

Use of drones in herbicide spot spraying: a systematic review

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Abstract: Herbicide Spot Spraying (PLH, *Pulverização Localizada de Herbicidas*) using remote imaging, performed by low-cost drone, represents an innovative method in Agriculture 4.0. It enables the identification of areas with the highest weed infestation, allowing for targeted herbicide application in strategic locations. This approach reduces both the quantity of herbicides applied and their associated ecological and economic impacts. Therefore, this study aimed to assess the impact of PLH through remote sensing with low-cost drones on weed control. It was based on a systematic review following the Prisma statement, that analyzed the evolution of remote sensing in agriculture, the economic and environmental impacts,

drone imaging technology and future prospects. In total, 26 works were selected, most literature focused in field monitoring by drones for weed control than for herbicide pulverization. Based in the synthesis of the existing literature through the PLH it is possible to reduce the quantity and volume of herbicide applications performed in the harvest, with greater efficiency and agility in controlling weeds, since, currently, the control of these invaders represents one of the most important challenges for agriculture, as these plants adapt quickly, developing resistance to new herbicide molecules, reducing productivity, contaminating food, reducing its quality, and consequently, raising final production costs.

Keywords: Localized spraying; Weed; Drone; Spot spraying.

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1. Introduction

Herbicides constitute one of the primary means to combat weeds in agricultural crops. However, the use of herbicide products with a high level of toxicity poses risks to human and animal health, as well as the environment, especially when employed without proper control measures. The most prevalent application method in today's market is conventional spraying, which is associated with issues like excessive herbicide application in areas deemed weed-free, leading to the degradation of fertile soil intended for cultivation. Furthermore, this method can contaminate pastures, indirectly impacting the health of grazing animals, resulting in economic losses in all these scenarios.

Brazil ranks among the world's top consumers of agricultural pesticides (FAO, 2021). The health risks and handling hazards are attributed more to "incorrect use" than to formulation toxicity or the widespread adoption of the agrochemical production model (Abreu, 2014). However, it's crucial to note that agribusiness contributes significantly, accounting for 27.4% of Brazil's GDP, as calculated by the Center for Advanced Studies in Applied Economics at the University of São Paulo (Cepea-USP) in collaboration with the National Confederation of Agriculture and Livestock (CNA). According to the Emater Institute 2018, approximately 46% of herbicide applications result in wastage due to human error. This underscores the critical need to expand research efforts in order to improve decision-making accuracy.

In an effort to reduce the volume of herbicide applied, minimize excessive losses from drift, and enhance operational efficiency and product yield, there has been a growing interest in exploring new methods, such as localized application. Through localized application, it is possible to achieve herbicide savings of around 69% to 79% in areas with low infestation levels (Castro et al., 2018). In essence, the localized application system is designed to deliver the herbicide directly to the target in the correct amount. In this system, remote sensing with drones is typically employed to pinpoint the target area. Remote sensing has found application in monitoring the quality of field crops, leveraging its capacity to gather extensive information via aerial photography (e.g. utilizing drones), satellite imagery, and other means. With the expertise of a qualified professional, it becomes feasible to conduct a precise diagnosis based on the acquired images.

The primary goal of pulverization technology is to deliver the correct amount of active ingredients onto the desired target, maximizing efficiency and cost-effectiveness while minimizing environmental impact (Durigan, 1989). Johnson et al. (1997), Stafford and Benloch (1997) and Antuniassi (1998) have proposed three distinct approaches for achieving localized herbicide application using different technologies. The first technology demonstrates the capability to real-time weed detection through digital cameras and sensors. This information is promptly processed, allowing for immediate spot spraying of herbicides exclusively in the required areas. However, it's important to note that this technology is sensitive and precise, requiring continuous calibration throughout the application process. The second technology involves weed mapping, where the mapping procedure is conducted prior to the spraying process. Subsequently, the recommended dosage for each location in the area can be accurately applied. However, this approach requires a positioning system to be effective. The third approach is linked to the localized application of pesticides based on the spatial variability of soil factors. Herbicide dosages can be adjusted according to variations in the previously mapped soil, forming the foundation for the construction of the prescription map.

Among the strategies for adopting Herbicide Spot Spraying (PLH), low-cost drones, also known as UAVs (Unmanned Aerial Vehicles), stand out as an excellent option. These drones employ imaging and data processing systems to generate georeferenced weed maps, which can be adapted to various spraying machines, including self-propelled sprayers, tractor-trailed sprayers, and spraying drones, commonly used in Brazil. Drones offer distinct advantages, aligning with modern PLH concepts, as they enable autonomous field imaging and execution of pre-programmed missions. When another drone is utilized for the spraying phase, it also conducts autonomously piloted missions based on the PLH map generated earlier. The combination of these two drones, one for imaging and the other for spraying, elevates the PLH system to a fully autonomous flight system, eliminating the need for an operator on board of any machine at any point in the process. This approach seems to minimize input usage, applies to areas with varying accessibility levels, enhances weed control, reduces crop phytotoxicity, boosts average productivity, and results in higher-quality industrial or direct-consumption agricultural products. In light of the aforementioned information and the significance of drone technology in modern agriculture, this comprehensive review aims to thoroughly investigate and evaluate the multifaceted utilization of drones as instrumental tools for enhancing weed control strategies within the context of PLH. This review will delve into the various aspects of drone-based solutions, including their capacity for precise imaging and data processing, georeferencing of weed

maps, adaptation to diverse spraying equipment, and the potential for fully autonomous mission execution. By exploring the synergistic use of drones for both field imaging and subsequent herbicide application, this study seeks to provide valuable insights into the operational efficiency, economic feasibility, and ecological benefits of incorporating drones into PLH systems.

2. Methods

A literature review was conducted, focusing exclusively on scientific studies that analyzed the impact of herbicide spot spraying (PLH) using drones. To guide our data collection planning, we adapted the step-by-step framework proposed by Parahoo (2006), which encompasses five distinct stages (Table 1).

Table 1 - Steps associated with planning data collection for this study

Phases	Description
1	Definition of the theme and guiding question of the study (PICo)
2	Definition of selection criteria (inclusion and exclusion of articles)
3	Selection of databases and descriptors to access the literature
4	Data collect
5	Analysis of results

Source: Adapted from Parahoo (2006)

To formulate the research question for this study, we followed an adaptation of the PICo strategy developed by Araújo (2020). This strategy employs an acronym representing the problem (P), phenomenon of interest (I) and context (Co). In this context, "P" signifies Weeds, "I" represents Drones, "Co" pertains to Herbicide Spot Spraying (PLH). In this way, the guiding question of this study was: "How is weed control achieved through the utilization of drones within the context of Herbicide Spot Spraying (PLH)?" To address this question comprehensively, we conducted a systematic search for scientific papers in November 2022. The database search was conducted across multiple platforms, including the Scientific Electronic Library Online (SciELO), Directory of Open Access Journals (DOAJ), Periódicos CAPES, and Google Scholar databases. Several descriptors were selected for this research, including "weed," "drone," "Remotely Piloted Aircraft System," "Unmanned Aerial Vehicle," and "precision spray" (refer to Table 2 for details). To efficiently encompass all these descriptors and minimize the inclusion of irrelevant results, a standardized search string was employed across all databases: ("weed" AND (drone OR Remotely Piloted Aircraft System OR Unmanned Aerial Vehicle) AND "precision spray"). In addition, within the Google Scholar

database, an alternative search was conducted using the same descriptors in Portuguese to broaden the search scope to articles published within the national/regional/local context, particularly those directly relevant to precision agriculture in Brazil. The search string employed for this purpose was (“plantas daninhas” AND (drone OR “Aeronaves remotamente pilotadas” OR “Veículo Aéreo Não Tripulado”) AND (“pulverização localizada” OR “pulverização de precisão”)).

Our inclusion criteria were limited to original articles published between 2004 and 2022, irrespective of language, and encompassing research conducted both within Brazil and internationally. Articles with relevant titles and abstracts related to the study’s theme were included, while duplicate entries within the searched databases were excluded from consideration. In addition, a complementary literature search involving citation-based selection, internet research, and library exploration was conducted. This method yielded scientific articles, government reports, theses, dissertations, and event abstracts for inclusion to avoid publication-bias in the search process (KORICHEVAoricheva *et al.*, 2013).

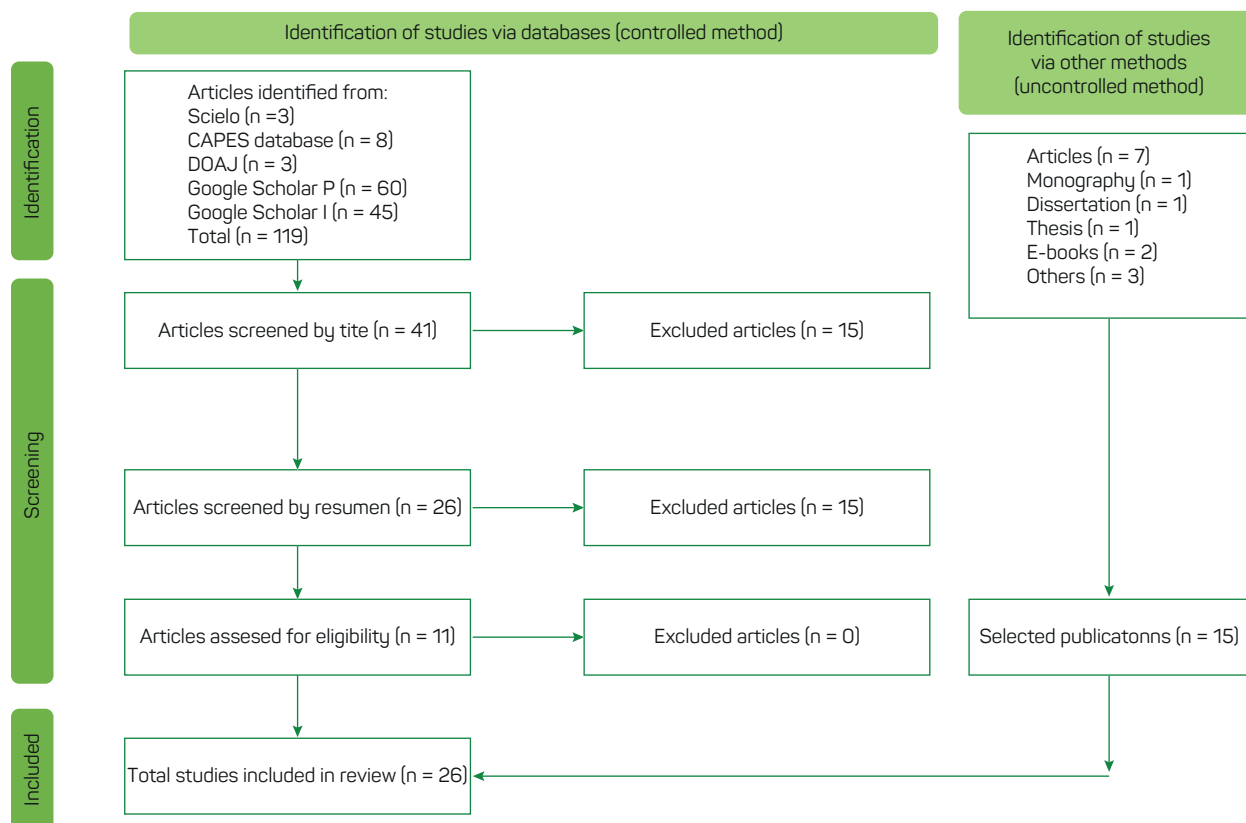
Table 2 – Description of the PICo strategy with definition of descriptors in English and Portuguese

Acronym	Definition	Descriptor (s)
P	Problem	English: Weed Portuguese: <i>Plantas daninhas</i>
I	Interest	English: Drone; Remotely Piloted Aircraft System; Unmanned Aerial Vehicle Portuguese: <i>Drone; Aeronave pilotada remotamente; Veículo Aéreo Não-tripulado</i>
co	Context	English: Precision spray Portuguese: <i>Pulverização localizada; Pulverização de precisão</i>

2.1 Selection and analysis of articles

The article selection adhered to the PRISMA guidelines with adaptations (Page *et al.*, 2020) (Figure 1). We conducted a descriptive analysis and organization of the chosen studies. Data collection encompassed year, authorship, country of origin (Figure 2), and insights into the evolution of remote sensing in agriculture, economic and environmental impact, drone imaging technology (Table 3), and future prospects. This article searches and selection process took place in November 2022.

PRISM 2020 Flowchart for news reviews systematic what include searches in bases in Dice, protocols and others sources



Source: Based on Page *et al.* (2020), with adaptations

Figure 1 – Prism Flow Diagram of article selection

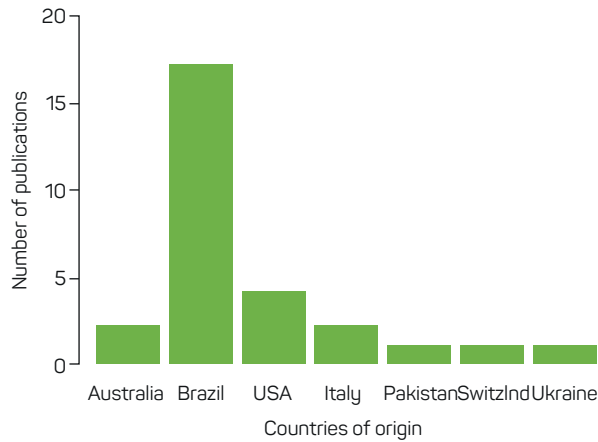


Figure 2 - Number of publications according to country of origin

3. Results and Discussion

In this review, we analyzed a total of 26 works, comprising scientific articles and various technical documents. It is worth noting that a significant portion of these studies were produced by Brazilian researchers (Figure 2), involving a range of one to eight authors, totaling 74 contributors across all the works. When examining the year of publication, a clear trend emerged, with the majority of these works being published from the year 2020 onwards, thus highlighting the innovation associated with the use of drones in PLH (Figure 3). Most literature is focused in field monitoring than the process of pulverization itself.

Table 3 - Description of works selected in the databases which address the impact of herbicide spot spraying (PLH) and imaging by drones

Technology used	Impacts	Crop	Effect	Economic/ Environmental	Type	Year	Authors
Drone used in herbicide spot spraying							
Precision spray equipment and consumer-grade UAV technology		NA	positive	both	article	2020	Jensen et al.
RBG imaging to create orthomosaic and further spray map		NA			article	.	.
Ground truthing system compared to whole paddock spraying	Provides a pragmatic and inexpensive spray system that can be used with contemporary precision spray systems.	NA	positive	economic	article	.	.
Drone used in crop monitoring/imaging							
Advanced sensors and imaging technology	Optimize processes and reduce costs.	cotton	positive	economic	tesis	2018	Silva A.
.	Provides valuable data for precision agriculture.	cotton	positive	economic	tesis	.	.
.	Helps to identify areas of concern such as pest infestations or nutrient deficiencies.	cotton	positive	both	tesis	.	.
.	Improves operational efficiency by reducing the time and labor required for tasks such as crop scouting, mapping, and monitoring.	cotton	positive	economic	tesis	.	.
.	Contributes to sustainable production practices by minimizing environmental impact through precise application of inputs and waste reduction.	cotton	positive	environmental	tesis	.	.
Real-time object detection algorithms (Faster R-CNN and YOLOv3)	Deep learning algorithms in an embedded system can provide a more efficient and selective approach to weed control in agricultural settings.	rape and viola in cotton and soybean crops	positive	economic	article	2022	Saboia et al.

Continue...

Table 3 - DContinuation

Technology used	Impacts	Crop	Effect	Economic/ Environmental	Type	Year	Authors
Deep learning method based on RGB imagery taken by a unmanned aerial vehicle	The system achieves an average accuracy of 95.3% in identifying weeds and an overall average accuracy of 94.73% for both crops and weeds.	peas and strawberries	positive	economic	article	2021	Kahn
Low-cost UAV (Parrot Anafi) with RGB	Reduces costs and accelerate the development of free tools for smart agriculture worldwide.	Corn	positive	economic	article	2021	Mattivi et al.
Mapping using high-resolution orthophotos	Permits the identification and analysis of weeds in both rows and interrows.	Corn	positive	economic	article	.	.
Weed mapping during harvest	Weed mapping during harvest underestimated the infested area by 6% compared to mapping after harvest using the grid method. The two methods were coincident in 45% of the marked area.	Corn	positive	economic	article	2004	Shiratsuchi et al.
Use of productivity monitors with the option of recording events like weed flags during harvest		Corn	positive	both	article	.	.
Unmanned aerial vehicle	Optimize processes, reduce costs and minimize environmentl impacts	NA	positive	both	article	2017	Chiacchio et al.
Drone use in general for agriculture 4.0	Optimize processes, reduce costs and minimize environmentl impacts	NA	positive	economic	article	2018	Villafuerte et al.
Unmanned aerial vehicle	Identify areas for aerial photography, monitoring agricultural areas, and areas prone to environmental problems	NA	positive	environmental	article	2020	Oliveira et al.
	Precise data collection, processing, and analysis	NA	positive	economic	article	.	.
Conservation Drone' or surveying and mapping forests and biodiversity	Highlighting the potential of the system for environmental and conservation applications	NA	positive	environmental	article	2013	Pin Koh & Wich
	Flight time of ~25 minutes and over a distance of ~15 km	NA	positive	environmental	article	.	.
	Recording of high-definition videos and acquisition of aerial photographs with pixel resolution of <10 cm, which can be stitched together to produce real-time geo-referenced land use/cover maps of surveyed areas.	NA	positive	environmental	article	.	.

3.1 Evolution of remote sensing in agriculture

The evolution of drones began with early attempts in 1849 when Austria used balloons with bombs in Venice, Italy, though these lacked control (Nardini, 2016). In 1898, the US Army employed cameras on kites for reconnaissance (Buzzo, 2015), while Nikola Tesla pioneered remote control technology in the same year (Tesla, 1898). World War II witnessed Germany's use of V-1 guided bombs, resulting in catastrophic consequences. In 1908, Júlio Neubronner patented pigeon-borne cameras, later employed by the

CIA during the Cold War (Santos, 2018). Israel's Chukar drone in 1973 marked a breakthrough with real-time data transmission (Silva, 2018). Technological advances led to quadcopter models like the AR Drone in 2010 and DJI's Phantom, transforming the drone industry (Webster, 2011). The rapid evolution of drone technology includes advancements such as obstacle sensors, high-resolution cameras, and camera stabilizers (Rodrigues, 2020).

Drones serve a wide range of purposes beyond imaging, including agriculture for pesticide spraying, product

delivery, and public safety (Rodrigues, 2020). UAVs offer advantages over UTVs, particularly in challenging conditions such as high-humidity soils, waterlogged areas, or areas with obstacles like stones and branches (Esposito et al., 2021). Current remote sensing technologies are moving towards real-time processing and IoT integration, automating processes from injury detection to data processing and application (SABOIA et al., 2022). Remote sensing with drones differs from satellites in terms of resolution measures: spatial resolution (smallest observed area size), spectral resolution (captured electromagnetic spectrum), and temporal resolution (number of visits to the same target). Drones excel in temporal and spatial resolution, while satellites offer superior spectral resolution (CHIACCIO et al., 2016). The use of drones in agriculture is experiencing significant commercial growth, offering precision, control, and data management benefits (Barbosa Júnior et al., 2022).

3.2 Economic impact

Farmers' main concern is often profitability, influenced by feasibility and investment costs. Large farms are more inclined to adopt Precision Agriculture Technologies (PATs) to deal with weed infestations driven by their access to information and market pressures. On the other hand, smaller farmers may adopt a more conservative stance towards technological innovations (Mattivi et al., 2021).

Weeds, often referred to as invasive plants, significantly impact agricultural production by affecting productivity, food quality, and production costs. This term doesn't exclusively relate to a specific plant species but encompasses any plant that disrupts the intended agronomic management (Barbosa Junior et al., 2022). Crop areas function as open ecosystems, thus are influenced by external factors leading to the common presence of unwanted plants. Invasive plants compete with crops for essential resources like water, light, and nutrients, necessitating specialized management (Barbosa Junior et al., 2022). Weed control in cropland is complex due to resistance to common herbicides, demanding specific and often costly management strategies, especially with rising input costs (Rosa, 2021). Common practice involves applying herbicides across the entire area, whether through trailed sprayers, self-propelled machinery, or drones. However, this approach isn't always ideal, as it may lead to herbicide wastage and environmental contamination when applied in non-weed areas (Marini, 2014).

The integration of drones in agriculture has led to increased interest from non-traditional professionals due to the infusion of technology into agribusiness. Drones not only impact farming practices but also influence the consumption of agricultural inputs. Enhanced knowledge and detailed rural monitoring can lead to the acquisition of specialized, environmentally friendly inputs (Anziliero, 2021). Drones offer economic benefits, improving labor

efficiency and safety in agriculture due to remote piloting (Chiaccio et al., 2016). Drones come in imaging and spraying types. Fixed Wing drones cover vast areas efficiently with extended flight ranges. Multirotor drones provide high-resolution images and easy data processing. In contrast, spraying drones include Smaller Drones, optimized for ease of operation, and Larger Drones, offering efficient coverage (Chiaccio et al., 2017). The Spray Specific Weed Management (SSWM) system by Shahbaz Khan et al. (2021) aims to efficiently control weeds by precisely managing herbicide application. It relies on georeferencing through remote sensing to monitor weed patterns and adapt herbicide dosage accordingly. This system is still in development but holds the potential to accurately identify and control weeds in agricultural areas (Khan et al., 2021).

3.3 Environmental impact

Utilizing drones for remote sensing enables the precise delineation of areas impacted by weed infestations and other agricultural injuries, facilitating a more judicious use of agricultural inputs (Anziliero, 2021). This approach aligns with a conservationist ethos, where the application of chemical or biological inputs is restricted to areas confirmed to be afflicted through remote sensing. This promotes more efficient and environmentally friendly agricultural practices, preserving the natural ecosystem while ensuring input application only where necessary. Different remote sensing techniques enable precise georeferencing of individual weeds or populations, allowing for targeted herbicide application. This reduces input usage and prevents herbicide application where not needed (Shiratsuchi et al., 2004). Such precision benefits both cost-effective weed control and environmental conservation by minimizing non-target area impact.

3.4 Drone imaging technology

The term "Agriculture 4.0" emerged during the 2011 Hannover Conference, aiming to integrate technology with agricultural production for better decision-making by producers (Ribeiro, Sulaiman, 2020). Meeting the increasing demand for food and electricity due to population growth while promoting sustainability is a significant challenge (Villafuerte et al., 2018). Agriculture 4.0 addresses this challenge using technologies like Big Data Analytics, cloud storage, IoT, Machine Learning, wireless sensors, and drones (Ferreira et al., 2021). These technologies, when managed effectively, lead to improved financial health and increased productivity in Brazilian rural properties (Zaparolli, 2020). Identifying where these technologies can be applied, such as crop monitoring, is crucial.

Drones have become ubiquitous in daily life, serving diverse functions, ranging from leisure activities to aiding firefighters in identifying fire outbreaks. They come in various models, shapes, and sizes, catering to a wide array

of purposes. Among these, military origins have played a pivotal role in driving advancements in drone technology. Since their inception to the present day, drones have witnessed significant progress in communication methods between control systems and the drone itself, resulting in enhanced autonomy and extended flight distances. Additionally, there have been notable improvements in flight quality and sensor capabilities, which have revolutionized data collection and utilization. These developments, among other factors, have underscored the growing significance of drones (Costa, 2019).

To enhance remote image capture beyond satellite-based sensing, Remotely Piloted Aircraft (RPAs), or drones, have emerged. Drones fly at lower altitudes than satellites, minimizing issues like cloud interference. They offer greater control over spatial and temporal resolution, with advancements in communication methods, autonomy, flight quality, and sensor technology. These developments have made drones increasingly valuable for capturing information periodically and with finer spatial detail (Oliveira et al., 2020). Additionally, onboard cameras on RPAs produce images with pixel sizes as small as 2 to 3 cm, significantly surpassing the spatial resolution of freely distributed satellite imagery (Koh, Wich, 2012). Building on this, acquiring images in different electromagnetic spectrum bands involves modifying the camera, such as adding filters or substituting it with other sensors. These adjustments expand the range of data available for calculating vegetation indices. Nevertheless, RGB sensors offer an outstanding cost-benefit ratio. They not only enable the extraction of indices from the interplay of the three bands (red, green, and blue) but also facilitate the creation of additional products like orthomosaics and 3D models, utilizing specialized geoprocessing software (Andrade et al., 2019).

Creating georeferenced orthomosaics using RGB data involves rectifying individual images with GPS data and compiling them into a comprehensive image covering the entire area. In contrast, multispectral sensors offer a broader range of data for vegetation index calculations, thanks to their greater number of radiometric bands (Esposito et al., 2021). On the other hand, hyperspectral sensors can record hundreds of narrow radiometric bands across the visible and infrared electromagnetic spectrum. However, working with hyperspectral applications can be more complex due to the need to select the appropriate number of radiometric bands for specific objectives. Each band or set of bands can be tailored to detect different field characteristics, necessitating a well-defined survey objective to make the correct sensor choice (Esposito et al., 2021).

Artificial Intelligence (AI) and deep learning are pivotal in revolutionizing weed recognition in agriculture, providing efficient strategies for weed management. These technologies harness high-resolution images obtained from drones and aerial platforms to identify and classify various weed species. Deep learning models, trained

on extensive datasets of weed images, excel at precisely detecting and categorizing weeds, empowering targeted and precise weed control measures. This automation aids farmers in early weed detection, enabling timely intervention to prevent weed competition with crops. By automating the weed recognition process, AI and deep learning technologies save time and reduce the need for manual labor in weed monitoring and management. Moreover, accurate weed recognition through AI supports the development of site-specific weed control strategies, curbing herbicide usage and minimizing environmental impact. Overall, the integration of AI and deep learning elevates weed management practices in agriculture, fostering improved crop yield and sustainable farming practices (Hafeez et al. 2022).

3.5 Future perspective

The utilization of UAVs for monitoring has been steadily increasing, driven by the emergence of new technologies that offer practical and efficient solutions to the evolving needs of the field (CHIACCIO et al., 2016). This trend is particularly evident in the realm of precision spraying, where prescription maps, developed using weed recognition algorithms based on UAV-captured orthophotos, yield numerous advantages. Beyond the economic benefits of judiciously applying the required amount of herbicides only to areas in genuine need, there are also important considerations regarding environmental and health aspects, stemming from the reduction in herbicide usage (Anziliero, 2021). However, there remains a notable gap in the availability of a comprehensive and automated system for generating herbicide application maps tailored for use with precision spraying equipment. Existing systems in the market do not offer direct and automated image capture, data processing, and application control (Jensen et al., 2020).

4. Conclusion

Drone services in agribusiness represent a rapidly evolving niche market with immense potential to revolutionize agricultural practices and resource consumption. Notably, these UAVs operate on battery power, offering a sustainable alternative to fossil fuels. However, to fully unlock their benefits, further research and exploration of these technologies are imperative.

One remarkable application of this technology is PLH, which holds the promise of significantly reducing both the quantity and volume of herbicide applications during the growing season. This approach brings increased efficiency and agility to weed control, resulting in reduced diesel consumption in equipment and a subsequent decrease in carbon dioxide emissions—a notable step towards environmental and economic sustainability. Moreover, the PLH system's precision in identifying areas infested with invasive plants ensures that herbicide application is targeted

exclusively where needed. This not only curtails herbicide usage but also alleviates plant competition in the field. As a result, higher average productivity in the surveyed area is anticipated, leading to improved profitability for the farmer by reducing management costs.

In essence, the integration of drone technology and precision agriculture, exemplified by the PLH system, offers a transformative approach to sustainable farming. It aligns environmental responsibility with economic viability, paving the way for a more efficient, environmentally friendly, and economically sustainable future for agriculture.

Authors' contributions

FLLN: conceived, designed the work and participated in the selection of articles. RFS and JLH: were dedicated to oversight and coordination. ALA: was dedicated to the research and selection of articles, while authors JAJ, FG, JACS, and MP: were dedicated to review and final adjustments. All authors critically reviewed the manuscript and approved the final version.

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