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REVIEW PAPER

USE OF REMOTELY PILOTED AIRCRAFTS FOR THE APPLICATION OF PLANT PROTECTION PRODUCTS

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ABSTRACT

The use of remotely piloted aircrafts (RPAs) to apply plant protection products has grown a lot in agriculture worldwide. However, little research data are available regarding the efficiency and safety of this method, especially in Brazil. Thus, this review aimed to present the current scenario of scientific research involving RPAs in the application of pesticides. Several factors interfere with the quality of this type of application. Among them are height and flight speed, droplet generator elements, application rate, and spray solution properties. In general, applications have been performed between 1.0 m and 3.0 m of height and 1.0 m s⁻¹ and 7.0 m s⁻¹ of speed. As for the droplet generator element, there is still no clarity as to the ideal system. Efficacy studies involving RPA applications demonstrate the potential of this method in replacing applications performed mainly by using knapsack equipment in an effort to reduce occupational risks. However, it is essential to observe the advantages of RPA use, while also taking into account the risk of drift. The aerodynamic effect in the droplets, qualified personnel, appropriate formulations, regulations, and details in labels are challenges that still need to be addressed for this new technology to be successful.

INTRODUCTION

The increasing global demand for food, either because of population growth or poor distribution, requires successive increases in production. Given this, farmers need to use technologies that result in increased productivity, with techniques involved in the application of plant protection products being among these technologies. The application technology of plant protection products has an extremely relevant purpose because it should ensure the deposition of the plant protection product on the desired target, whether it is the soil, leaf, or an insect, efficiently, and also prevent losses to the environment (Berger-Neto et al., 2017; Cação et al., 2019).

Besides accounting for a substantial amount of the production cost, phytosanitary treatments are also among the main components of the production process of any crop,

as the application of fungicides, insecticides, and herbicides help preserve the health of the crop until the end of the production cycle, thereby assisting each cultivar or variety to reach its production quantity and quality potential, as determined by its genetics (Cunha et al., 2018). However, the use of these products, especially when they are applied indiscriminately, can damage the crop, the environment, and living beings, either by direct or indirect contact, owing to the persistence of its molecules in the biotic and abiotic environments of ecosystems (animals, soil, air, water, plants, etc.) (Carvalho, 2017; Jallow et al., 2017).

However, if performed within well-defined technical criteria, the application of phytosanitary products is safe. The use of so-called good practices, such as the use of personal protective equipment and equipment that is in good condition and correctly managed and regulated, associated with the application of products with less toxicological

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potential, can considerably reduce the problems arising from the application of these products (Susaeta et al., 2018).

Given this scenario, the use of a new application technology has grown worldwide; the application of plant protection products with the use of unmanned aircrafts (Martinez-Guanter et al., 2020). Much has been said about this technique, but little research data are available, especially from studies conducted in Brazil, which has generated incongruous information without scientific support, which hinders a more technical analysis of agronomic, environmental, and economic feasibility.

Thus, the present review aimed to present the current scientific research scenario and critical analysis involving unmanned aircrafts in applying plant protection products.

REVIEW

The preparation of this literature review was preceded by an extensive search for scientific articles in different databases. All of these articles were studies related to the theme proposed in this study. In this sense, the following databases were initially consulted: Web of Science (www.webofknowledge.com), Scopus (www.scopus.com), Science Direct (www.sciencedirect.com), Springer Link (www.link.springer.com), and Scielo (www.scielo.org). The Google search engine (www.google.com) was used to complement some subjects less covered in scientific articles.

Different search strings were elaborated, using the combination of various keywords, such as remotely piloted aircraft, unmanned aerial vehicle, drone, unmanned aircraft

system, sprayer, agricultural spraying, aerial application, crop dusting, and agricultural aircraft. Due to its great importance in the scientific environment, the English language was used as the standard in most databases, except in Scielo, where the Portuguese language was used. This way, we sought to increase the search spectrum of the studies and, consequently, reduce the risk of bias.

Employment of remotely piloted aircrafts in spraying

A remotely piloted aircraft is an unmanned aircraft piloted from a remote piloting station with a purpose other than recreation (Anac, 2017). These aircrafts are commonly referred to as drones, but as far as the Brazilian National Civil Aviation Agency (ANAC) is concerned, they are known as remotely piloted aircrafts (RPAs). The acronym ARP (the Portuguese initials for remotely-piloted aircraft) is not used by ANAC because it refers to the aerodrome reference point. Another term used is unmanned aerial vehicle (UAV). UAV has been widely used in the areas of engineering and computing because it also refers to fully autonomous vehicles.

The installation of a spray system on RPAs allows the application of plant protection products and fertilizers. This technique, like the rest, has advantages and disadvantages that need to be understood (Table 1). Xiongkui et al. (2017) cite as an advantage the “downwash” effect generated by the rotors, which can improve the deposition on target. Hunter III et al. (2019 b) also highlight the ability to apply products in difficult to access areas and with irregular topography and complex geometries.

TABLE 1. Advantages and disadvantages of the use of RPAs for the application of crop protection products.

Advantages (Xiongkui et al., 2017)	Disadvantages (Berner & Chojnacki, 2017)
RPA does not require a runway, thus it is able to operate close to the areas the products need to be applied	The high cost of the equipment compared to other possibilities, such as knapsack sprayers
Short turning radius and good maneuverability	Reduced pesticide tank volume
Possibility of vertical flight and good performance in low altitude flights	Short flight time
Possibility of working in small and/or sloping areas	Risk of drift
The high degree of automation	Need to follow civil aviation regulations
Reduced workload for operators	
Possibility of application in specific areas	

Another point is that there is still some uncertainty about the quality of the applications (Richardson et al., 2020 a). Hunter III et al. (2019 b) comment that although applications with RPAs are already available in the USA, there is a literature gap in terms of optimizing the use of this technology. Lan & Chen (2018) also discuss the need for more studies regarding crop protection with RPAs, mainly due to the reduced application rates, among other challenges. It is noteworthy that the manufacturers of RPAs are continually modernizing and improving their products, thereby minimizing some of these limitations.

The “downwash effect” refers to the droplets’ tendency, after being launched by the generating element, to be pushed downward by the aerodynamic effect promoted by the rotor blades, which direct the air downwards. This airflow in rotary-wing sprayers is distinct

from other equipment and directly affects the deposition (Ramasamy et al., 2012). Qing et al. (2017) studied this effect in RPAs and concluded that it increases droplet fall speed (from 5 m s⁻¹ to 12 m s⁻¹), uniformizes droplet deposition, and increases the deposition swath width. However, all of these effects depend on the position of the spray nozzle relative to the airflow. According to Zheng et al. (2018), the study of such behavior is quite complex, given the variables involved, and dependent on the flight height.

An intrinsic characteristic of the application with RPAs is the use of lower application rates to make the operation feasible (Martinez-Guanter et al., 2020). This increases autonomy and operational capacity. In general, the working ability of an RPA per unit of time is limited according to the load capacity of each piece of equipment, which requires frequent refueling. However, there is a

tendency to increase the allowed load with the evolution of technology and the emergence of new equipment. Until this occurs, the solution almost always applied has been to use smaller volumes of water per area. The field, the availability, and capacity of batteries also influence the area of application along the working day, among other factors. On the other hand, the time spent refueling and replacing the battery have been significantly reduced, thereby conferring high field efficiency. As an example, an RPA DJI AGRAS MG-1, working with four nozzles, a 5.0-m swath, an application rate of 10 L ha⁻¹, and a speed of 20 km h⁻¹, is capable of spraying approximately 4 ha h⁻¹, which is a much higher volume than what a knapsack sprayer can apply (Mendes, 2020).

However, this reduction in the application rate requires an improvement in the application technology used in the field. The difficulty is associated, mainly, with obtaining good coverage of the target. In this context, it is essential to understand the relationship between target coverage and the factors that interfere with it. Courshee (1967) presented a model in which the target coverage is positively affected by the application rate, droplet spread, and recovery rate, and negatively affected by the leaf area to be treated and the size of the droplets sprayed. Therefore, it is noted that there must be a clear understanding of these relationships to ensure adequate target coverage with environmental safety. Merely changing a single parameter, such as the application rate, can reduce target coverage and, consequently, the efficacy of the treatment applied.

Therefore, it can be suggested that the application of pesticides using RPAs, despite its great growth in recent years, poses some challenges, which need to be understood and properly managed to ensure the success of applications, either from the agronomic or environmental points of view. As this is something relatively new, there is still a lack of information.

Description of the main types of RPAs

There are several types of RPAs on the market. However, there is no single worldwide classification for all equipment; on the contrary, several classifications complement each other. According to ANAC (Anac, 2017), RPAs are classified according to the maximum takeoff weight (TW) as follows: (1) Class 1: RPAs with a TW greater than 150 kg; (2) Class 2: RPAs with a TW greater than 25 kg and less than or equal to 150 kg; (3) Class 3: RPAs with a TW less than or equal to 25 kg.

Another type of classification, according to Villalobos et al. (2018), refers to the type of sustainment: (1) aerostat and (2) airship. Airship is the designation given to a lighter-than-air aircraft. The aerodrome is the generic designation of a heavier-than-air aircraft, with or without its own means of propulsion. The latter is the most commonly used type and may be classified as (1) fixed-wing, (2) rotary-wing, and (3) hybrid (Radoglou-Grammatikis et al., 2020). As for the power source, the equipment can be equipped with internal combustion or electric engines.

For the application of phytosanitary products, the most used RPAs are the rotary-wing ones, more specifically the multirotors, given their stability and capacity for vertical and static flight. In general, there is equipment with three to eight rotors or more. In some countries, such as Japan, it is common to use helicopters (one rotor) for aerial applications. This was the first country in the world to

employ this type of equipment. According to Xiongkui et al. (2017), most small farms were not suitable for boom sprayers, which led the country to invest in RPAs. In 1985, the company Yamaha developed the first agricultural RPA, the helicopter model R50.

Another country that uses this technology intently is China, which boasts more than 200 manufacturers. Chinese RPAs, in general, have an empty weight between 10.0 kg and 50.0 kg, working height between 1.0 m and 5.0 m, and working speeds less than 8.0 m s⁻¹, while most RPAs have electric motors and tank volumes ranging between 5.0 L and 30.0 L (Xiongkui et al., 2017).

Multirotors consist of independent propellers in different numbers, which ensure a lift in flight. In general, in a piece of equipment with four rotating wings (quadrotor), engines one and three rotate counterclockwise and engines two and four rotate clockwise; this is because the rotating engines create not only vertical forces responsible for sustainment but also horizontal forces that create the rotational movement of the quadrotor around its central axis. The fact that a pair of engines rotate in the opposite direction creates two opposing horizontal forces, thus controlling the rotational movement of the quadrotor around its central axis and increasing controllability. The altitude can be controlled by increasing or decreasing the four motors' speed simultaneously (Yepes & Barone, 2018).

Factors that interfere with the spray deposition on the target

The quality of an application of a plant protection product is evaluated, among other factors, by the spray deposition on the target and also by its uniformity of distribution along the crop canopy. Several factors, such as the height and flight speed of the RPAs, size and droplet generating elements, application rate, and spray solution properties, including the use of adjuvants, can interfere with this process.

In general, applications have been performed between 1.0 m to 3.0 m of height and 1.0 m s⁻¹ to 7.0 m s⁻¹ of velocity, as can be observed in the works of Liao et al. (2019), Wang et al. (2020 c), Ahmad et al. (2020), and Chen et al. (2020). Wang et al. (2020 d) showed that it is critical to find a balance between height and speed to achieve a satisfactory application. Tang et al. (2018) studied the effect of flight height on application quality with an RPA in citrus. They concluded that a distance of 1.2 m from the target provided good spray distribution along the canopy. Liao et al. (2019) verified that RPAs performed well in the defoliation of cotton, with the best working speeds ranging between 1.5 m s⁻¹ and 3.8 m s⁻¹.

Droplet throw height and nozzle distance were studied by Guo et al. (2020) in an application using the XR 110 015VS flat fan spray tip. The authors found that the spray jet angle was the factor that most influenced the size of droplets. According to the authors, there is an overlap of the spray jets when using an RPA, which interferes with the droplet spectrum and makes it challenging to predict drift and deposition on target.

Additionally, the flight height interferes with the deposition width. Reducing the application rate is only possible when there is a uniform cross-sectional distribution. Homogeneous target coverage requires uniform distribution, characterized by low coefficients of variation along the treated ranges, which in general for

aerial applications should be less than 25% (Martin et al., 2019). This transverse uniformity depends on several factors, such as the tip used, the overlap of the jets, and the spray system's geometry, and is specific to each type of RPA.

Martin et al. (2019) evaluated the deposition swath of a DJI AGRAS MG-1 octocopter RPA. The authors found that the flight speed did not influence the deposition swath's width, but the flight height interfered with this parameter. The effective deposition range (considering a CV of 25%) varied from 4.6 to 7.6, depending on the operational condition. Hussain et al. (2019) evaluated the distribution uniformity of a hexacopter flying at different heights and also found good distribution uniformity with the RPA at heights of 1.5 m and 2.0 m. However, the authors noted that at 3.0 m, there was a worsening of uniformity, attributed mainly to the crosswind's negative effect.

For Wang et al. (2020 e), the droplet launch height influences its evaporation as it moves from 1.5 m to 4.0 m until it reaches the target. However, other factors can interfere with the droplet launch, such as the lateral wind and the flight path. In this sense, algorithms, information technology, and artificial intelligence are tools capable of correcting such effects and maintaining the aircraft's stability in variable conditions of wind and topography.

Aircrafts are usually equipped with sensors for flight safety, which identify the terrain's irregularities to maintain a constant height and flight stability. The absence of this technology compromises the process of droplet deposition on the plant canopy. Wang et al. (2018 a) highlighted that an advantage of RPAs is the flexibility of application in difficult to access terrain. The authors indicated that the maintenance of the trajectory during the flight is fundamental for the quality of the application, corroborating the data presented by Hunter III et al. (2019 a).

In general, applications are conducted at a constant height and speed over the plant canopy. However, there are systems where the aircraft makes a directed application on each plant, as described by Richardson et al. (2020 c), who used an aircraft XAG P20 at a height of 3.0 m that rotates, as a function of application time, under its own axis at six revolutions per minute (rpm), until applying the pre-set volume. This dynamic allows localized applications on the target plant in high value-added crops and places that are difficult to access.

Zhang et al. (2020 a) observed that the airflow of a multicopter aircraft is different as a function of variation in height (1.5 m to 3.5 m) and speed (2.0 m s^{-1} to 5.0 m s^{-1}) of flight. Similar results were obtained by Guo et al. (2019). The increase in flight height reduces the effect of airflow that projects the droplets toward the target, thereby altering their deposition on the plant canopy. Ahmad et al. (2020) also observed that increasing the flight height and speed reduces the droplet deposition on the target. In tree crops, Meng et al. (2020) studied the effects of speed (2.0 m s^{-1} to 5.0 m s^{-1}) and flight path (intra- and inter-planting line) on the percentage of target coverage and observed that both factors were influenced by the shape of the plant canopy in a peach crop.

Regarding the droplet generation process, hydraulic tips (Guo et al., 2020; Wang et al., 2020 c; Ahmad et al., 2020; Chen et al., 2020) and atomizing rotating disc type devices (Liu et al., 2020) have been used in research with good results, but without the possibility of preference of the application technology aspects for good agricultural

practices. However, the cost of both perhaps explains the higher frequency of use of hydraulic tips. In sugarcane crops, for example, a droplet size between $50 \mu\text{m}$ and $300 \mu\text{m}$ has been shown to be optimal for application (Zhang et al., 2020 c), which can be obtained with both droplet-generating elements. RPA spraying has been performed with a broad spectrum of droplets, from fine to extremely coarse, with selection influenced by weather conditions and airflow from the propellers (Richardson et al., 2019).

Hewitt et al. (1994), who studied the droplet spectrum simulating manned aerial application in a wind tunnel, found that the rotary nozzles produced a more homogenous droplet spectrum, i.e., with less relative amplitude than the hydraulic tips. This, in principle, is a great advantage for applications with RPAs, as the success of spraying with reduced application rates is linked to the formation of droplets of uniform size. In this sense, there is a field for further research.

Liu et al. (2020) studied deposition and droplet loss in apple orchards, using ground and unmanned aerial application, a flight height of 2.5 m, and an autonomous mode. In the ground and aerial applications, the average depositions were $2.79 \mu\text{L cm}^{-2}$ and $0.6 \mu\text{L cm}^{-2}$, respectively, with higher concentrations in the position frontal to the fan in the hydropneumatic application and more homogeneously along the plant canopy with the aircraft. The application with RPA reduced approximately five times the losses to the soil. The drift produced by the hydropneumatic sprayer was greater. The use of the aircraft resulted in greater drift at a height of 1 m from the ground level, owing to the reduction of airflow from the propellers that displace the drops downwards. On the other hand, Soela et al. (2020) studied the deposition in conilon coffee plantations using different flight heights. They observed higher values along the canopy and less runoff to the ground at a flight height of 1 m.

Another critical factor in the deposition is linked to the spray mixture. The droplets' dynamic evaporation has a characteristic behavior as a function of the interactions among temperature, relative humidity, and adjuvants in various concentrations. Each adjuvant and its respective dose have a particular connection with the solution under different meteorological conditions (Wang et al., 2020 e). Wang et al. (2020 c) studied the effect of adjuvant addition in applications at 9 L ha^{-1} and 18 L ha^{-1} and found that droplet deposition was higher at the 9 L ha^{-1} rate in the presence of an adjuvant. Chen et al. (2020) also observed beneficial effects of adding an adjuvant in the application at different development stages of rice crops.

Martinez-Guanter et al. (2020) verified that the application with RPA in olive and citrus orchards, compared to the application with a hydropneumatic sprayer, resulted in a greater droplet density on the target and more uniform droplet diameters. However, they pointed out that both application systems can be combined to obtain homogeneous applications with higher deposition. Liao et al. (2020) detected a negative correlation between leaf area index and droplet deposition when applying a defoliant to cotton, regardless of the application rate.

In Brazil, the use of these aircrafts for spraying plant protection products is commonplace. However, few scientific papers are published on this subject, probably due to the cost of acquiring RPAs by research institutions. Regarding operating expenses, in Brazil, it has been

observed that the value per hour worked of unmanned aircraft is still higher than in traditional agricultural aviation and with ground sprayers (Mendes, 2020). However, in Germany's Bavarian region, for example, Leroy et al. (2019), who compared the costs of manned and unmanned aircraft operation, stated that RPAs have lower operational costs.

Studies of control effectiveness by means of RPA applications

It is essential to consider the control efficacy of RPA application, and ideally, it should be compatible/similar to that of traditional application methods, considering the advantages and challenges of RPA application. Thus, studies have been conducted to evaluate the control effectiveness of crop protection products applied by RPA. Most studies compare this application method with the backpack sprayer, which is widely used in small farms in countries worldwide, such as China.

For example, Zhang et al. (2020 b) evaluated the effects of herbicide application on wheat yield components with RPA and knapsack application. RPA application provided higher wheat yields and was more efficient than knapsack application. The number of ears and grains per ear was not directly affected by the different spraying methods. However, the application with RPA increased the mass of 1,000 grains, resulting in a 14.6% increase in wheat yield.

Chen et al. (2019 a) evaluated the efficacy of weed control in wheat crops with pre and post-emergent herbicides applied by RPA and knapsack sprayer. The control with pre-emergent herbicides, applied by RPA, was similar to the knapsack sprayer application in a study area with higher soil moisture and less straw cover. On the other hand, control efficacy was lower when these herbicides were applied by an RPA in an area with lower soil moisture and greater straw cover. This suggests that for applications of pre-emergent herbicides with RPA, it is imperative to have adequate soil moisture to allow herbicide activation as these applications are performed with a low volume of water. The results were similar or slightly lower than those of the backpack application of post-emergent herbicides. This demonstrates the possibility of the application of herbicides with RPA. However, the effectiveness may be affected due to the method's characteristics, such as lower droplet density and lower penetration of these drops in the weed canopy.

The formulation and active ingredient characteristics also influence control efficacy. As the concentration of an active ingredient in the droplets can be up to 30 times higher with an RPA application, this may result in the increased uptake of the herbicide due to the concentration gradient in the leaf or reduced uptake due to necrosis in the leaf tissue where the droplets were deposited (Chen et al., 2019 a).

Choosing a tip that produces fine droplets with good deposition and density may result in better control efficacy (Chen et al., 2020; Yan et al., 2020). Besides, the addition of adjuvants may help improve effectiveness by ensuring better deposition and coverage of the target or by prolonging the retention of the plant protection product on the surface (Chen et al., 2020; Qin et al., 2018). Systemically acting products are also more suitable for RPA applications (Nahiyoon et al., 2020).

Seeking to improve the control efficacy of insecticides applied with RPA, Wei et al. (2020) evaluated the use of an oily formulation, known as ultra-low-volume

(ULV), of the insecticides chlorantraniliprole and thiamethoxam for the control of *Spodoptera frugiperda* in corn crops. This formulation consists of dissolving the insecticide in a high boiling point solvent mixed with adjuvants. The application of these insecticides with RPA, using the ULV formulation at an application rate of 3 L ha⁻¹, resulted in 83% control of *S. frugiperda* larvae. In comparison, the application with a knapsack sprayer at an application rate of 450 L ha⁻¹ resulted in 70% control, thereby demonstrating that appropriate formulations for low volume application are crucial to ensure better control efficacy.

Xiao et al. (2020 a) compared the application of fungicides in wheat using RPA with other application methods (electric knapsack sprayer, self-propelled sprayer, and mist sprayer). The application with RPA and with an atomizer (mist sprayer) resulted in the largest fungicide deposits in all thirds of the wheat plants, ensuring the best effectiveness against *Fusarium graminearum* (FHB - *Fusarium* head blight) control and the reduction in mycotoxin concentration. Besides, the RPA application resulted in the lowest fungicide loss to the soil, which was only 21%. In contrast, applications with an electric knapsack and auto-propelled sprayers led to losses of 59% and 73%, respectively. This reduction in product loss is related to the greater droplet density and target coverage, which are characteristics of RPA and atomizer applications, which employ fine droplets.

Wang et al. (2019) observed that RPA application at an application rate of 18 L ha⁻¹ resulted in a higher control efficacy of powdery mildew and aphids in wheat than the rate of 9 L ha⁻¹. Similarly, Wang et al. (2020 c) studied the impact of application rate and the addition of adjuvants on the control efficacy of fungicides and insecticides applied with RPA. Droplet density and coverage increased with the increment in the application rate from 9 L ha⁻¹ to 18 L ha⁻¹ and the addition of adjuvants (methylated oil). Thus, in this study, the authors obtained greater control against rice brusone (*Pyricularia grisea*) (rice blast) and rice leaf roller caterpillar (*Cnaphalocrocis medinalis*) (rice leaf roller) when compared to the application with a knapsack sprayer. Xiao et al. (2020 b) obtained lower droplet density and uniformity of deposition with RPA. Still, the effectiveness against *Phytophthora capsici* and aphid control in a pepper cultivation was similar or slightly lower than that using a knapsack sprayer.

Leroy et al. (2019) tested the application of two insecticides with the aid of RPA for the control of defoliating insects, in a forest area with altitudes between 245 m and 278 m. The biological efficacy was three and five times higher than the control, especially in trees with higher leaf density. The authors reported the effectiveness of the technology employing RPA and the reduction of the application costs in spraying insecticides in forests compared to experiments using manned aircrafts. According to Li et al. (2020), pest control in orchards with dense leaf canopies presents a challenge using RPA. The authors emphasize the importance of determining the minimum spray volume and state that the use of this technology can provide complementary assistance to ground spraying.

Richardson et al. (2020 b), evaluated the operational conditions of herbicide application in the control of wild conifers and concluded that the application performed with agricultural aircrafts and hydraulic tips resulted in high drift

potential, with a volumetric median diameter (VMD) ranging between 356 μm and 400 μm . The authors stated that, in terms of drift, herbicide application with RPA requires similar care compared to that using a piloted aircraft, even with the aid of the air flow generated by propellers. For any aerial herbicide treatment, droplet size choice represents a compromise between the benefit of greater efficacy and leaf coverage achieved with smaller droplet sizes versus reducing the risk of herbicide drift.

Risk of drift losses

The drift of active ingredients is one of the main problems in their application in agricultural areas (Godinho Júnior et al., 2018). This can be succinctly defined as the process of the physical movement of droplets out of the application area (Wang et al., 2020 b). This problem has been studied in applications using RPA (Wang et al., 2018 b), and can be aggravated when working with droplet sizes less than 150 μm (McGinty et al., 2016; Chen et al., 2019 b) and reduced application rates (low volumes or ultra-low volumes) (Wang et al., 2020 a), characteristics commonly seen in applications with RPA, as well as inadequate altitude and flight speed (Wang et al., 2020 a). Therefore, the correct regulation and calibration of these pieces of equipment may ensure greater efficiency of using the technology (Wang et al., 2020 b).

Hussain et al. (2019) comment that high flight heights promote drift and low distribution uniformity and recommend heights between 1.5 m and 2.0 m for uniform deposition. On the other hand, Yang et al. (2018) show that heights close to 1 m can result in low distribution uniformity due to turbulence promoted by the airflow generated by propellants. There may also be a loss of solution directly to the soil due to the non-retention by the foliar.

Wang et al. (2020 d) evaluated a single-engine combustion RPA operating in a pineapple crop in China and observed that 90% of the drift was concentrated at distances from 3.7 m to 46.5 m under different operational conditions. The authors pointed out that such observations are related to flight height and speed, type of RPA used, and the meteorological conditions of the study region. According to these authors, the flight speed of 3.0 m s^{-1} and flight height of 3.5 m in the pineapple crop resulted in the worst quality of application, which led them to recommend flight heights of less than 2.5 m and wind speeds of up to 2 m s^{-1} .

Spray tips, working direction in relation to the crop area, and wind speed also influence drift applications with RPA (Faiçal et al., 2014; Wang et al., 2018 b). Chen et al. (2019 b) studied the adjustment of the working pressure and the angle of attack of the spray tips using algorithms and achieved a 33.7% reduction in drift evaluated in a wind tunnel.

Hunter III et al. (2019 a), using the AIXR 11002VP air-induction flat fan spray tip (Spraying Systems Co., Wheaton, IL, USA) on a multirotor RPA, obtained greater target coverage and reduced drift potential when compared to the other tips used in the study. The hollow cone tip, HC, and flat fan tip, XR, showed a higher risk of drift, while the deflector flat fan tip with air induction, TTI, resulted in less target coverage. It is worth noting that choosing the appropriate tip does not only depend on the type of aircraft but also on other factors such as treatment objective and crop.

The use of agricultural adjuvants is also an essential tool in drift management. Wang et al. (2018 c) evaluated

different adjuvants and concluded that the use of appropriate concentrations could reduce drift by up to 65%. The same authors, using combustion-engine RPAs, observed drifts more than 10 m in the absence of adjuvants.

Wang et al. (2017) observed a displacement of 90% of the droplets when the application occurred in the wind direction, in a range of up to 14.5 meters, emphasizing the importance of considering an area without application (buffer zone) when spraying with the wind in favor of the flight. Thus, evaluations before application, taking into account wind speed and direction, are essential in using RPA.

In this context, it is crucial to observe the advantages of using RPA in pesticide applications, taking into account the risk of drift. Field studies aiming to know the characteristics inherent to the drift process and its interaction with the spraying process are of fundamental importance in the context of different situations, crop characteristics, and environments.

Future challenges

Any technique for applying plant protection products should aim at the correct deposition of the product on the target, with minimum losses and occupational risks. This also applies to RPAs. Owing to the nature of some application techniques, these will often result in reduced application rates and fine droplets, which can compromise the balance between performance and environmental safety (Lan & Chen, 2018; Guo et al., 2020). The droplet dynamics in relation to the airflow are different using RPAs compared to using other methods and need to be better understood to result in good deposition and lower drift losses. Therefore, the people involved in this type of operation should be appropriately qualified, although the availability of people with adequate training is still limited.

The physicochemical characteristics of the spray mixture, adjuvants, electrostatic spraying, and droplet generating elements are points that still need to be better understood in terms of their interaction with RPAs. Undoubtedly, they have great potential to mitigate problems and improve the quality of applications. However, scientific research has not kept up with the rapid evolution in the agricultural scenario. Thus, there is still a knowledge gap to be filled by performing field trials (Xiongkui et al., 2017; Richardson et al., 2020 b). Pesticide formulators will need to develop new formulations that are more suitable for applications with RPAs, especially considering the characteristics of working with more concentrated solutions.

Another point that also needs to evolve refers to the regulation of the sector. According to Hunter III et al. (2019 a), the lack of technical information about the technology hinders the development of standards indicating safe practices. RPA operators must have clarity about the operation regulations. As this is a relatively new technology, many countries have no regulations or the existing regulations are incipient and do not fully address the needs. The labels themselves will need to be updated, taking into account this new technology.

Besides, there is a lot of talk these days about fully autonomous vehicles. With the development of technology, this will be a reality for some sectors that employ RPAs. However, for the application of pesticides, there will be a need for a broad discussion on the benefits and risks involved and the adequacy of the sector's regulations as, in some countries, this technology is not allowed. Owing to the

existing risk linked to the use of phytosanitary products, an in-depth analysis of the convenience of entirely autonomous applications will be necessary.

CONCLUSIONS

Several factors interfere with the quality of the pesticide application using RPAs. Among them are height and flight speed, size and droplet generating elements, application rate, and spray solution properties. Thus, it is essential to know the effect of these factors on the effectiveness of treatments; however, especially in Brazil, the availability of scientific research is still minimal. Most of the studies already carried out are concentrated in China, aiming to replace the knapsack sprayer application.

In general, the agronomic efficacy studies involving applications with RPAs demonstrate the great potential to replace the applications performed mainly by small equipment, with reduced risks of contamination of those involved in the operation. Other uses are also promising, such as localized applications in areas that are difficult to access. Despite not having been companies' initial objective, the application in extensive areas is already thought mainly with work fronts with a cloud of aircraft or use of equipment with greater tank capacity. The development of adjuvants and specific formulations may also help improve the quality of applications by RPA, resulting in greater control effectiveness of plant protection products.

In terms of environmental safety, the employment of reduced application rates and a fine droplet spectrum, as well as the drift problem should be considered. The use of drift reduction techniques, such as larger droplets, lower flight heights, and the addition of adjuvants, has proven promising but requires the careful technical monitoring of the applications.

Technological advances in remote sensing, digital image processing, and artificial intelligence indicate, in the short term, that the application of plant protection products will be associated with instantaneous monitoring (Castro et al., 2020). This scenario will tend to boost the use of RPAs, thereby allowing a synchronized action between occurrence identification with analysis and management decision-making, determination of plant canopy volume, and application of compatible spray volume. Initiatives of this type have already been presented for application rate determination (Campos et al., 2020). However, Hunter III et al. (2019 b) stated that systems that are easier for applicators and technicians to operate still need to be developed to popularize these integrated tools.

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