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Revolutionizing agriculture from the skies: exploring the potential of spraying drones in precision farming

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ABSTRACT

This article explores how agriculture is evolving and adopting new technologies to achieve higher efficiency. Precision agriculture is a key factor in this evolution, and drones are identified as a tool that can contribute for the precision agriculture, particularly in areas with high labor costs, hard-to-reach areas, and small farms. This article focuses specifically on the use of spraying drones and their benefits, such as lower costs than those of tractor sprayers, faster spraying, access to crops that are difficult to reach, and the ability to be programmed to fly at specific times. The article also acknowledges the limitations of spraying drones, such as their low capacity, which can lead to the use of higher-pressure spraying, and the high cost of the equipment to smaller farmers. The main issue of spraying drones is identified as their batteries, which must be lightweight, but also tough to provide the drones with enough power to operate. Overall, while the use of drones in agriculture is promising for increasing efficiency and precision, there are still issues that should be addressed to make them more accessible and adopted by farmers.

Index terms: agricultural innovation, battery technology, drone technology, precision crop management, sustainable farming.

Revolucionando a agricultura pelos céus: explorando o potencial dos drones de pulverização na agricultura de precisão

RESUMO

Este artigo analisa o modo como a agricultura está evoluindo e adotando novas tecnologias para atingir elevada eficiência. A agricultura de precisão é um fator-chave para esta evolução, e o uso de drones é identificado como uma das ferramentas que contribuem para a agricultura de precisão, particularmente em áreas onde o custo de mão de obra é alto, em áreas de difícil acesso e em pequenas fazendas. O artigo foca especificamente no uso dos drones de pulverização e seus benefícios, como menor custo e pulverização mais rápida do que os de pulverizadores tratorizados, acesso à culturas que são difíceis de se atingir, e habilidade de serem programados para voar em momentos específicos. O artigo também aborda as limitações dos drones de pulverização, tais como sua baixa capacidade, que pode levar ao uso de altas pressões de trabalho, e o alto custo dos equipamentos para os pequenos produtores. O maior desafio dos drones de pulverização são suas baterias, que precisam ser leves, mas fortes o suficiente para suprir a operação do drone. De modo geral, o uso dos drones na agricultura é promissor para o aumento de eficiência e precisão, mas ainda há detalhes que precisam ser discutidos, para que eles se tornem mais acessíveis e adotados pelos produtores.

Termos para indexação: inovação na agricultura, tecnologias de bateria, tecnologia de drones, gestão de agricultura de precisão, agricultura sustentável.

Ideias centrais

- Spraying drones are capable of spraying at higher speeds and accessing difficult terrains compared to tractor-mounted ones.
- The total weight of spraying drones is the key to the success of the technology, as it allows them to operate with the lowest possible energy consumption.
- Drone batteries are the major bottleneck of the technology, as they need to be lightweight while maintaining the drone operational.
- High spraying pressure, drift, local regulations, and high equipment acquisition costs are barriers to the adoption of the technology.

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INTRODUCTION

Agriculture has evolved dramatically over the last century, when technological advancements have played a crucial role in increasing productivity, efficiency, and sustainability. Precision agriculture has emerged as a key concept in this evolution, using cutting-edge technologies to manage crops with greater accuracy and precision (Danbaki et al., 2020).

Precision agriculture is a modern farming approach that uses advanced technologies, such as global positioning systems (GPS), sensors, drones, and other data-driven tools, to manage crops with greater accuracy and precision (Shikur, 2020). This approach is transforming the agricultural industry by enabling farmers to make informed decisions, improve crop yields, reduce waste, and minimize environmental impacts.

The use of precision agriculture has grown significantly in recent years, with farmers around the world adopting this approach to meet the increasing demand for food, fiber, and fuel, while also addressing environmental concerns. The application of precision agriculture can be seen across various stages of the crop production cycle, including land preparation, planting, crop monitoring, and harvesting (Priya et al., 2022). By leveraging data and technology, precision agriculture offers the potential to increase the productivity, profitability, and sustainability in farming operations, by adopting eco-friendly practices. Drones, with their versatility and adaptability, have emerged as a potent technology to facilitate precision agriculture, especially for small-scale farmers who have limited access to resources, and for regions that are hard to reach or have higher labor costs (Nyaga et al., 2021; Yaqot et al., 2021).

Among the different types of drones, spraying drones have gained prominence in agriculture, as they offer precise and efficient spraying of chemicals, which results in lower environmental impact, possibility of increased yield, and cost savings. Spraying drones are smaller, lighter, and more agile than traditional sprayers, which makes them easier to maneuver through crops and apply chemicals only where they are needed. Additionally, they can cover larger areas of land and work at a faster pace, thus reducing labor costs (Seo & Umeda, 2021; Ghafoor et al., 2022).

Spraying drones offer multiple benefits over conventional sprayers, including access to hard-to--reach areas, improved safety, reduced chemical use, and higher accuracy. They can also be programmed to operate autonomously, which reduces the need for skilled labor and increases productivity. Moreover, they can be equipped with various sensors, such as multispectral cameras, thermal cameras, and Light Detection and Ranging (LiDARs), which provide real-time data and enable farmers to monitor crop health, to detect diseases and pests, and to optimize resource use (Gordan et al., 2021; Matthews, 2021; Seo & Umeda, 2021).

Despite these advantages, the use of spraying drones in agriculture still faces several limitations, including the low equipment capacity, high equipment costs, and battery limitations. One of the critical challenges is battery life, which is a major constraint in the use of drones for prolonged spraying operations (Hu et al., 2021; Matthews, 2021). Since drones are powered by batteries, they need to be lightweight, besides showing a high-performance, and to be durable to operate under challenging environmental conditions. However, the current battery technology is not advanced enough to support prolonged drone operations in the field, which leads to a limited flight time and reduced productivity (Yi et al., 2021).

To overcome these limitations, research efforts are focused on developing high-performance batteries that can meet the energy demands of spraying drones. Lithium-ion batteries are currently the most widely used batteries for drones, due to their high energy density and low self-discharge rates (Kebede et al., 2021; Nakamura et al., 2021). However, they are not suitable for prolonged use, as they tend to degrade over time and are susceptible to overheating that leads to a shorter battery life.

Newer technologies such as solid-state batteries, lithium-sulfur batteries, and flow batteries are being developed as potential alternatives to lithium-ion batteries. Solid-state batteries are considered the most promising ones as they offer higher energy density, longer life, and improved safety than the conventional lithium-ion batteries. However, they are still in the research phase, and their commercialization is expected to take some time (Zhao et al., 2022).

Another solution to overcome battery limitations is to develop drone-swapping stations, where depleted batteries can be swapped with fully charged ones, thereby reducing downtime and increasing productivity. This solution also eliminates the need for farmers to invest in expensive generators and battery banks, which can add to the overall cost of drone operation (Yi et al., 2021).

DISCUSSION

Precision agriculture and drones

Precision agriculture driven by the integration of drones has emerged as a pivotal subject in recent years. The use of drones in farming is gaining considerable attention as a precision agriculture tool, due to its potential to revolutionize field management (Danbaki et al., 2020; Hammerschmidt et al., 2021; Priya et al., 2022). Drones offer to farmers detailed, high-resolution images of crops, soil conditions, and other factors affecting crop growth. These images enable farmers to swiftly and accurately identify problems such as nutrient deficiencies (Onyango et al., 2021), pests, and diseases (Yu et al., 2022), allowing of timely corrective measures and avoiding crop losses (Maimaitijiang et al., 2020; Dorbu et al., 2021; Hara et al., 2021). The ability to detect such issues at an early stage is crucial for optimizing yields and ensuring agricultural sustainability (Xie & Yang, 2020).

Moreover, drones provide farmers with comprehensive information on crop health and growth patterns (Pessi et al., 2020; Dorbu et al., 2021; Matthews, 2021). Equipped with sensors like infrared cameras, drones can detect variations of plant vigor, biomass, and other indicators of crop health (Maimaitijiang et al., 2020; Xie & Yang, 2020; Mesquita et al., 2021). By leveraging this information, farmers can make well-informed decisions regarding the application of fertilizers, water, and pesticides, thereby optimizing yields and minimizing waste (Corcoran et al., 2021). Drones also play a significant role in gathering detailed data on soil properties and topography (Maimaitijiang et al., 2020). These data empower farmers to adopt precise field management strategies to optimize the resource allocation and to minimize waste.

Despite the immense potential benefits, the use of drones in precision agriculture is not without its challenges. The cost of acquiring and maintaining drones equipped with high-resolution cameras and sensors can be prohibitive for small and medium-sized farmers, particularly in developing countries (Mesquita et al., 2021). Additionally, farmers should have specialized training to operate drones effectively and to extract valuable insights from the data collected. This training requires investment in both hardware and software, as well as in ongoing training and support for farmers, to leverage the full potential of drone technology (Corcoran et al., 2021).

Another critical challenge associated with the use of drones in precision agriculture relates to data privacy and security. As drones capture images of farms and their surroundings, concerns arise regarding data privacy and ownership. Furthermore, the data collected by drones are susceptible to hacking and other cyber-attacks, posing a risk to the confidentiality of farmers' information.

However, despite these challenges, the use of drones in precision agriculture is expected to witness a substantial growth in the foreseeable future. The technology becomes more affordable and user-friendly, while companies are actively developing specialized drones and software tailored for precision agriculture. Furthermore, the integration of artificial intelligence (AI) and machine-learning holds promise for enhancing the analysis of data collected by drones, enabling more accurate and efficient decision-making.

Looking ahead, the future of drones in precision agriculture showcases exciting potential developments, one of which is the use of drone swarms, which are multiple drones working collaboratively, to provide farmers with even more detailed and comprehensive information on crops and soil conditions. Swarm technology can facilitate even more precise field management. Additionally, drone swarms could collaborate to perform tasks such as crop spraying or planting, reducing the reliance on manual labor and streamlining agricultural operations (Jackisch, 2020; Oldeland et al., 2021).

Moreover, the adoption of autonomous drones for precision agriculture is another potential advancement on the horizon. Autonomous drones can be programmed to carry out specific tasks like crop spraying or monitoring, freeing up farmers' time and allowing them to focus on other aspects of farm management. Furthermore, autonomous drones can operate in challenging or hazardous conditions, minimizing the risk of injury to farmers.

Drones as sprayers on farms

The use of spraying drones in agriculture is a relatively new concept that is quickly gaining traction worldwide. Spraying drones are unmanned aerial vehicles (UAVs) equipped with spray nozzles that can deliver precise amounts of chemicals, fertilizers, and pesticides to crops. With the use of advanced technology, spraying drones can fly over fields and spray crops much more efficiently than traditional spraying methods, saving both time and money to farmers. In recent years, the use of spraying drones has increased significantly, and it is now being adopted by farmers worldwide (Bouyer et al., 2020; Shaw & Vimalkumar, 2020; Xie & Yang, 2020).

Spraying drones come in different models, each one with varying capacities for payload, spraying speed, and coverage area. Here are some examples of spraying drones:

- DJI Agras MG-1P – This drone has a maximum payload capacity of 10 kg and can cover up to 4,000-6,000 m^2 per hour. It also has up to 7-10 m s^{-1} spraying speed, and it can operate for up to 10-24 min depending on the payload weight (Dà-Jiang Innovations, South 4th Floor, West Wing, Skyworth Semiconductor Design Building, No. 18 Gaoxin, Nanshan District, Shenzhen, China).

- Yamaha YMR-01 – This drone has 30 kg as maximum payload capacity, and it can cover up to 1 ha per flight. It also has a spraying speed of up to 5-10 m s^{-}1 and can operate for up to 1 hour, depending on the payload weight (Yamaha Motor Co. Ltd – Fukuroi Factory). 3080 Yamashina, Fukuroi, Shizuoka 437-0066, Japan).

- XAG P100 – This drone has 40 L as maximum payload capacity and can cover up to 4,000-6,000 m^2 per hour. It also has a spraying speed of up to 6-12 m s^{-1} and can operate for up to 20-25 min depending on the payload weight (XAG, XSpace, 115 Gaopu Road, Guangzhou, China).

- DJI T30 – This drone has 30 L as maximum payload capacity, and it can cover up to 4,000-6,000 m^2 per hour. It also has a spraying speed of up to 6-10 m s^{-1} and can operate for up to 20-30 min depending on the payload weight (Dà-Jiang Innovations, South 4th Floor, West Wing, Skyworth Semiconductor Design Building, No. 18 Gaoxin, Nanshan District, Shenzhen, China).

While this technology is relatively new, it has the potential to significantly improve crop yields, reduce labor costs, and minimize environmental impact. In this literature review, we will explore the functioning of spray drones, their potential applications in agriculture, and the related questions that must be addressed.

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Benefits of using drone as a sprayer

The use of drones as sprayers on farms has several benefits, and one of the main advantages is that they reduce the need of human labor. When using traditional methods of spraying, farmers have to spray their crops manually or use a tractor-pulled sprayer, which requires a driver. However, drones can be programmed to fly over the fields and spray crops without human intervention, which reduces the need of farm labor and can lead to significant cost savings for farmers.

Shaw & Vimalkumar (2020) concluded that the use of UAV sprayers can help to reduce labor costs and increase the efficiency of pesticide application in agriculture. Xie et al. (2021) reported that drones reduce labor costs in general, and that that such reductions greater in regions with high labor costs.

Using drones as a sprayer has significant advantages over traditional methods of spraying. One of the most significant benefits is the ability to apply chemicals with a higher degree of precision. Traditional sprayers, whether handheld or tractor-mounted, often apply chemicals unevenly, which can result in over-application in some areas and under-application in other ones (Zhang et al., 2016; Butts et al., 2019; Partel et al., 2019). This uneven distribution of chemicals can have a significant impact on crop quality, yield, and overall efficacy of the treatment. Conversely, drones can be programmed to apply chemicals with a high degree of accuracy and precision. Using GPS and other advanced technologies, drones can fly over crops and spray chemicals in a highly targeted manner, which results in more even coverage and less waste, as well as in reduced chemical runoff, which can have environmental benefits (Jiménez López & Mulero-Pázmány, 2019).

Furthermore, using drones for precision agriculture has other benefits that traditional spraying methods do not provide. For instance, by using remote sensors and imaging technologies, drones can identify crop stress, nutrient deficiencies, and even pest infestations (Bhattarai et al., 2019). This information can be used to create highly targeted and customized treatments that are tailored to the specific requirements of the crop, reducing the need of broad-spectrum chemicals and improving overall crop health.

The ability of drones to access hard-to-reach areas on farms is a significant advantage for precision agriculture. In traditional agriculture, farmers have to rely on manual labor or large machinery to manage their crops, which often results in uneven application of fertilizers and pesticides. This can lead to lower yields, reduced crop quality, and environmental harm (Yao et al., 2017; Boursianis et al., 2022). However, with the use of drones, farmers can overcome these challenges and manage their crops with greater precision and efficiency.

One of the most significant challenges for traditional sprayers is to access steep hillsides or narrow areas between crop rows. These areas are often difficult to reach with large machinery, and manually spraying them can be both time-consuming and dangerous (Partel et al., 2019). However, drones equipped with advanced sensors and softwares can easily navigate these areas, ensuring that crops receive proper treatments (Matthews, 2021).

Drones are also beneficial in accessing crops that are difficult to reach due to their height. For instance, fruit trees can be difficult to manage using traditional methods, as they often require ladders or other equipment to reach the upper branches. Drones equipped with advanced sensors and cameras can easily access these areas, making it easier for farmers to manage their crops (Hiebert et al., 2020; Matthews, 2021).

In addition, drones can be programmed to fly at specific times, ensuring that chemicals are applied at the optimal time for maximum effectiveness; for instance, applying pesticides at night can be more effective, as insects are typically more active during this time. Drones equipped with advanced sensors and software can be programmed to fly at specific times, ensuring that chemicals are applied at the optimal time for maximum effectiveness (Cai et al., 2019).

Moreover, using drones as a sprayer reduces the need of human labor, which can lead to significant cost savings for farmers. With traditional methods of spraying, farmers have to manually spray their crops or use a tractor-pulled sprayer, which requires a driver, which can be time-consuming, labor-intensive, and costly. Nevertheless, drones can be programmed to fly over the fields and spray crops without human intervention. This not only reduces the need for farm labor, but can also lead to increased safety for workers, as they are not exposed to harmful chemicals during the spraying process.

In addition to the above mentioned benefits, using drones as a sprayer has also potential environmental benefits. By reducing the amount of chemicals needed to treat crops and reducing chemical runoff, drones can help to mitigate the environmental impact of farming (Liu et al., 2016).

Using drones as a sprayer can also increase the efficiency on the farm. Traditional sprayers are limited by the size of their tanks and the speed of their operation; however, drones can cover a much larger area in a shorter amount of time, by their ability of fast flying. Even if drones need to stop to reload more often, their speed make them a more efficient method of spraying than the traditional sprayers. The use of drones can allow farmers to spray their crops more quickly and with less downtime, which results in higher productivity.

In small farms, drones can play an essential role to increase productivity, which is particularly significant in developing countries, where small farms are prevalent. Small farmers often face challenges such as lack of access to credit, high input costs, and low productivity. By using drones, small farmers can improve their productivity and increase their income, which can have a significant impact on their livelihoods (Cruzan et al., 2016).

Limitations of using drones as a sprayer

While there are many benefits of using drones as a sprayer on farms, there are also some limitations that need to be considered, such as their size and payload capacity. Drones are limited for the amount of chemicals they can carry, and for the area they can cover before they need to refuel or recharge. The amount of chemicals that can be carried by a drone is determined by its payload capacity, which is the weight it can carry in addition to its own weight. The payload capacity of drones can range from a few pounds to several hundred pounds, depending on the model and size of the drone (Villa et al., 2016; Jiménez López & Mulero-Pázmány, 2019).

In order to spray larger areas with the low weight that the sprayer drones can carry, farmers are using more pressure on spray tips, resulting in more weather-sensitive spraying, which can lead to a higher spray drift, that can finally hit the operator and bystanders (Chen et al., 2020).

One approach to develop a more advanced spraying is the use of mapping and targeting systems that can optimize the spray patterns based on real-time data about the crop and environmental conditions. A study by Qin et al. (2021) proposed a precision spraying system that combines a spraying drone with a ground-based sensor network to provide real-time data on crop health and environmental conditions. This system uses the data to generate a customized spraying plan for each field, optimizing the spray coverage and reducing drift.

The area that a drone can cover before it needs to refuel or recharge is also limited. This is determined by the size of the drone's fuel or battery tank, which is smaller than the tank of a traditional sprayer (Villa et al., 2016). A traditional sprayer can cover several acres before it needs to be refilled, while a drone may need to be refueled or recharged after covering only a fraction of that area. As a result, larger farms may require multiple drones to cover all their crops or may need to refill or recharge the drone multiple times, during the spraying process (Shaw & Vimalkumar, 2020).

Another limitation of using spraying drones is that they are sensitive to fly at intense weather conditions. Drones cannot be flown in high winds or heavy rain, since these conditions can limit the

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amount of time they can be used for spraying, and this can be a significant limitation in areas with frequent weather changes, or in areas with high rainfall (Jiménez López & Mulero-Pázmány, 2019).

The cost of purchasing and maintaining drones is also a limitation that needs to be considered. Although drones become more affordable, they still represent a significant investment for farmers. In addition to the initial purchase cost, farmers should also consider the cost of maintenance, repair, and replacement of the drone (Shaw & Vimalkumar, 2020).

Local regulations about the use of drones on farms can also be a limitation. Different countries have different regulations regarding the use of drones for agriculture, and farmers must comply with these regulations to avoid legal issues. In the United States, the Federal Aviation Administration (FAA) is responsible for regulating the operation of unmanned aircraft systems (UAS), which includes spraying drones (FAA, 2020; eCFR, 2023). Commercial operators must obtain a Part 107 Remote Pilot Certificate, which involves passing a knowledge test and a background check. The certification is valid for two years and requires renewal upon expiration (FAA, 2023). Similarly, in Europe, the European Union Aviation Safety Agency (EASA) is responsible for the regulation of drones (EASA, 2022a, 2022b). The EASA has developed a set of regulations known as the EU UAS Regulation, which provides a common framework for drone operations across Europe. Under the regulation, drone pilots are required to obtain an operator's certificate, and the specific requirements for certification depend on the type of operation being conducted (EASA, 2023).

In Brazil, the Agência Nacional de Aviação Civil (ANAC) – the National Agency for Civil Aviation – regulates the use of drones, including spraying drones (ANAC, 2023b). ANAC requires individuals who operate drones for commercial purposes to obtain the application form Solicitação de Acesso de Aeronaves Remotamente Pilotadas (SARPAS) – an access application for certifying remotely piloted airplanes –, which involves meeting specific training requirements for pilots and passing a knowledge test. In addition, pilots must comply with specific safety measures and operational limitations, when operating spraying drones (ANAC, 2023c).

These regulations are necessary to ensure the safe and responsible use of spraying drones. The potential risks associated with the use of these drones include collisions with other aircraft, damage to property or crops, and harm to people or animals. By requiring individuals to obtain authorizations and certifications, regulators can ensure that drone pilots have the necessary knowledge and skills to operate the drones safely and efficiently.

Spray drift – operators and bystander exposures

There are a considerable number of studies that were considered both relevant and reliable because there is a precedent for trial conduct ,in the form of an ISO standard on measuring drift of plant protection products, with detailed specifications for ground sprayers (ISO, 2005).

However, a standard test protocol for unmanned aerial systems (UAS) is still required, as highlighted by the data available. Although some studies provided data as a 'percentage of spray solution applied', some studies made this calculation from a measure of what was deposited in the canopy, which is highly variable. The scientifically rigorous method of doing this can only be the measuring of what was sprayed out of the tank, at the end of each treatment run with a precise measure of the area treated (OECD, 2021).

One of the longest downwind distances included in a study was conducted by Xue et al. (2014) with a Z3 UASS, in which, Mylar cards were placed at various distances, and the results showed that 90% of the drift was concentrated within the first 8 m downwind of the sprayed area.

Wang et al. (2020) compared the drift potential of three different droplet size distributions of 100, 150, and 200 µm with centrifugal nozzles. These authors found that the deposition at 12 m downwind decreased by an order of magnitude, in comparison with the average deposition within the in-swath zone. At 12 m downwind, deposition was 0.02 µg cm^{-2}, calculated as 0.034% of the applied rate measured in the canopy. Samplers extended to 50 m downwind, where deposition amounts were lower than the detection limits of 0.0002 μL m^{-2}. The results from these authors indicated that the drift distance of this specific UASS) models (WQF120-12, Anyang Quanfeng Aviation Plant Protection Technology Co., Ltd., Henan, China; 3WM6E-10, TT Aviation Technology Co., Ltd., Beijing, China; 3WM8A-20, TT Aviation Tchnology Co., Ltd., Beijing, China) and nozzle setup (hollow cone nozzle TR 80-0067) was less than that of manned aerial applications.

In a study conducted in vineyards with a singlerotor RMAX, the deposition averaged 0.4% of the application rate at 7.5 m downwind, and 0.03% at 48 m downwind (Brown & Giles, 2018).

Meanwhile, a robust study that investigated the influence of flight height and wind speed with a single-rotor UASS (3WQF120-12) found that 90% of the spray deposited within 6.9 m at a 1.5 m flight height, and within 10 m at a 2.5 m flight height and 4.7 m s^{-1} wind speed.

The risks associated with pesticide exposure during operations are a concern that requires further investigation. Exposures can occur not only from direct contact with the spray, but also from residues on the equipment and during tasks such as mixing, loading, maintaining, cleaning, and transport. The use of high in-use concentrations may also increase the risk of sensitization or irritation. During the application, the complex turbulent flow from UASS, particularly multi-rotor aircrafts, can cause residue of the active ingredient to accumulate on the aircraft. Additionally, there is risk for the aircraft to fly back through spray that has not yet settled out (OECD, 2021).

In an experiment conducted by Li et al. (2021), filter papers were attached to each side of the boom holder, on each of two UASS arms, and one on the UASS top cover. Recovery numbers showed that < 6 µg were recovered per filter paper, which would put the maximum deposition at 0.2 µg cm^{-2}. This result supports the conclusion that unmanned aerial applications can be a relatively clean operation. However, the spray boom and drone arms had the highest residues; since the drone arms are used for lifting the aircraft by the ground crew, proper personal protective equipment (PPE) as required for applicators on product labels is important to avoid exposure.

Relevant data for assessing bystander exposure are the measurements of airborne spray drift downwind of the target area. To understand the pattern of spray drift from UASS, and how it differs from conventional application methods, it is necessary to collect air concentrations from monofilament lines erected at different heights from the ground and different distances from the treated area. Monofilament lines placed 2 m from the edge of the field are a measure of potential drift and should be considered for information on bystander exposure. The height and volume of the plume exiting the targeted spray area, its droplet size distribution, and the meteorological conditions determine the distance it travels (OECD, 2021).

Studies by Wang et al. (2020, 2021) collected data on airborne drift with different droplet size distributions, at different distances and heights from the edge of the field. They found that the airborne spray drift in vineyard applications was higher than in the arable crop scenario, due to the release height of the hollow cone nozzles (fine particles) versus the air induction nozzles (coarse particles) that released significantly more spray from the target area. Wang et al. (2018) conducted a drift study in a pineapple crop, using a single-rotor UASS operated at a fixed velocity and medium droplet size distribution; the authors found that deposition measured on monofilament lines was close to zero, at low operating height and under low wind speeds.

The main limitation: batteries

Arguably, the main challenges associated with the use of these drones are the use of batteries. As these drones require a significant amount of energy to operate, the weight and capacity of the battery is critical for optimal performance. In this section, we will delve deeper into the battery problems with sprayer drones, and their impact on overall efficiency and productivity (Dorling et al., 2017; Stolaroff et al., 2018; Li & Liu, 2019).

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One of the main uses of energy in a spraying drone is the pressurization of the tank, which is critical for delivering the spray to the targeted crops (Wang et al., 2021). The pressure required for this function can be as high as 10 bar, which translates to a high energy requirement (Yu et al., 2020). Additionally, the energy consumption to keep the engines of the propellers running, transmitting and receiving data from the pilot, and running the other electronics further adds to the energy demands of the spraying drone (Zhang et al., 2021). All of this must be powered by a battery that is lightweight and compact enough to be carried by the drone. The challenge, therefore, lies in finding a battery that can meet the power demands of the spraying drone without adding unnecessary weight to the overall system.

In the United States, the FAA has issued regulations on the use of drones for commercial purposes, which includes the use of spraying drones for agriculture. The FAA has mandated that the drone and its components, including the battery, must meet certain standards before they can be authorized for commercial use (Raj & Sah, 2019).

In Europe, the EASA has also issued regulations on the use of drones, including spraying drones and their components. These regulations include requirements for the certification of drones and their components, such as batteries, to ensure that they are safe and reliable for commercial use (Raj & Sah, 2019).

In Brazil, the ANAC has also issued regulations on the use of drones for commercial purposes, including spraying drones for agriculture (ANAC, 2023b). The regulations require that the drone and its components, such as batteries, must be certified by ANAC, before they can be used for commercial purposes. This certification process includes an assessment of the safety and reliability of the drone and its components, as well as their compliance with technical standards (ANAC, 2023a).

Despite the regulatory requirements for batteries in spraying drones, there are still concerns about their overall performance and efficiency. One of the main issues is the weight of the batteries, which can limit the amount of water that the drone can carry and spray over a given area (Shaw & Vimalkumar, 2020). This can be a significant problem, especially for large-scale agricultural operations, for which the ability to spray a larger area can have a significant impact on productivity and efficiency.

To address this issue, researchers have been exploring alternative battery technologies that can provide more power with less weight. One such technology is the use of solid-state batteries, which are lighter and more efficient than traditional lithium-ion batteries. Solid-state batteries have also a higher energy density, which means that they can store more energy per unit of weight. This makes them an attractive option for spraying drones, as they can provide the necessary power without adding unnecessary weight to the overall system (Tan et al., 2016; Famprikis et al., 2019).

In addition to battery technology, there are also efforts underway to optimize the overall design of spraying drones to minimize the energy consumption. For instance, the use of more efficient propellers and motors can help to reduce the overall energy demand of the drone (Zhang et al., 2021). Additionally, the use of sensors and other advanced technologies can help to optimize the spray application process, reducing the need of excess spraying, thereby conserving the battery power (Butts et al., 2019; Mahmud et al., 2021).

As this evolution is still unavailable to the farmers, they need to purchase and use generators to charge the extra batteries during the use of the drones. This increases both the investment in equipment and the running costs, as the generators are mostly run by gasoline.

Drones and helicopters, airplanes, and traditional sprayers

While the existing literature explores the efficiency and advantages of spraying drones, a comprehensive evaluation comparing the efficiency of these drones against other conventional spraying methods is very salutary, to enlighten the advantages and specificities of each equipment.

Traditional sprayers – The efficiency of traditional sprayers lies in their affordability, simplicity, and ease of operation. Farmers with limited resources and smaller land areas often rely on these sprayers for crop protection. Although they may not offer the same speed and coverage as their modern counterparts, traditional sprayers run at 40 km h^{-1} at maximum and carry more than 6.000 L of spray solution in their tanks (Deere & Company, 4101 JohnDeere Expy, Moline, Illinois, 61265, United States of America), providing farmers with a cost-effective means for managing pests and diseases, contributing to financially stable practices.

Moreover, traditional sprayers allow for greater control and flexibility for dosage and application. Farmers can manually adjust spray patterns and volumes based on specific crop requirements, which results in more precise and targeted treatments (Butts et al., 2019). The hands-on approach of traditional sprayers also allows farmers to closely observe the crop condition during spraying, making adjustments or addressing any issues promptly (Chen et al., 2019; Morales-Rodríguez et al., 2022).

Nonetheless, airplane sprayers have been a traditional method of crop spraying for several decades. These fixed-wing aircraft are renowned for their speed and efficiency in covering vast agricultural areas swiftly. Airplane sprayers are often preferred for large-scale commercial farming operations, due to their capacity to handle high workloads (Gregorio et al., 2015). Modern airplane sprayers have greater capacity than the old ones; today, they can carry more than 3.000 L of spray solution and spray at working speed up to 250 km h^{-1} (Air Tractor Inc. 1524 Leland Snow Way, Olney, Texas, 76374, United States of America).

The efficiency of airplane sprayers stems from their ability to cover extensive areas in a short amount of time (Li et al., 2022). With their high-speed capabilities, these aircraft can rapidly cover large fields, reducing the overall time and costs associated with spraying. Airplane sprayers are particularly beneficial in regions with flat topography, where accessibility and maneuverability are less challenging compared to those of helicopter sprayers (Zhang et al., 2018).

Additionally, airplane sprayers offer versatility for the variety of agrochemicals that can be applied, including seeds and fertilizers (Zhang et al., 2015; Shevchenko & Pasichnaya, 2020). Their larger storage capacities than the spraying drones, besides enabling prolonged operations without the need of frequent refilling, enhancing efficiency, and reducing downtime (Bravo-Mosquera et al., 2018).

Helicopter sprayers have long been employed in agricultural operations, particularly in medium to large-scale farms and hard to reach terrain. These aerial platforms offer certain advantages over traditional ground-based sprayers because of their ability to cover large areas quickly with excellent maneuverability, besides being capable of delivering a concentrated spray directly to the target area (Zhang et al., 2017; Seo & Umeda, 2021).

The efficiency of helicopter sprayers lies in their versatility and adaptability. They can navigate challenging terrains and reach areas that are inaccessible to ground-based sprayers (Montes et al., 2020). Additionally, helicopter sprayers have higher load capacities in comparison to spraying drones or airplane sprayers, which allows them to carry larger volumes of agrochemicals – up to 600 kg of products (Rotor Solutions Australia Pty Ltd. 16 Heron Court, Albury Airport NSW, 2640, Albury, Australia). This capacity enables them to spray larger fields in a single operation, minimizing the time and resources required for spraying.

Moreover, helicopter sprayers can take advantage of their hovering capability, which allows of precise targeting and controlled application of agrochemicals. By reducing the risk of overspray and drift, helicopter sprayers contribute to efficient resource use and less environmental impact (Sehsah, 2012).

To compare the efficiency of these spraying methods, several factors need to be considered. These factors include the size of the farming operation, the nature of the crops being sprayed, the terrain, weather conditions, and the specific goals and requirements of the farmer.

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As mentioned earlier, spraying drones excel in precision spraying, providing targeted and controlled application of agrochemicals. They are particularly effective in accessing hard-to-reach areas, which enables data-driven decision-making through real-time monitoring (Jiménez López & Mulero-Pázmány, 2019; Partel et al., 2019; Matthews, 2021). However, their load capacity and coverage area may be limited, in comparison to that by helicopter and airplane sprayers, making them more suitable for smaller farms or specific crop management needs (Villa et al., 2016; Jiménez López & Mulero-Pázmány, 2019).

Helicopter sprayers offer versatility and coverage, making them ideal for medium to large-scale farms with expansive fields and challenging terrains. They can carry larger volumes of agrochemicals and quickly cover extensive areas. The hovering capability of helicopters allows for precise targeting, ensuring effective treatment. However, their operational costs and requirements, such as skilled pilots and maintenance, should be considered (Sehsah, 2012).

Airplane sprayers excel in speed and coverage, making them highly efficient for large-scale commercial farming operations. They can rapidly cover vast areas, reducing overall spraying time and costs (Li et al., 2022). However, their precision and accuracy may be compromised, in comparison to those of spraying drones or helicopter sprayers. Factors such as altitude, speed, and potential drift may affect the dosage control and distribution (Bravo-Mosquera et al., 2018).

Traditional sprayers remain relevant for small-scale farming operations, providing cost-effective and customizable solutions (Morales-Rodríguez et al., 2022). While they may lack the efficiency and speed of modern methods, they offer flexibility and hands-on control, particularly in localized applications and specific crop management scenarios (Butts et al., 2019).

CONCLUSION

The potential of spraying drones in precision agriculture cannot be underestimated. They have emerged as a powerful tool for farmers, to increase productivity, efficiency, and sustainability. The benefits of spraying drones, such as lower running costs, faster spraying, and the ability to access difficult areas, are undeniable.

However, the challenges and limitations, such as low capacity, high acquisition cost, and regulations, need to be addressed for the technology to become widely adopted by farmers, especially the small-scale farmers.

The issue of batteries is crucial for the successful implementation of spraying drones in precision agriculture, and more research and development are needed to make lightweight, durable batteries that can meet the demands of the drone's power source.

The integration of spraying drones alongside existing spraying equipment and methods has the potential to revolutionize the efficiency and effectiveness of crop protection practices in the agricultural industry.

Despite these challenges, the use of spraying drones in precision agriculture is a step towards revolutionizing agriculture, and it is a promising technology that can significantly contribute to increase efficiency, sustainability, and profitability in farming. Further innovation and investment in this area are essential to fully accomplish the potential of spraying drones in precision agriculture, and to create a more sustainable and efficient agricultural sector for the future.

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