Recently, crops cultivated in India are being threatened by invasive pests such as fall army worm (*Spodoptera frugiperda* JE Smith) in corn and Rugose spiraling whitefly in coconut (*Aleurodicus rugiperculatous* Martin), causing extensive damage during 2018 and 2019 (Lal and Bikram, 2019). The fall army worm has become a serious matter of concern to the farmers of India, first hitting the Indian subcontinent in May 2018 in the State of Karnataka. The Indian Agricultural Research Institute–Natural Bureau of Agricultural Insect Resources estimated the intensity of infestation to the tune of 9–62% with an economic yield loss of 34%. The incidence of FAW has spread to the neighboring state of Tamil Nadu where more than 20 districts out of 38 were badly affected in 2019. The effective and rapid interventions and implementation of strategic work plans included drone technology that helped to lessen the incidence of FAW and protect maize crop from infestation while ensuring crop productivity. These pests are to be meticulously monitored and proper technology capsules are to be adopted to save the crops from devastation. Several plant protection strategies are being followed in an integrated way to ensure that crops are protected during the entire crop growing season.

The plant protection measures are to be taken on a community basis so as to ensure effective management of pests and diseases. In India, more than 80% of farmlands are in the category of small and marginal (<1 ha), so it is very difficult to manage invasive pests. If one field is sprayed, the pests simply shift their feeding to the neighboring fields. The invasive pests have enormous potential to multiply in an alarming proportion and are almost impossible to manage with conventional methods of plant protection strategies. It is reported that the annual global use of plant protection chemicals against trans-boundary pests was more than 3 billion kg (Heidary et al., 2014). The utilization of pesticides that are sprayed on the crops exceeds 20–30% and the remaining 70–80% goes as run-off, leaching, evaporation, and drift that cause soil and aquatic pollution as well as deteriorating the quality of the crop produce (Markle et al., 2016; Torrent et al., 2017).

Under these circumstances, effective and timely spraying of plant protection measures are very important. For this, miniaturized unmanned aerial vehicles possess a wide array of benefits that include high efficiency, reduced labor requirement, saving of time and energy, quick response time, and vast area coverage, as well as environmental safety (Meng et al., 2018;

Shamshiri et al., 2018). The agricultural research institution State Department of Agriculture have devoted attention to designing and fabricating drones that suit Indian conditions.

The design of UAVs should consider various parameters such as droplet size, wind speed, flight speed, and flight height (Zhang et al., 2012, 2015; Qin et al., 2014). Further, meteorological parameters like wind speed, temperature, and relative humidity can affect the efficacy of pesticide sprays under field conditions (Wang et al., 2018). Under natural conditions, it is very difficult to control the meteorological parameters and thus scientists have attempted to study the drones under protected conditions.

Lv et al. (2019) have examined the efficacy of drones under a protected environment in order to prevent the external interference and the impact of drone flying speed on droplet size, shape, distribution, and uniformity. The study is very useful in optimizing various parameters to determine the effective spray of pesticides using drones. One of the most important criteria for the successful delivery of pesticides or any other input is droplet size. Lv et al. (2019) have conducted a series of elegant experiments to set the parameters for drones to enable pesticide spray and its impact on crop productivity.

DELIVERY OF DROPLETS

One of the critical factors to be considered for the effectiveness of drone-enabled spray is droplet deposition. The parameters used for measuring the effectiveness of droplet deposition include density, area coverage, and arithmetic mean of droplet size and variation coefficient (Zhu et al., 2011). The **droplet deposition density** is defined as the number of droplets deposited per unit area which is often measured using blotting paper. **Droplet deposition coverage** is yet another parameter usually recorded for assessing effectiveness, and is the area of all droplet particles deposited per unit area (Cunha et al., 2012). The **arithmetic mean droplet size** is the average value of all droplet diameters in one spray sample (Fan, 2011). The co-efficient of variation (CV) measures the uniform spread of droplet deposition in an aerial spraying operation. These four indices can be calculated using the formulae outlined below:

a. **Droplet deposition density** (D)
   No. of droplets deposited (n)/area of droplet collection material (A)
b. **Droplet deposition coverage** (C)
   Area of droplet deposition (S)/Area of the blotting paper (A)
c. **Arithmetic mean of droplet size** $(D_0) = \Sigma\ D_i\ N_i / \Sigma\ N_i$
   D_i is the droplet diameter over time interval
   N_i is the number of droplets over time interval
d. **Co-efficient of Variation (CV)** = SD/X

$$StandardDeviation(SD) = \sqrt{\frac{\sum_{i=1}^{n}(x_i - u)^2}{n-1}}$$

Xi is the droplet deposition particle size per unit area of blotting paper.

μ is the average droplet size per unit area of blotting paper.

SD is the standard deviation.

n is the number of droplets per blotting paper.

When the CV is smaller, the distribution is considered as uniform, the spray covers the target area, and improves the effectiveness of the sprayed pesticides.

INFRARED THERMAL IMAGING

Thermal imaging is a technique to improve the visibility of the reference objects in a dark environment by detecting it using infrared radiation and creating an image based on the information. Thermal imaging, near-infrared illumination, and low-light imaging are the three most commonly used night vision technologies. Infrared thermal imaging can be exploited for assessing the droplet size and distribution in drone-enabled pesticide sprays.

Lv et al. (2019) have used the infrared thermal imaging technique to accurately measure droplet deposition. After the drones spray, there will be changes in leaf temperature and the infrared thermal imaging technique detects infrared-specific band signal of object thermal radiation by optoelectronic technology, which was used as a supplementary means for droplet deposition measurement. In order to avoid external interference, closed environmental chambers can be employed along with the acquisition of thermal images after the spray test. With a view to prevent changes in temperature before and after spraying, sampling can be done in the middle of the fields using infrared thermal imaging (Lv et al., 2019). A classic method developed by Lv et al. (2019) can be employed to determine droplet deposition with the drones. They have optimized the droplet density, deposition coverage, and droplet size decreases with the drone flight speed. Their studies further inferred that the infrared thermal imager is highly useful for assessing the droplet deposition in the farm drone-enabled spraying. The Tamil Nadu Agricultural University, India, has initiated work on infrared imaging of rice fields using a quadcopter attached with a sensor in order to monitor the health status of the plant (**Figure 1**).

RICE

Aerial Spray for Brown Plant Hoppers in Rice

Rice is a staple food crop for more than 2.7 billion people in Asia; the loss of productivity of the crop has been estimated as more than 20% (Brookes and Barfoot, 2003). The brown plant hopper (BPH) *Nilaparvata lugens* causes considerable loss of crop yields globally and is a major pest in India in the late season rice crop planted during September–October (Zhang et al., 2011). The BPH causes damage at the late stage of rice growth. During the late stage of the crop, it is very difficult to undertake manual

FIGURE 1 | Quadcopter imaging rice fields to determine the health status using infrared imaging.

spraying as the leaves of the rice canopy overlap (Sheng et al., 2002). Further, BPH often colonize at the lower part of the plant which is inaccessible through a manual sprayer. In addition, the muddy fields and overlapping plants makes the conventional system of pesticide spray difficult. In order to overcome the bundle of practical difficulties and acute labor shortage, aerial spray of pesticide using UAVs becomes inevitable (Zhou et al., 2013).

Qin et al. (2016) have explored the possibility of using a miniaturized UAV for pesticide spray with high efficiency with no damage to the rice crop in hilly areas of China. They found that the deposition and distribution of droplets increased with the progression of rice growth which synchronizes with operational height and velocity of crop spraying as executed by the UAV. They have standardized flying height (1.5 m) and speed (5 m s^{-1}) that provides effective delivery of pesticides at the lower leaf as well as uniform distribution (CV = 23%). This also registered an insecticidal efficacy of 92–74% from 3 to 10 days after spraying insecticide. Qin et al. (2016) have offered a strong data base for the optimized design, improved performance, and rational application of UAV in spraying insecticide in rice fields. The range of drone flying height (0.8 and 1.5 m) and flight speed (3 and 5 m s^{-1}) have shown distinct performance in the deposition of droplets. Since the BPH stays in the bottom of the leaves, increased spraying height and speed can enable effective delivery of pesticides and control of pests. Overall, the study has clearly shown that UAV spraying exhibited a superior efficiency than the conventional stretcher sprayer, especially when operated at an altitude of 1.5 m and a velocity of 5 m s^{-1}. Moreover, even 5 and 10 days after pesticide application, a high controlling efficiency was still observed, indicating that the spraying method of low volume and high concentration enhanced the duration of pesticide activity.

Recently, the Tamil Nadu Agricultural University, Coimbatore, India, made a maiden attempt to study the efficacy of pesticide spray (fungicide copper oxychloride 53.8% @ 35 g 16 L^{-1} against bacterial and fungal diseases) in rice fields using drones during the cropping season of September 2020. A hexacopter type drone (payload 16 L; fuel capacity 3.5 L) was employed to study the application of pesticides in rice fields

FIGURE 2 | Hexacopter spraying pesticides in rice fields of Tamil Nadu Agricultural University Farm in Tamil Nadu, India during October 2019.

(**Figure 2**). Preliminary studies have shown the optimal flying height (3 m), speed (5 m s^{-1}), swath (4 m), and the area coverage (4 min acre^{-1}). The literature review in combination with the preliminary data from Tamil Nadu Agricultural University, India, clearly demonstrate that drone-enabled pesticide spray is an emerging potential technology to overcome labor shortages and to carry out plant protection measures without loss of time.

COTTON

Cotton is predominantly cultivated in Australia, Pakistan, India, China, Brazil, and the USA, constituting 80% of the global cotton produced (https://www.wto.org/english/news_e/news16_e/cdac_01jul16_e.pdf). The crop is badly affected by a wide array of defoliating, boll feeding, and sucking pests that devastate the crop to the tune of 10–80% (Sharma et al., 2017). In order to protect the crop from insect pests, huge quantities of pesticides have been used in the past several decades. Indeed, cotton crop alone accounts for 16% of pesticides used globally (https://ejfoundation.org/resources/downloads/the_deadly_chemicals_in_cotton.pdf). This led to the introduction of Bt cotton to reduce the pesticide use to some extent (Krishna and Qaim, 2012). As cotton is cultivated in contiguous blocks, there is every chance that the insect pests will shift their habitat if neighboring fields are sprayed. This situation warrants drone spray to enable a quick response and protect the crop from devastation. There are a few classic works that are summarized below.

Droplet Drift, Deposition, and Distribution Pattern

The unmanned aerial vehicles (UAVs) performance is often affected by environmental factors such as wind speed, direction of wind, temperature, and rain. When spray is undertaken with drones, a small portion of the dosage does not reach the target area, which is popularly referred to as droplet drift or spray drift (Kirk, 2004). Such drift in pesticides is closely associated with wind speed and direction. In order to reduce the drift and wastage

of pesticide use, optimal meteorological parameters are set in a standard operational protocol for drone-enabled spray of agro-chemicals. The optimal flight height of 1.5–2.0 m, flight speed 5 m s^{-1}, in combination with wind speed of below 5 km h^{-1} was found to be effective for spraying pesticides with drones.

Lou et al. (2018) have established a relationship between CV of droplet distribution and flight heights of UAV in cotton fields. Their studies have shown that the co-efficient of droplet densities in the upper, middle, and lower layers of the cotton canopy were at 1.5 m (117.1, 178.1, and 85.8%) and 2.0 m (79.4, 50.3, and 146.4%), respectively. The CV of upper and middle droplet densities at the flight height of 1.5 m was significantly higher than 2 m. It is observed that the reduced flight height, which generates a strong downward swirling airflow that causes the plants to sway substantially and affects the droplet density, causes a significant change of the cotton canopy (Qin et al., 2014). In the study, the droplets' distribution in the vertical direction was considered as density of the droplet. The coverage at the drone flying altitude of 1.5 m (2.5, 3.2, and 1.9%) and 2 m (4.9, 5.5, and 5.0%) were on the upper, middle, and lower layers of the cotton. The spread of the pesticide was more effective in 2 m than 1.5 m. As the flight height increases, the downward pressure gets weakened with wind field below the rotor. There may be a small portion of drift which may be associated with the lateral wind effects.

Aerial Spray of Pesticides on Aphids and Spider Mites in Cotton

In cotton, aphids and mites are serious sucking pests of great concern that cause extensive damage to the crop (Lou et al., 2018). In order to address these pests, aerial sprays using drones were attempted. Lou et al. (2018) studied the efficacy of unmanned aerial vehicles (UAVs) on cotton aphids and spider mites. Similar to other literature, they too recorded that droplet uniformity, spread of the pesticide, and deposition were higher at a flight height of 2 m. The control of aphids and spider mites in cotton were registered as 63.7 and 61.3%, respectively, and the efficacy was lower than boom spraying. They also observed that the UAV spray was slightly less effective in comparison to boom spraying due to the spiral arrangement of leaves in cotton. These data serve as the basis to determine the theoretical prediction of the pesticide effectiveness in cotton fields using drones.

CHILLIES

The chilly crop is badly affected by pests and diseases causing yield reduction to the tune of 30–40% (Zhang et al., 2013). One of the most dreadful diseases is the *Phytophthora capsica*, the causal organism for *Phytophthora* blight in pepper, which shows typical symptoms in the roots, stems, leaves, and fruits, and causes deadly diseases throughout the world (Hausbeck and Lamour, 2004). The spread of the disease is very quick and rapid action is required to contain the disease at the early stage of incidence (He et al., 2019). Yet another sucking pest, Aphids *Aphis gossypii* Glover, is equally as devastating and reduces crop yield drastically. Aphids suck the plant sap of pepper plants, causing the leaf to curl and its associated honeydew

secretion attracts sooty mold infestation, leading to reduced photosynthesis and yield reduction (Chen et al., 2018). In order to address these devastating pests and diseases in chillies, recently, Xiao et al. (2020) have used drones to contain them effectively, rapidly, and with good time management.

Droplet Coverage and Density

Droplet coverage is crucial to measure the effectiveness of drone spray. Xiao et al. (2020) have compared the droplet coverage rate of the electric air-pressure knapsack (EAP) sprayer with drone spray. They found that the EAP coverage was twice as high than that of UAV-enabled spraying of pesticides (21.12 vs. 1.83% and 18.59 vs. 1.43%). Such reduction in coverage closely coincided with the spraying volume of the EAP sprayer (300 L/ha), which was 20 times that of the UAV sprayer (15 L/ha). The results clearly demonstrate that the coverage of pesticide is positively correlated with spray volume. With the progression of plant growth, the droplet coverage was lower in the middle and lower part of the plant in comparison to the first spray. As the leaf area index of the chillies increases with the advancement of growth, the droplet coverage decreased progressively. On the other hand, when double spraying was done, both the upper and middle parts of the plant had better droplet coverage in drones spray as well as EAP (Xiao et al., 2020). Scattered growth within the plants affects the spray fluid penetration in the plants (Zhu et al., 2004). In chillies, there are several pests and diseases that occur in the lower part of the plant and that can be effectively controlled only through droplet penetrability (Wang et al., 2019b). This study further suggests that the penetration of droplets from the UAV-enabled spray is still worse than an EAP sprayer. Spray deposits decreased from the top to bottom of the canopies and decreased linearly with the increase in leaf area index.

Droplet density is also equally important to determine the effectiveness of the drone-enabled spraying (Yuan and Wang, 2015). Xiao et al. (2020) established a relationship between the spray volume and droplet intensity. Spray volume has a remarkable impact on the droplet size and the increasing spray volume increased the droplet intensity. The droplet density of upper, middle, and lower part of the chillies plants and the ground were 34.91, 23.03, 15.06, and 9.50 cm^{-2}, respectively, while EAP had twice as high droplet intensity regardless of the position of the plant. The uniformity of the deposition is also very important for controlling pests and diseases. The uniformity is better in upper layers of the plant canopy than that of the middle and lower layers. Further, such measurements decreased with the progression of crop growth due to expansion of the canopy spread area and leaf area index. In addition to the droplet density, distribution, and uniformity, penetrability of the pesticides is very significant in determining the efficacy of UAV-enabled spray (Xiao et al., 2020).

The pest and disease control efficiencies of both EAP sprayer and drone spray were critically evaluated. Xiao et al. (2020) have shown that the control efficiency of drone spray was more effective only when one-third of the concentration of pesticide was used in comparison to the conventional spray. Since EAP sprayer had better deposition and uniformity, the control of processing peppers with *P. capsici* was more effective. Similarly,

TABLE 1 | Drone spray parameters.

Indices	Spray fluid (L ha^{-1})	Flying height (m)	Flight velocity (m/s)
Deposition density			
Upper	15	3	4
Middle	15	2	4
Lower	15	2	4

control of aphids was also better in EAP than in UAV spraying. These data clearly demonstrate that drone spray has the potential to reduce the pesticide use, which is safer and reduces the cost to farmers.

SUGARCANE

Sugarcane is widely cultivated in tropical countries and India is one of the leading producers and consumers of sugar. In the past decade, areas producing sugarcane have declined drastically, particularly in Tamil Nadu, where the area under sugarcane reduced from 5 lakh ha to <1 ha in the past 5 years. One of the prime reasons for such a phenomenon is the requirement of labor and mechanization which is very scarce (Huang et al., 2014) (**Table 1**). During the cropping period, any intercultural spray pesticides, nutrients, or bioinoculants are extremely difficult due to the morphology of the crop and sharp edges of the leaf blades which often injure workers (Gebregiorgis, 2012). Further, some of the pests (internode borer, top borer) diseases (smut, red rot, yellow leaf disease) are highly devastating and farmers find it difficult take up any plant protection measures. Under these circumstances, drones may be of help to deliver sprays in sugarcane fields (Lan et al., 2017).

Optimal UAV Parameters for Sugarcane

Sugarcane is a long duration crop, and the canopy arrangements are different from other crops. Aerial spray by drones may be advantageous as accessibility to the cropped field is very difficult in sugarcane (Zhang et al., 2011). Use of UAV in sugarcane is very limited. Zhang et al. (2020) conducted experiments to optimize various spray parameters (spray volume, flight height, and flight velocity) and three levels by quad-rotor drone.

The results revealed that with a comprehensive consideration of the density, uniformity, and penetration of droplet deposition, the optimal spraying parameters were 15 L/ha of spray volume, 3 m of flight height, and 4 m/s of flight velocity, which could be used as a reference parameter for drones when applied in sugarcane crop.

Drones to Manage Fall Army Worm in Sugarcane

The Fall Army Worm (*Spodoptera furgiperda*) is one of the invasive pests causing extensive damage in maize (Ganiger et al., 2018). The pest, originally from the USA, migrated to Africa in 2016 and entered southern India in 2018 (Padhee and Prasanna, 2019). It is a polyphagous pest that feeds on a wide range of cereals, millets, sugarcane, banana, and other crops (Khan et al., 2018). It causes extensive damage in a very short span of time.

TABLE 2 | Application of UAVs with the set of parameters (Flight height, Flight speed, Nozzle Type) for pesticides spray in various crops and their efficiencies in comparison to conventional sprayers.

No	Crops	Pesticide	UAV type	Flight height (m)	Flight speed (m/s)	Nozzle type	Spray drift (%)	Efficiency/area covered	Comments	References
1	Rice	Pesticide	Four-rotor electric UAV	Maximum 1–6	Maximum 0–8	–	–	–	–	Guo et al., 2019
2	Rice	Pesticide	UAV single rotor drone	1.5–3	3–6	Hollow cone, flat cone	–	–	–	Li et al., 2019
3	Rice	Plant Protection	Six-rotor UAV	3.5	Maximum 10	–	–	–	–	Yang et al., 2017
4	Rice	–	Wind Speed Sensor Network measurement system (WWSSN) UAV	0.98	3.2	–	–	Droplet deposition in effective spray area 76.45%	–	Chen et al., 2017
5	Rice	Tebuconazole	Single rotor UAV	2	5	Flow of single nozzle/L/min −0.80	–	High efficiency of UAVs is not fully achieved	Liquid distribution was un-uniform due to application of Pesticide in UAVs and low precision level	Wang et al., 2017
6	Rice	Pesticide	Single rotor UAV	1.5	5	TEEJET nozzle	–	High control efficiency	UAV was more effective against plant hoppers	Qin et al., 2016
7	Rice	Pesticide	Multi rotor UAV	1.5	5 with 1.9~2.5 wind speed	TEEJET nozzle	23.06	–	Droplet deposition uniformity, 21.62%	Chen et al., 2020
8	Rice	–	UAV	1	1	Flat fan nozzle 4 nos.	5	Spray uniformity 98.5%	Field performance in paddy crop was found to be 1.08 ha/h	Yallappa et al., 2018
9	Rice	Fluorescent dye Rhodamine-B	UAV	5	3	Two fan nozzles	90% drift within 8 m	92.8%	Using the low altitude helicopter, droplets can penetrate and liquid deposition occurs to the lower part of crops	Xue et al., 2014
10	Small bell stage Corn	Plant Protection	UAV	1	4	Two fan nozzles	–	–	–	Zheng et al., 2017
11	Corn	Plant Protection	UAV	2	2	Two fan nozzles	–	–	–	Zheng et al., 2017
12	Wheat	Pesticide	UAV	2	5	3 nozzle	–	effective spraying width was 5 m 16.8 L/ha@0.4 MPa	UAV and EAP performance were compared. Low volume with fine nozzle was better than coarse nozzle with high volume	Wang et al., 2019b

(Continued)

TABLE 2 | Continued

No	Crops	Pesticide	UAV type	Flight height (m)	Flight speed (m/s)	Nozzle type	Spray drift (%)	Efficiency/area covered	Comments	References
13	Wheat	Fungicide	UAV	5	4	Rotary atomizer nozzle Low volume and high concentration	–	Droplet distribution was uniform and the CV was 33.13%. Control efficiency reached 55.1%	Droplet deposition was higher in lower layers of wheat than the upper layer by about 45.6%	Qin et al., 2018
14	Cotton	Defoliation 540 g/L thidiazuron and diuron SC: 180	UAV Spraying volume (L/ha) 15.0–22.5	2	≤5	–	–	–	Bolls opened in Shihezi and Hutubi experimental sites are 40.74 and 36.90%, respectively.	Meng et al., 2019
15	Cotton	Pesticide	ASPEE with maximum Psi up to 1,400 kPa,	–	0.8333	11 m boom sprayer	–	Field efficiency 63.03%	Uniformly distributed in 600 kPa Psi with swath width of 1,235. The average theoretical field capacity was 3.3 ha/h and the average effective field capacity was 2.08 ha/h.	Hunt, 1983; Sanchavat et al., 2018
16	Cotton	Pesticide	UAV	1.5	–	4 nos centrifugal nozzle	5–15	Effectiveness against aphids and spider mites were 63.7% and 61.3%, respectively	The droplet uniformity and deposition were satisfactory	Lou et al., 2018
17	Groundnut	–	UAV	1	1	Flat fan nozzle 4 nos.	5	Spray uniformity 98.5%	Field performance in groundnut was found to be 1.15 ha/h	Yallappa et al., 2018
18	Soybean	Pesticide	Medium-quality sprays	–	–	Flat fan nozzle	–	Spray fluid 145 L/ha	Fine-quality sprays should be avoided for treating lower portions of a canopy unless some other form of energy, such as air-assistance spray, will help move deeper into a canopy.	Derksen et al., 2008
19	Sugarcane	Pesticide	Quad-rotor drone	3	4	Positioning system and centrifugal atomizing nozzle	–	–	Drone application efficiency can be 60 times higher and spray fluid application rate is 20–30% lesser than conventional spray	Zhang et al., 2019

(Continued)

TABLE 2 | Continued

No	Crops	Pesticide	UAV type	Flight height (m)	Flight speed (m/s)	Nozzle type	Spray drift (%)	Efficiency/area covered	Comments	References
20	Sugarcane	Pesticide	UAV	3	3	–	–	Control efficacy against Fall Armyworm (*Spodoptera frugiperda*) applied with chlorfenapyr–chlorantraniliprole–lufenuron were 94.86 and 94.94%, respectively	Highly efficient and flexible and has been successfully applied in sugarcane	Lan et al., 2017; Song et al., 2020
21	Sugarcane	Stem Borer (Lepidoptera)	Multi-rotor UAV	3	4	Centrifugal atomizing nozzle	–	spray efficiency was 21.3 min/ha pesticide need is lesser than 90.65% compared to conventional spary	UAV spray was found to be 40.0%, which was higher compared to knapsack electric sprayer KES (30.0%)	Zhang et al., 2019
22	Pineapple	Pesticide	UAV Oil driving single rotor Droplet size/μm−268.6 Flow rate single)/mL/min−800	< 2.5	1.14–2.82	–	11 to < 26.44%.	90% spray drift distance can control in 10 m.	Effectively control the spray drift.	Wang et al., 2018
23	Pineapple	Pesticide		Upto 3.5	2.02–3.59	–	55.76%	90% spray drift distance can be up to 33.54–46.50 m.	Total spray drift percentage also increased.	
24	Tea	Pesticide	UAV simulation platform	2	0.3	Four VP110015 flat-fan nozzles		Coverage 26.8%	Increase of the UAV flight speed resulted decrease in droplet distribution uniformity.	Lv et al., 2019
25	Pepper	*Phytophthora capsici*	UAV	2	–	–	–	Electric Air-Pressure Knapsack EAP 21.12% vs. UAV 1.83% Less	UAV sprayer (15 L/ha) Efficiency was higher since 20 times lesser than that of the in EAP sprayer (300 L/ha)	Xiao et al., 2020
26	Pepper	*Aphis gossypii*	UAV	2	–	–	–	Less	UAV sprayer (15 L/ha) Efficiency was higher since 20 times lesser than that of the in EAP sprayer (300 L/ha)	Xiao et al., 2020
27	Grassland	5% urea aqueous solution	Helicopter	2	4	hydraulic CP flat nozzles	–	62.83%	–	Yao et al., 2020

(Continued)

TABLE 2 | Continued

No	Crops	Pesticide	UAV type	Flight height (m)	Flight speed (m/s)	Nozzle type	Spray drift (%)	Efficiency/area covered	Comments	References
28	–	Pesticide	Single rotor UAV	3	5	Two flat standard nozzles	–	–		Wang et al., 2016
29	–	Pesticide	UAV	–	–	Rotary Atomization sprayer	–	–	Rotary Atomization sprayer is more suitable for low-volume and variable-rate spraying, both are not possible with hydraulic nozzles.	Gong et al., 2019
30	–	–	Octocopter	3	1	Extended-range flat-spray nozzles	Less	30–60%	–	Joseph et al., 2019
31	–	–	Octocopter	3	3	Extended-range flat-spray nozzles	more	13–22%	–	
32	–	Pesticide	Six symmetrically positioned rotors	0.6	1.3	Flat fan nozzle with 0.2 MPa Psi	–	–	–	Bogusława and Jerzy, 2017
33	–	Pesticide	Unmanned helicopter	–	2.2	Rotary nozzles	–	–	Precision nutrient management	Huang et al., 2014
34	–	Plant protection	UAV	5	–	Two centrifugal rotary atomizers	–	spraying swath 5 m, their coefficient 41%	The Standard for ultra-low volume spraying variation coefficient, which is less than 60%	Xue et al., 2016
35	–	–	Single-rotor Unmanned Agricultural Helicopter	–	0.5	Centrifugal atomization nozzles	–	Downwash covers approximately a circle area of 3.0 m radius	–	Zhang et al., 2017
36	–	Pesticide	UAV	–	2	–	–	–	–	Zhang et al., 2019
37	–	Pesticide	UAV	6	2.2	Four spray nozzles, Micronair Ultra-Low-Volume (ULV) nozzles	–	30 m (100 ft) effective spray swath and able to spray 0.4 ha/min (1 acre/min)	Drone spraying is excellent for vector control (<50-μm droplet size)	Huang et al., 2009
38	–	–	Fixed-wing applications	0.35 m	Wind speed 0.084 (120–305 km/h)	Flat fan nozzle	–	–	The increment of the tube pressure will strongly decrease the droplet diameter at a lower wind speed and *vice versa*	Tang et al., 2016

In order to control the pest, quick action has to be taken to ensure that pest population is kept at bay. Drones are highly useful technology to undertake spray quickly to contain the pest population. Song et al. (2020) have shown that the application of chlorfenapyr–chlorantraniliprole–lufenuron through drones had control efficacy of 94.94% and declined the pest population by about 94.86%.

CONCLUSION

An extensive review was undertaken to determine the feasibility and utilization of Unmanned Aerial Vehicles (UAVs) or drones for pesticide sprays in various crops; the output from the literature is summarized in **Table 2**. The table clearly suggests that there are several studies that have been undertaken and demonstrated on the use of drones successfully in pesticide spray in agricultural and horticultural crops. The following are the observations:

1. Drone application in agriculture is primarily focused on pesticide applications. Extensive research has been done on optimization of spray volume, droplet size, spread of droplets, and penetrability as well as efficacy of pesticides in insect pest control (Lou et al., 2018). Many of the optimization parameters indicated were done mainly for pesticides use in agriculture.

2. A majority of the research on UAV for pesticide spray in crops was carried out in rice (Qin et al., 2016), wheat (Wang et al., 2019a), corn (Zheng et al., 2017), cotton (Lou et al., 2018), pepper (Xiao et al., 2020), and sugarcane (Zhang et al., 2019) as these crops consume more pesticides than any others. Further, these crops are cultivated in larger areas in contiguous blocks in developed and developing countries where drone application is feasible.

3. In order to improve insecticidal use efficiencies in crops, drone operational parameters such as flight speed, flight height, nozzle type, payload, and drone type are be optimized for the given situation. Overall, flight height of 2–3 m, flight speed of 3–5 ms^{-1}, two fan nozzle, four rotor UAV, and 15 L payload are found to be optimal to undertake pesticide sprays using drones in agricultural crops (Zhang et al., 2011).

4. Drone efficiencies are to be examined for certain application parameters such as droplet size distribution, droplet coverage, uniformity of droplets, droplet penetrability, droplet drift, and insecticidal efficiency prior to commercial use of drones in agriculture (Lv et al., 2019).

5. There are potential benefits to drone usage in agriculture that include large area coverage, less quantities of pesticides, labor saving, quick response time, and timely operation well before pest occurrence exceeds economic threshold levels (Huang et al., 2018).

6. Despite the fact that there are ample advantages attached to drone technology, every country has its own regulatory guidelines for the use of drones in agriculture (Ayamga et al., 2021). Prior approvals are required from local authorities to use drones in agriculture.

Overall, the literature review clearly demonstrated that drone technology is very effective in delivering pesticides for a wide array of crops. The effectiveness has been validated with conventional hand-operated sprayers. The data suggest that, although the operational parameters and delivery parameters have been optimized for a specific crop or a particular pests/disease, some fine tuning is required to improve the efficacy for a given situation. This literature review has given an overview of drone technology employed for pesticide sprays. Since there are no ultralow volume pesticide formulations available in the market, the conventional pesticides were used in drone technology with the same optimized concentration. Thus, there is an urgent need to develop innovative new nano formulations to improve the efficacy of drone technology while minimizing the cost and improving environmental safety.

AUTHOR CONTRIBUTIONS

KS: synthesis and orchestration of the review. SP: responsible for drones enabled application. GS: collection of literature and plagiarism check. RS: drone application in agriculture. NS: entomologist involved in drone enabled spray. All authors contributed to the article and approved the submitted version.

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