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REVIEW

Drone Technology Reshaping Agriculture: A Meta-Review and Bibliometric Analysis on Fertilizer and Pesticide Deployment

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Abstract

Purpose This study aims to uncover recent research trends and primary focal points associated with the use of drones in the application of fertilizers and pesticides within the agricultural sector. The research seeks to explore the global impact of agricultural drones, highlighting their benefits in reshaping traditional farming practices and promoting sustainable agriculture.

Methodology A bibliometric analysis was conducted, reviewing 46 academic publications from 2015. This comprehensive review aggregated findings related to the use of drones in fertilizers and pesticides applications, focusing on the advancements, benefits, and future potential of drone technology in modern agriculture.

Results The integration of drones in agriculture has shown a notable reduction in pesticide usage, ranging from 30 to 65% compared to conventional methods like knapsack spraying. Additionally, the application of pesticides and fertilizers via drones has led to crop yield increases of 3.6% to 9.7%, thereby enhancing food production. Drones have also demonstrated effectiveness in pest control, with rates between 63.7% and 94.94%, reducing the reliance on chemical pesticides. Furthermore, drones contribute to significant water conservation, with potential reductions in water usage by up to 90%. The ability to cover 2 to 6 hectares per hour enables rapid response to agricultural challenges, improving pest and disease management.

Conclusions Drones offer substantial benefits in modern agriculture, promoting eco-friendly practices, enhancing efficiency, and contributing to sustainable food production. The future of agricultural drone technology lies in enhancing capabilities such as extended flight durations, increased payload capacities, and integrating artificial intelligence for data-driven decision-making. These advancements are likely to encourage the widespread adoption of drones, fostering sustainable, efficient, and environmentally friendly agricultural practices on a global scale.

Keywords Bibliometrics · Drone · Meta-analysis · PRISMA · UAV

Introduction

In response to the expanding global population and the escalating impacts of climate change, there is an urgent requirement to improve global food production (Thierfelder et al., 2018). Agriculture, as the primary food source globally, faces significant challenges due to increasing food prices, concerns about food safety and security, and the need for environmental protection, water conservation, and sustainability (Friha et al., 2021; Inoue, 2020). The world population is projected to reach 9.7 billion people by 2050, indicating an anticipated continuation of this demographic trend (Rejeb et al., 2022). People's nutritional needs cannot be met efficiently by traditional farm management. Additionally, several pests and plant diseases endanger an adequate supply of plant goods. The environmental issues and demand for more workers grow along with the scale of the farms (Shahrooz et al., 2020). In developing nations, approximately 25 million cases of symptomatic pesticide poisonings have been documented among agricultural laborers. Nagenthirarajah and Thiruchelvam (2010) emphasized that acute pesticide

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poisoning posed a significant threat to farmers in Sri Lanka, particularly those who manually applied pesticides through handheld sprayers. This resulted in a multitude of health issues (Tsimbiri et al., 2015).

Information and communications technology (ICT) services, particularly through the Internet of Things (IoT) and the rapid development of unmanned aerial vehicle (UAV) technology alongside picture data analytics, hold promise for addressing these critical concerns by offering effective Precision Agriculture (PA) solutions (Radoglou-Grammatikis et al., 2020). In Precision Agriculture (PA), satellite imagery is often prohibitively costly for the average farmer. Moreover, the resolution and quality of these satellite images are often insufficient and impractical due to weather conditions. On the other hand, aerial images taken by crewed aircraft offer better quality than satellite images but come at a high cost. In contrast, small Unmanned Aerial Vehicles (UAVs), commonly referred to as drones, are seen as a more cost-effective solution capable of delivering high-quality images (Matese et al., 2015; Zongjian, 2008). Drones can offer precise data about biomass levels, and their NDVI readings can be analyzed to draw valuable insights about crop health, including disease, water stress, pest issues, nutrient deficiencies, and other factors impacting crop output (Tucker et al., 2001). For example, Chin et al. (2023) demonstrated effective use of drone technology for detecting plant disease. Sun et al. (2023) showed use of UAV-based multispectral remote sensing imagery combined with DRIS method to diagnose leaf nitrogen nutrition status in a fertigated apple orchard. Advanced drones are valuable tools for farmers and drone pilots, enhancing various aspects of agricultural processes and increasing overall efficiency. This technology is employed in tasks such as crop monitoring, planting, livestock management, irrigation, and land mapping (Kumar et al., 2022).

In addition to crop monitoring, Unmanned Aerial Vehicles (UAVs) find application in Precision Agriculture (PA) for pesticide spraying. This practice originated in the 1980s in Japan, where unscrewed helicopters were paired with small pesticide tanks. Contemporary UAVs have advanced capabilities, equipped with sizable tanks, some exceeding 10 L in capacity, facilitating efficient pesticide application. (Radoglou-Grammatikis et al., 2020). Furthermore, these UAVs boast a liquid discharge rate that can exceed one liter per minute, enabling the rapid coverage of a hectare-sized crop area within a span of 10 min. UAVs have been extensively examined as a versatile technology in agriculture from various perspectives, including their use in agricultural spraying (Chen et al., 2021; Dou et al., 2022; Vitória et al., 2023; Xin et al., 2018; Zhichkin et al., 2023). In simpler terms, UAVs can use environmental data to accurately spray water and insecticides in specific quantities. Table 1 presents the advantages of using drones in agriculture spraying.

Several researchers have delved into the comparison of drone application with traditional spraying methods in agriculture. In various commercial spray situations, unmanned aerial vehicles (UAVs) have been used with low-volume applications, using fine and extremely fine droplets, promoting efficient and water-saving pesticide delivery (Wang et al., 2022).Comparing UAV treatments to Electronic knapsack sprayer (EKS) treatments, droplet deposition significantly increased (Vitória et al., 2023; Wang et al., 2023). In 2016, Qin et al. (2016) explored the use of a small UAV for pesticide spraying in China's hilly regions, demonstrating its high efficiency and minimal impact on rice crops. They examined the efficacy of UAV spraying for harvest aids, comparing it to ground-based field sprayers. Their findings indicated that the UAV achieved the required defoliation rate for mechanical harvesting when the spray volume exceeded 18 l/ha, and the flying speed remained below 5 m/s.

When the spraying duration and application doses are the same, the UAV's defoliation rate is similar to the field sprayers. This comparison used a single-rotor, helicopter-type UAV due to the distinct downwash wind field associated with multi-rotor UAVs (Cavalaris et al., 2022). Using agricultural drones for spraying offers the advantage of reducing chemical usage. While many pesticides are typically applied in liters per hectare, some are dosed per hectare, leading to significantly reducing in insecticide use. In contrast, when liters per hectare are employed, users often add extra pesticide to the spray solution to cover the area adequately. In traditional methods, if one liter of pesticide is sufficient, users may unnecessarily add two or three liters. The contemporary drone spraying approach ensures precise application of the recommended amount of insecticide on field and plant leaves, reducing usage by up to 30% (Shahrooz et al., 2020; Tewari et al., 2020). UAV use is rising as it is a safer and cleaner technology. the available fertilization options to generate grain with high Zn biofortification at minimal input costs (Xu et al., 2021). Unmanned aerial vehicles (UAVs) must take the place of conventional sprayers since the rural-to-urban migration of people results in high labor costs. Advancements in Unmanned Aerial Vehicle (UAV) technologies and the reduced weight of payload devices have led to significant changes in remote sensing for crop monitoring. This innovation saves money and time and catches non-destructive, high-resolution photos(Hafeez et al., 2023). Because of their superior plant protection capabilities, low volume spraying, low altitude, quick and uniform functions, and high efficiency, UAVs cannot be disregarded. UAVs have been quickly replacing manual sprayers in recent years (Hussain et al., 2022).

This systematic review's major goal is to give readers a thorough analysis of the most recent research on UAV-based drone spraying compared with traditional spraying. There were 46 journal articles were reviewed for this purpose,

Table 1 Key findings and research gaps in current studies on drone technology for agriculture

Authors & Year	Focus area	Key findings	Research gap
Matese et al., 2015	UAV-based remote sensing	UAVs provide high-resolution images for crop monitoring, offering advantages over satellite imagery	Limited studies on UAVs' effectiveness in varying climatic conditions and large-scale farms
Qin et al., 2016	UAV pesticide spraying and optimization	Optimized UAV spraying parameters (height 1.5 m, velocity 5 m/s) significantly improved droplet deposition and insecticidal efficacy on rice canopy, outperforming traditional methods	Need for further exploration of UAV spraying on different crops and terrains, and the impact of varying environmental conditions
Dos Santos Ferreira et al., 2017	Weed detection in soybean crops using ConvNets (CNNs)	Achieved above 98% accuracy in detecting and classifying broadleaf and grass weeds using Convolutional Neural Networks (CaffeNet), outperforming traditional machine learning techniques like SVMs, AdaBoost, and Random Forests	Further research needed to validate the method across different crop types, environmental conditions, and to integrate the detection system with automated herbicide application systems
Shahrooz et al., 2020	Precision agriculture and spraying drones	Spraying drones are efficient and reduce water usage but have limitations like battery life	Need for improvements in battery efficiency and addressing other limitations
Chen et al., 2021	Pest detection and pesticide application using edge intelligence and drones	Developed an intelligent pest recognition system using Tiny-YOLOv3 on NVIDIA Jetson TX2 to detect Tessaratoma papillosa in real-time. Optimized pesticide spraying routes using an agricultural drone, reducing pesticide use, environmental damage, and increasing crop yield	Future work could focus on expanding the system to detect other pests and integrate it with other smart farming technologies to enhance overall crop management efficiency
Friha et al., 2021	IoT-based smart agriculture	Comprehensive review of emerging IoT technologies (e.g., UAVs, SDN, NFV, cloud computing) and classification of IoT applications in smart agriculture; highlighted real projects using these technologies	Need for further research in blockchain integration and addressing open challenges in IoT applications for agriculture
Hafeez et al., 2023	Drone technology in agriculture	Analyzed drone technologies and their evolution over the past decade, focusing on crop monitoring and pesticide spraying in Precision Agriculture. Discussed innovations in drone structure, sensor development, spot area spraying, and the application of AI and deep learning for remote crop monitoring	Lack of Integration of advanced AI and sensor technologies to enhance drone performance and efficiency in agriculture

and the information from those reviews was used to create a database. This database was used to study the effect of drone spraying on water and pesticide use, crop yield, the efficacy of insecticides/pesticides and operation time (ha/hr).

Methodology

Bibliometric Analysis

A bibliometric analysis was performed in the present study, to investigate the performance of drone applications in agricultural spraying. The intellectual framework of the knowledge domain is revealed by this quantitative methodology, along with the existing state, trending issues, and possible future research directions (Martins et al., 2023). Using the *VOSviewer* software (Centre for science and technology studies, Leiden university, The Netherlands), all keywords were checked for co-occurrence (Andreo-Martínez et al., 2020). A bibliometric study, commonly used for extensive datasets, summarizes existing literature to uncover hidden communication patterns and discipline development (Rejeb et al., 2022).

Bibliometric methods, such as citation analysis, co-citation analysis, bibliographical coupling, co-author analysis, and co-word analysis, provide a quantitative approach to mapping and evaluating scientific literature (Zupic & Čater, 2015). Originating with Eugene Garfield's work in the mid-twentieth century, these methods have evolved to manage extensive data volumes, highlighting influential papers, research networks, and emerging trends. While offering objectivity and scalability, the reliance on database accuracy and quantitative measures means that qualitative aspects and long-term trends may be overlooked. Thus, integrating these methods with qualitative reviews can offer a more comprehensive understanding of research fields (Donthu et al., 2021).

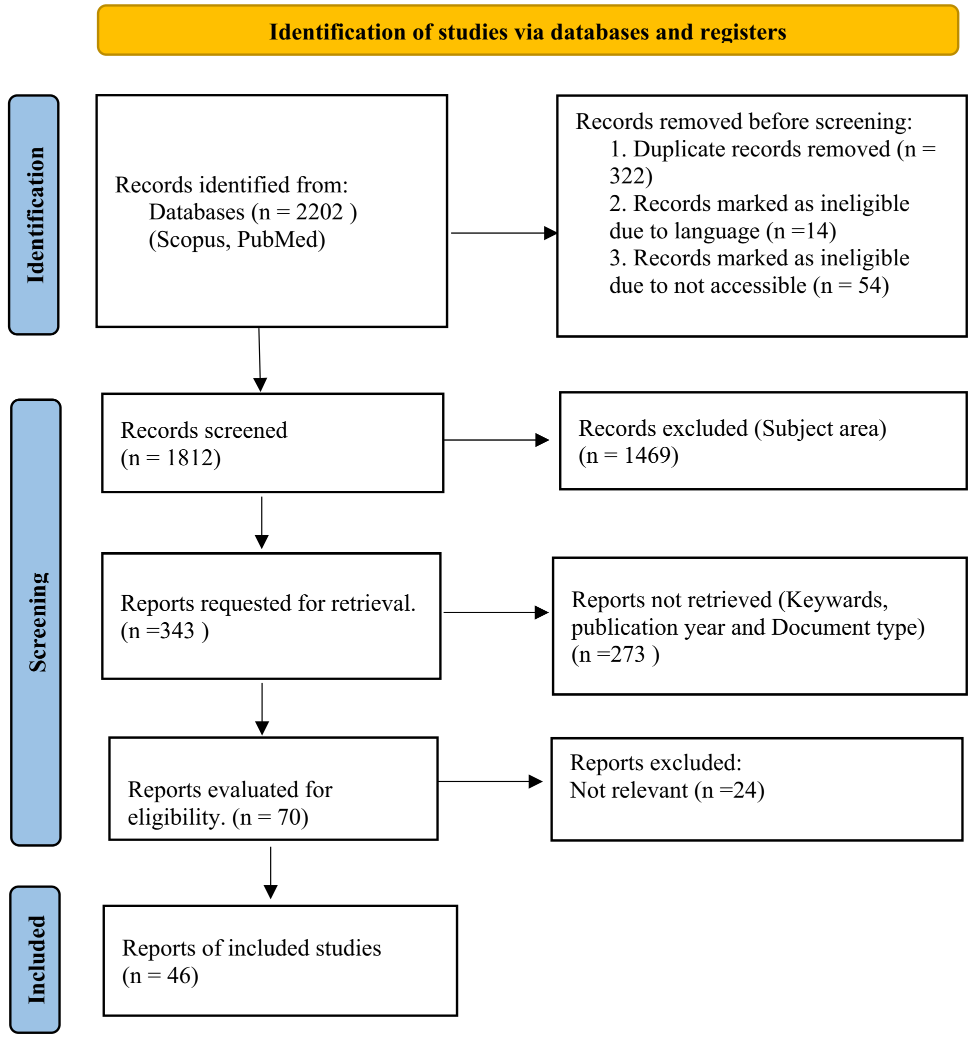
PRISMA Guidelines

The *PRISMA* guidelines were used as the foundation for this systematic review's technique to collect pertinent documents. Figure 1 shows the flowchart procedure for this study. On August 2, 2023, the *Scopus* and *PubMed* databases were searched to gather pertinent scholarly publications for the identification phase. Scopus (the largest database of bibliometric information indexed more than 94 million scholarly records and over 29,200 active 141 serial titles from 7000 registered publishers with 2.4 billion cited references) was chosen for its extensive journal coverage and robust citation analysis capabilities, offering about 20% more coverage than Web of Science and aiding in comprehensive citation tracking and keyword searching (Falagas et al., 2008). According to Pranckutė (2021), Scopus was shown to perform better than Web of Science both in regard to precision and sensitivity. However, nearly all the documents retrieved from the Scopus and PubMed in this study were covered by the Web of Science. PubMed was selected for its optimal update frequency and free access, making it the best resource for the latest drone literature and current research. Furthermore, Scopus provides a more comprehensive coverage of the scientific literature compared to Ei Compendex, with similar focus on the engineering field. Because our study primarily concentrates on the latest research, we only chose papers that were published in 2015 and after. Along with subject ("Agriculture"), source type ("Journal and Conference publications"), publication year ("Above 2015"), keyword ("drones," "UAV," "unmanned aerial vehicle," and "Agricultural" and "pesticides/fertilizers"), language ("English"), and document type ("Article and Conference Paper"). On the basis of these parameters, we also limited the search results. Due to these restrictions, the search results were whittled down to 70 documents that were evaluated for eligibility before being retrieved for subsequent processing. When we screened the 70 papers, we looked at their titles and abstracts and discovered that 24 records were not relevant to this study. All 46 documents that were included in the current evaluation underwent comprehensive full-text screening by the authors. Given that this research relies on a total of 46 publications, including conference papers, it is important to address potential concerns regarding the robustness of the results. Indeed, we applied strict inclusion criteria to ensure that all sources, regardless of publication type, met high standards of relevance and methodological quality. Conference papers can vary in review rigor compared to peer-reviewed journal articles, which may impact the perceived reliability of the findings. Therefore, conference paper was selected based on their impact, citation count, and the reputation of the conference. We cross-referenced findings from conference papers with those from peer-reviewed journal articles to validate the consistency and reliability of the results. Where discrepancies were found, they were noted and discussed.

Findings and Discussion

The changes in publishing output in the recently published literature on agricultural drones are studied. Figure 2a and 3b depict the temporal distribution of scholarly research from *Scopus* and *PubMed* datasets respectively. From the year 2015 (13 publications), a sharp increase in publications was observed (Fig. 2a), and from the year 2016 (10 publications), a sharp increase in publications was observed (Fig. 2b). In Fig. 2a and b, we observed an average of four papers published annually between 1993

Fig. 1 Flowchart describing the systematic review process

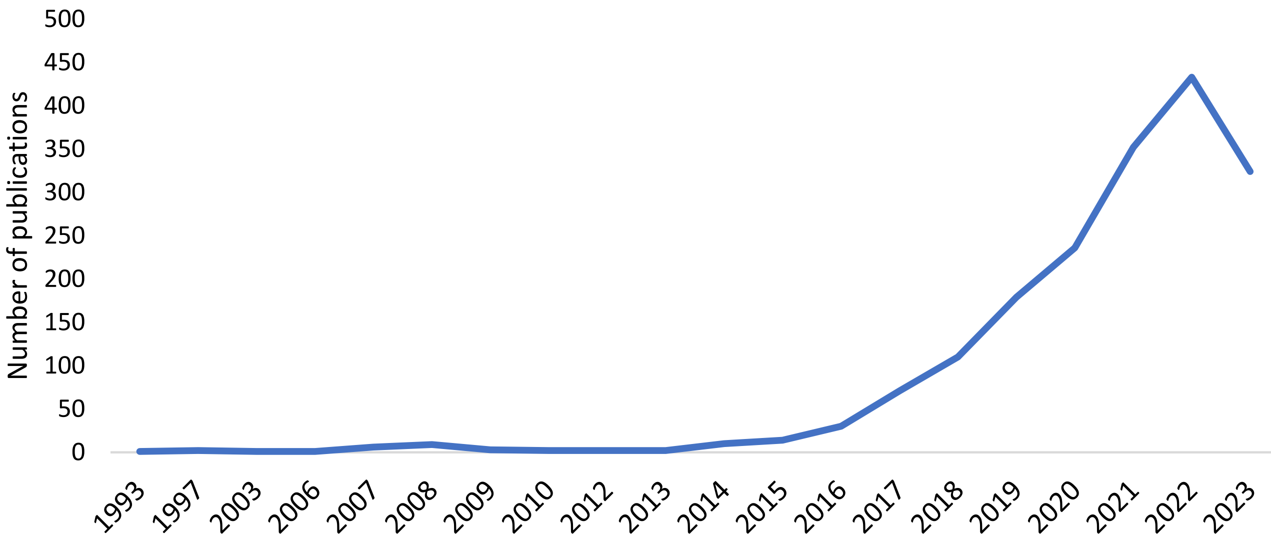


and 2015. Since 2015, more publications have indicated, the growing interest among researchers and the usage of drones for crop spraying and crop health monitoring (Xin et al., 2018). Particularly, there were 433 publications in 2022 compared to 17 in 2015. A total of 1,752 and 367 articles were published between 2015 and 2023, as shown in Fig. 2a and b, respectively. As a result, we chose to emphasize our analysis on the growth stage since it encompasses the most recent and crucial advancements in agricultural pesticide and fertilizer spraying.

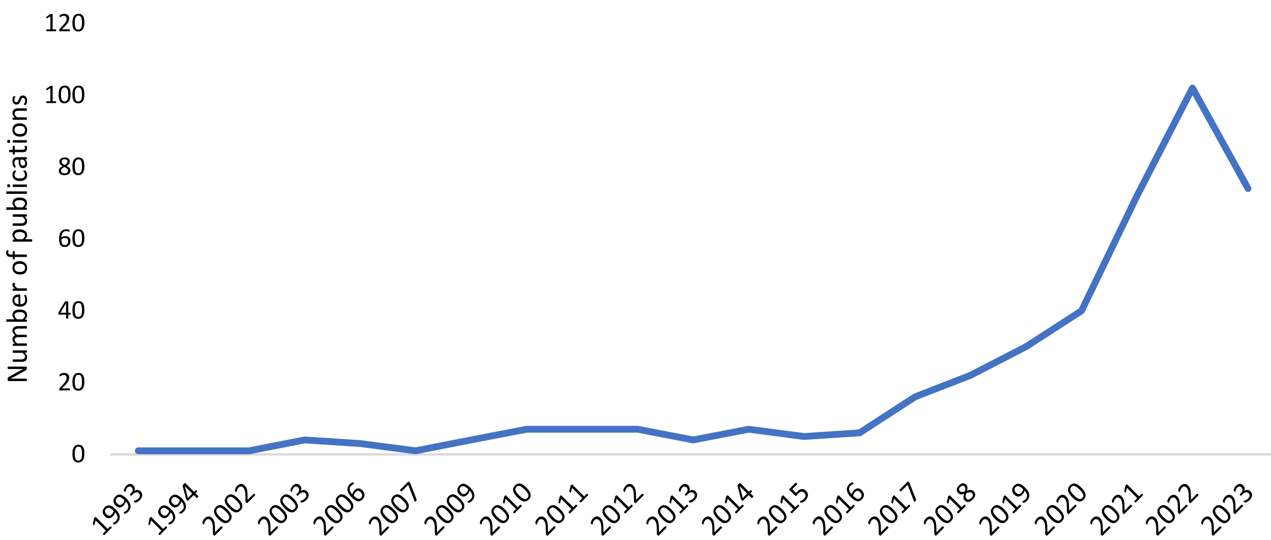
The considerable increase in publications since 2015 reflects a pivotal shift in research focus toward agricultural drones. The number of articles increased dramatically from 17 in 2015 to 433 in 2022, indicating a growing interest in drone applications for crop management. This surge reflects not only the increasing acceptance of drone technology, but also its growing importance in improving agricultural operations. The huge increase in research production since 2015 underscores the crucial significance of drones in upgrading agricultural techniques and addressing pesticide and fertilizer application issues.

Keywords Analysis

In order to perform a work to be represented and disseminated effectively among scientific communities, authors must carefully consider the keywords and choose for their publications (Kim et al., 2016). The process of extracting keywords from various pertinent research papers in a particular field is known as "keyword analysis." This method helps unveil broader trends and directions in research (Dixit & Jakhar, 2021). After analysing the annual distribution of publications from datasets, we compiled keywords to investigate our topic from 2015 to 2023, enabling us to identify the pivotal terms. Table 2 presents the top seven keywords and it indicates that "Drone" is a more frequently used keyword, followed by "Precision agriculture".



(a)



(b)

Fig. 2 The annual distribution of publications from the a) Scopus and b) PubMed datasets

This emphasizes the growing importance of drones in enhancing crop spraying and expediting crop health monitoring with improved efficiency, surpassing conventional ground-based spraying systems. Furthermore, drones excel in delivering precise amounts of pesticides and fertilizers (Parmar et al., 2021; Yan et al., 2021). Agricultural drones offer the potential to decrease fertilizer, pesticide, and water usage, enhance operational efficiency, create new market opportunities through a "sale + services" approach, and mitigate production expenses and labor shortages (Wang et al., 2022).

The commonly used keyword "deep learning," drones equipped with aerial photography were employed for disease detection in crops. Through the analysis of these aerial images, deep learning demonstrated its effectiveness in disease detection (Chen et al., 2021). Remote sensing (RS) technologies serve as an early warning system, helping the agricultural community tackle issues before they impact crop productivity. Advances in sensors, data management, and analytics have broadened the range of RS choices for agriculture. (Khanal et al., 2020). In the current agricultural landscape, internet of things (IOT) plays a pivotal

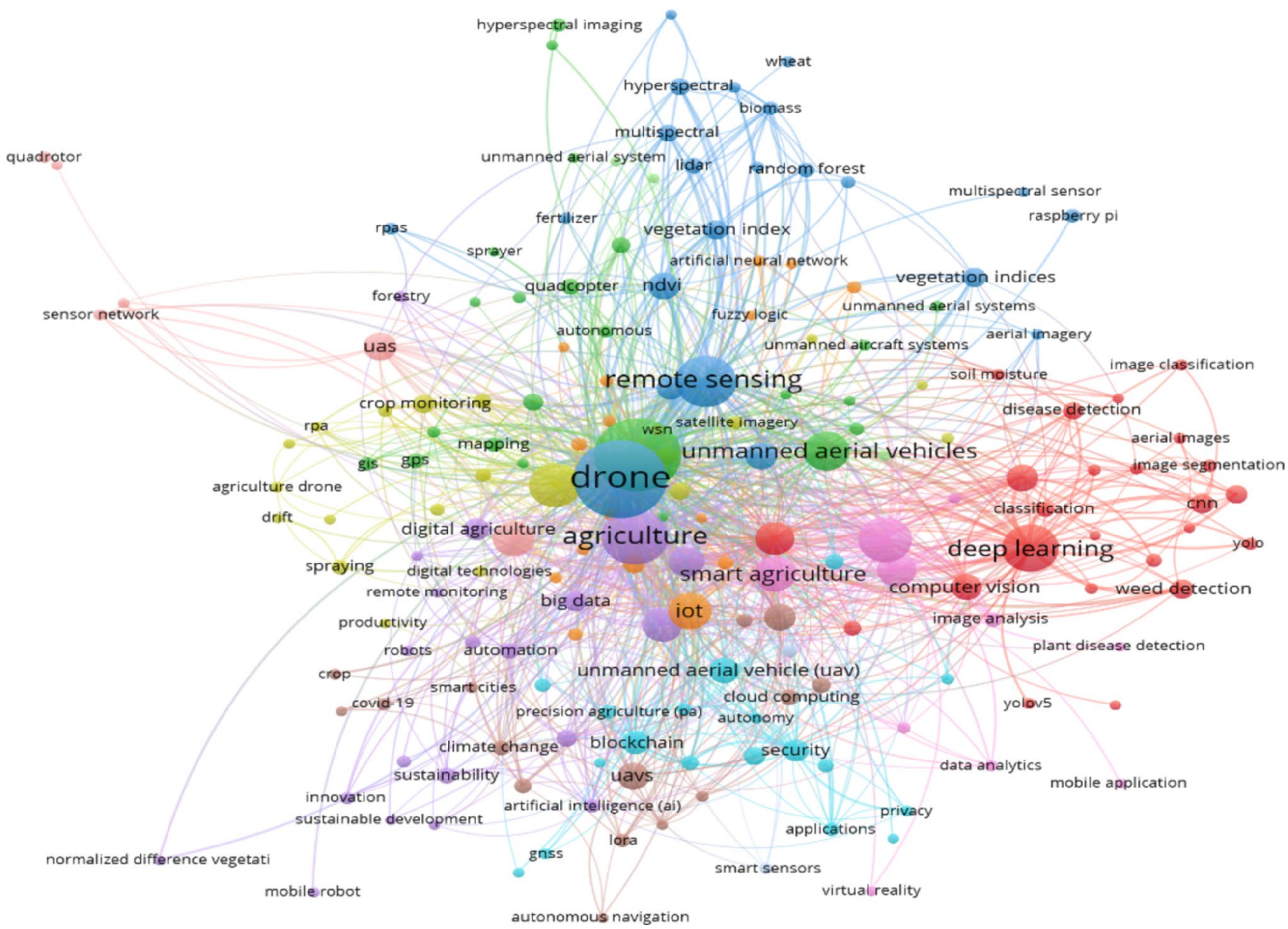


Fig. 3 Keyword associations within the timeframe of 2015 to 2023

Table 2 List of most commonly used keywords

Rank	2015–2023	No. of occurrences
1	Drone	304
2	Precision agriculture	264
3	Remote sensing	132
4	Smart agriculture	143
5	Machine learning	104
6	IOT	68
7	Deep learning	61

role. Diseases can be detected through cameras mounted on Unmanned Aerial Vehicles (UAVs) (Reinecke & Prinsloo, 2017). Figure 3 shows the Keyword associations within the timeframe of 2015 to 2023.

The analysis of keyword associations from 2015 to 2023 reveals significant insights into the evolution and interconnections of research topics in agriculture and technology. The prominence of "Drone" and "Precision agriculture" in our dataset underscores a growing focus on integrating aerial technologies with agricultural practices to enhance crop management and efficiency. The frequent co-occurrence of "Drone" with "Machine learning" and "Deep learning" highlights the increasing application of advanced data analytics and artificial intelligence in processing aerial imagery for precision agriculture. Additionally, the association of "Remote sensing" with "IoT" and "Deep learning" indicates a trend towards combining remote sensing technologies with smart, connected systems to provide real-time insights and early warnings about crop health. The trend analysis suggests a shift towards more sophisticated, data-driven approaches to agriculture, leveraging advancements in technology to address challenges such as disease detection, resource management, and operational efficiency. These associations not only reflect the integration of various technological innovations but also point to a growing emphasis on reducing environmental impact and improving productivity through precision and efficiency.

Citation Analysis

Citation analysis is a common method for evaluating the impact of articles, despite being subject to certain limitations. It's widely used to assess the influence of research papers in the academic community (Rejeb et al., 2022). We performed a citation analysis to identify and outline the most impactful papers on agricultural drones from 2015 to 2023, as detailed in Table 3. Utilized the Scopus dataset updated until September 16, 2023. Campos et al., (2021) and Lezoche et al., (2020) were the two most cited articles between 2015 and 2023, amassing 890 and 314 citations, respectively. (Campos et al., 2021) introduced ORB-SLAM3, an advanced SLAM system capable of visual, visual-inertial, and multimap SLAM with different cameras. It stands out for its tightly integrated visual-inertial approach, offering significant accuracy improvements over previous methods. Another innovation is its multiple map system that helps it handle poor visual data over extended periods, seamlessly merging new maps with previous ones. Notably, ORB-SLAM3 achieves an impressive 3.5 cm accuracy in the EuRoC drone, making it ideal for AR/VR applications. The paper by (Lezoche et al., 2020) is highly cited due to its significant contributions. "Agri-Food 4.0," akin to "Industry 4.0," leverages digital technologies for real-time data transmission and supply chain efficiency in agriculture. Electronic controls, sensors, including those related to drones, are enhancing agricultural processes, contributing to the emergence of "Agriculture 4.0." This survey evaluates more than a hundred papers discussing emerging technologies and supply chain methods influencing the Agri-Food sector's future. The third most referenced article, (Dos Santos Ferreira et al., 2017) focused on weed detection in soybean crops using Convolutional Neural Networks (ConvNets). They created a dataset of over fifteen thousand images, including soil, soybean, broadleaf, and grass weeds, and used the CaffeNet architecture for training. The study achieved exceptional accuracy of over 98% in detecting broadleaf and grass weeds compared to soil and soybean, with an overall average accuracy exceeding 99%. Leveraging data-driven techniques has the potential to substantially improve agricultural productivity through yield optimization, loss reduction, and decreased input costs. Nevertheless, the limited adoption of these approaches stems from the elevated expenses associated with manual data collection and challenges related to connectivity. A comprehensive Internet of Things (IoT) platform, named FarmBeats, has been created to tackle these challenges, facilitating smooth data collection from diverse sensors, cameras, and drones. FarmBeats has been successfully deployed for extended periods on U.S. farms, contributing to improved agricultural productivity (Vasisht et al., 2017).

Table 3 Most cited authors within the articles listed keyword search

First Authors	Citations
Carlos C	890
Lezoche M	314
Dos Santos Ferreira A	300
Vasisht D	270
Shamshiri R.R	254
Misra N.N	163
Weersink A	162
Miranda J	157
Chung S.H	154
Jakob S	141

Digital farming employs advanced technologies like sensors, robotics, and data analysis to automate tasks in agriculture, focusing on weed control, field scouting, and harvesting. Challenges include object recognition, task planning, sensor optimization, and creating virtual farms from aerial and ground-based data. Agricultural robotics trends emphasize small-scale robot swarms and drones for optimizing farming inputs, but a completely automated farming system is not foreseeable in the near future (Shamshiri et al., 2018). The Internet of Things (IoT) generates substantial streaming data, often referred to as "big data," which revolutionizes monitoring in agriculture and food industries. This review explores IoT, big data, and AI's transformative impact, focusing on agricultural applications like greenhouse monitoring, intelligent farm machinery, and drone-based crop imaging. It also discusses the significance of social media in food industry innovation, food quality assessment, and safety measures using gene sequencing and blockchain-based traceability. Commercial application status and research outcomes are given special attention (Misra et al., 2022). Agriculture is undergoing a digital transformation, leveraging data collection from sources like drones and satellites to boost productivity while minimizing environmental impact. Challenges include data interpretation and farmer training in using these tools. This article explores Big Data's potential and barriers in revolutionizing agriculture. (Weersink et al., 2018). The agri-food sector is moving towards 'Agri-Food 4.0', incorporating IoT, automation, and resource-efficient technologies. This article delves into the evolution of 'sensing, smart, and sustainable (S3)' technologies in the agri-food sector, emphasizing the necessity for design roadmaps. It also provides case studies featuring an intelligent greenhouse, sun tracker, hexapod robot, and agricultural drone (Miranda et al., 2019). The work by Chung et al., (2020) explores optimization approaches in civil drone and drone-truck combined operations across different sectors. It delves into mathematical models, synchronization methods, and barriers, with a focus on identifying research gaps and outlining future directions. Drone-borne hyperspectral imaging offers high-resolution data for diverse applications, primarily in precision agriculture and photogrammetry. Although hyperspectral sensors are now available for drones, complex corrections are needed for geological studies. The paper introduces a processing toolbox designed to rectify geometric and radiometric distortions in drone hyperspectral data. This enhancement renders the data suitable for lithological mapping and mineral exploration.(Jakob et al., 2017). Figure 4 displays the chronological overlay of highly cited researchers.

Meta-analysis

Our analysis compares five parameters that lead to drones being preferred over traditional sprayers: 1. Reduction in water use, 2. Reduction in pesticide usage, 3. Yield analysis, 4. Efficiency in killing insecticides/pesticides, and 5. Operational time, based on co-citation clusters generated. Our meta-analysis method involved an extensive literature review of peer-reviewed papers, reports, and case studies examining the use of drones versus traditional sprayers in agriculture. We collected quantitative and qualitative data from these sources, aggregated and synthesized the data using statistical techniques, and assessed each study's quality and potential biases. These parameters consistently appeared as critical factors in the reviewed studies, demonstrating the advantages of drone technology in modern agricultural practices.

Reduction in Water Use

The water application rates for drone spraying were 25 L/ha for flood jet nozzles and 75 L/ha for atomizer nozzles, which are significantly lower than the conventional spray requirement of 200 L/ha, as reported by Kaniska et al., (2022). In a study by Cavalaris et al., (2022), the authors compared the use of UAVs and air-assisted field sprayers for plant protection and care in cotton fields. The UAVs used a spray volume of 16 L/ha, while the field sprayers required 400 L/ha. This comparison demonstrated the potential of UAVs in various applications related to cotton farming. By utilizing drone technology and their smaller tanks compared to conventional sprayers, there is an opportunity to achieve a significant reduction in water usage, potentially conserving up to

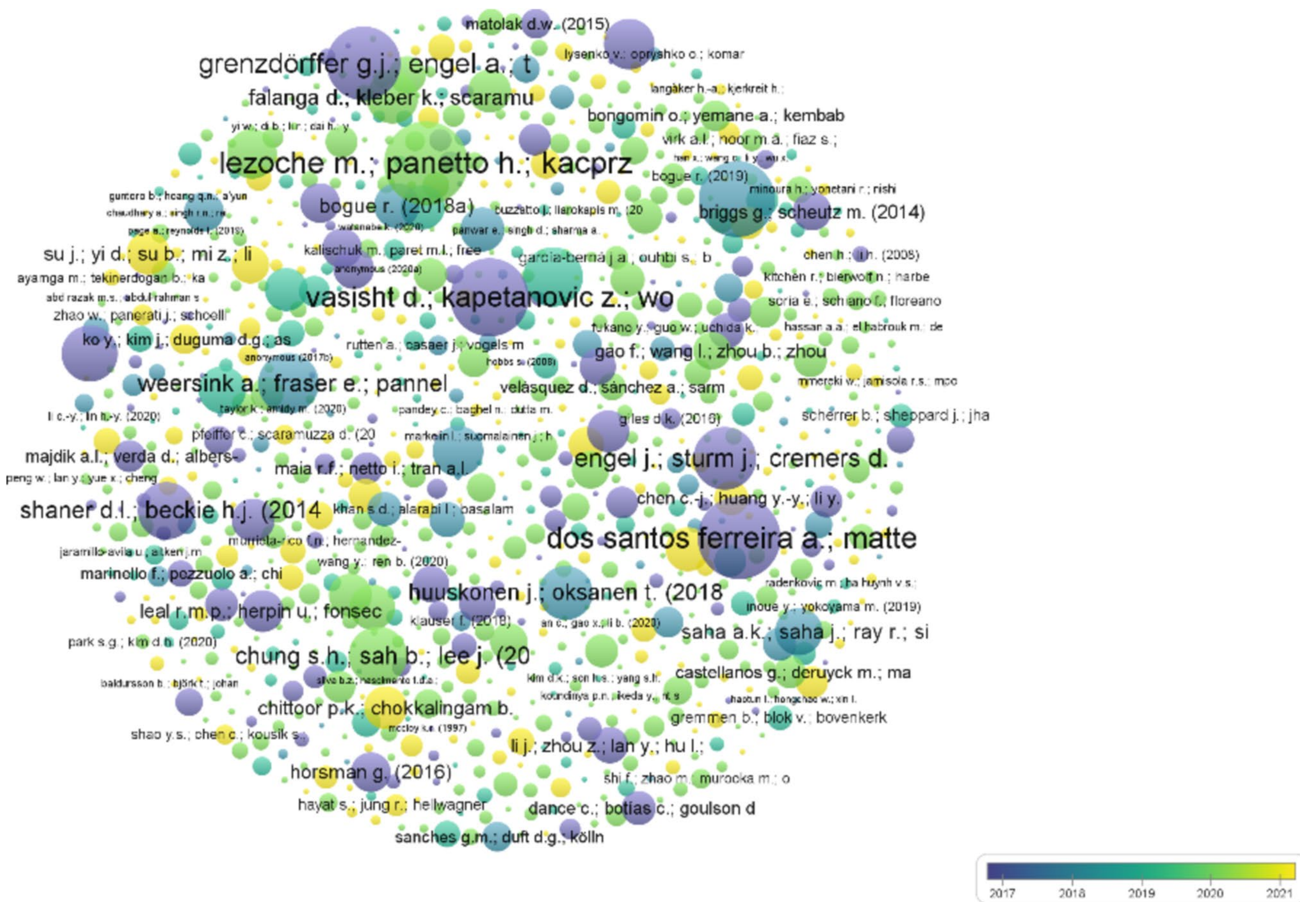


Fig. 4 Overlay of highly cited researchers

90% of water (Shahrooz et al., 2020). In an experimental comparison between a UAV with a spray volume of 18 L/ha and a boom sprayer with a spray volume of 600 L/ha, it was noted that the UAV application of a chemical topping agent significantly improved pesticide utilization rates, agronomic properties, cotton yield, and fiber quality. (Dou et al., 2022). Employing a UAV for fungicide applications is an effective method for managing fungal diseases in mountain coffee crops. This efficiency is evident when using a drone with a spray volume of 15 L/ha, compared to a pneumatic sprayer with a much higher volume of 400 L/ha (Vitória et al., 2023). Employing Unmanned Aerial Vehicles (UAVs) for plant protection spraying offers a notable reduction in pesticide exposure levels while maintaining effective pest control efficiency. (Arakawa & Kamio, 2023). This aligns with the trajectory of contemporary intensive and sustainable agricultural practices. Experimental analysis has shown that drones utilize a maximum of 37.5 L/ha for water application, whereas traditional knapsack sprayers require up to 600 L/ha (Yan et al., 2021). In this experiment, the UAV application of droplets at rates of 15 and 30 L/ha resulted in a deposition efficiency of 47.04%, which was 8.89% higher than that achieved with the traditional knapsack sprayer (450 L/ha) (Hussain et al., 2022).(Wang et al., 2023) Examined the effects of UAV spraying at rates of 15 L/ha and 30 L/ha, alongside Electronic Knapsack Sprayer (EKS) spraying at a rate of 450 L/ha, on droplet deposition distribution. Figure 5 illustrates the comparative analysis of water use between drones and traditional sprayers, while Table 4 furnishes details about the authors and their associated crops used for water reduction analysis.

Table 4 List of crops considered for water reduction analyses

Crops	Authors
Maize	Kaniska et al., 2022
Cotton	Cavalaris et al., 2022; Dou et al., 2022
Rice	Shahrooz et al., 2020
Coffee	Vitória et al., 2023
Cowpea	Yan et al., 2021
Wheat	Hussain et al., 2022

Reduction in Pesticide Usage

In contemporary drone spraying techniques, a precise quantity of pesticide is applied to both the field and plant leaves, resulting in a potential reduction of up to 30 percent in pesticide usage (Shahrooz et al., 2020). The outcomes indicate that utilizing drones for *T. papillosa* pest management can achieve more than 95% pest control and cut down pesticide consumption by 70% (Chen et al., 2021). In contrast to conventional ground-based pesticide application, the efficiency of UAVs has seen a remarkable increase, exceeding 60 times. Additionally, there has been a reduction in pesticide dosage by approximately 20–30%, which is accompanied by a significant decrease in the level of labor required (Desa et al., 2023; Qin et al., 2016). The consumption of costly medications and fertilizers is reduced by approximately 25–35% (Zhichkin et al., 2023). The unmanned helicopter spraying system achieved pesticide savings of up to 50% as compared to high-clearance crop sprayers. The increased rotor speeds resulted in a more consistent distribution of droplets (Parmar et al., 2021). Utilizing a UAV sprayer leads to a notable

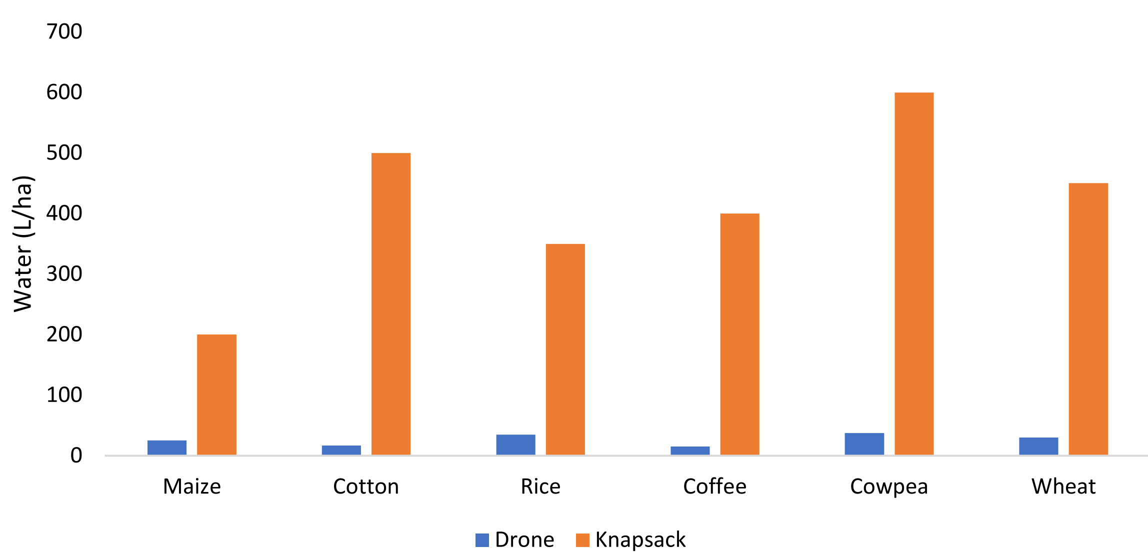


Fig. 5 Comparative analysis of water use between drone and traditional sprayer

decrease in insecticide usage, typically ranging from 30 to 40%. This reduction in pesticide application significantly impacts the environment by preserving soil fertility (Hanif et al., 2022; L. Wang et al., 2022). The spray efficiency of UAVs was measured to be 14.37 times greater than that of KES, resulting in a remarkable 90.65% reduction in pesticide volume requirements (Zhang et al., 2019). Using drones for fertilizer application led to a 3.6% increase in winter barley yield, accompanied by a 2% reduction in fertilizer application (Truflyak et al., 2023). The average percentage reduction in pesticide uses for similar crops presented in, as shown in Fig. 6 Table 5 provides information regarding the authors and their respective crops in pesticide reduction. The findings indicate that the minimum pesticide use reduction was observed for olive crops, with a reduction of up to 30%. In contrast, wheat crops exhibited the highest reduction, reaching up to 65%.

Table 5 List of crops considered for pesticide reduction analyses

Crops	Authors
Olive (30%)	Shahrooz et al., 2020
Rice (40%)	Qin et al., 2016; Desa et al., 2023
Cotton (40%)	Parmar et al., 2021; Zhichkin et al., 2023
Wheat (50%)	Wang et al., 2022
Maize (34.1%)	Pelosi et al., 2015; Wang et al., 2022
Citrus (35%)	Hanif et al., 2022

Increase in Yield

According to research statistics, precision farming technologies, such as drones, have the potential to enhance agricultural yields by around 5%, representing a substantial improvement in an industry typically characterized by low profitability (Suwandej et al., 2022). The data indicates a 6.25% increase in yield and a 2.25% improvement in quality. Notably, there is a moderate correlation coefficient of 0.6 between the factors influencing paddy productivity both before and after the integration of drones. (Noor & Noel, 2023). Cavalaris et al., (2022) conducted an analysis, revealing that, on average, using a low altitude 2 m UAV resulted in a 9.7% higher yield in Field 2 and a remarkable 27% higher yield in Field 1. Moreover, the best performance was consistently observed in the 16-L capacity—UAV flying at a 2 m altitude in both fields. By leveraging drone technology for precise fertilizer application, winter barley yields experienced a 3.6% increase (Truflyak et al., 2023). The percentage increases in yield are visually represented in the results through Fig. 7. Meanwhile, Table 6 provides details on the respective crops and authors associated with these yield increments.

Efficacy to Kill Pesticides/ Insecticides

Drone spraying technology significant boost efficiency when it comes to pest and insect control (Fig. 8), delivering precise and effective pesticide application with unmatched precision. After spraying the insecticide, the insecticidal efficacy ranged from 74 to 92%, indicating the variable effectiveness of the pesticide in controlling the target insects (Qin et al., 2016). The droplet coverage rate, deposition, and drifting capability significantly increased at a UAV flight height of 2 m. Consequently, the UAV spraying achieved a 63.7% control rate for cotton aphids and a 61.3% control rate for spider mites (Lou et al., 2018). Plots treated with UAV-based

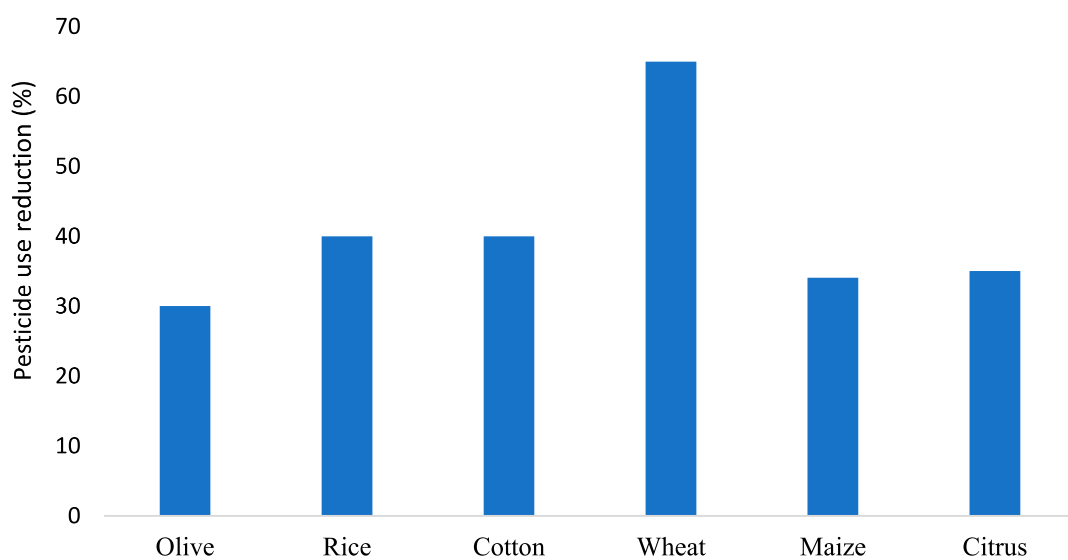


Fig. 6 Percentage reduction in pesticide usage by using a drone sprayer compared to the traditional sprayer

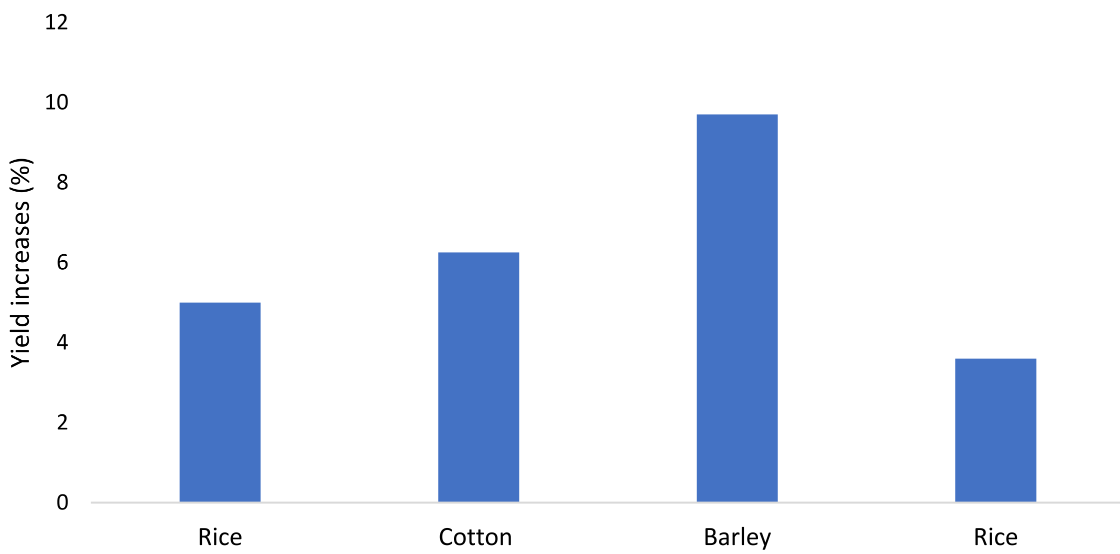


Fig. 7 Percentage in yield increases by using a drone sprayer

Table 6 List of crops considered for yield analyses

Crops	Authors
Rice (5%)	Suwandej et al., 2022
Cotton (6.25%)	Cavalaris et al., 2022
Barley (9.7%)	Truflyak et al., 2023
Rice (3.6%)	Noor & Noel, 2023

spraying exhibited a markedly reduced infestation rate compared to untreated plots, leading to a 92% control efficacy (Arakawa & Kamio, 2023). In the context of UAV spraying, the highest reduction in the white fly population, specifically 84.85%, occurred after 7 days of treatment at a speed of 2 m/s and a height of 0.5 m. Similarly, the most significant reduction in the BPH population, at 67.42%, was observed after 7 days of treatment with a speed of 2 m/s and a height of 1 m (Parmar et al., 2021). The control effectiveness of UAV spraying reached 76.4%, leading to a 59.3% reduction in the larvae population (H. Xu et al., 2023). The findings indicated that a combination of chlorfenapyr, chlorantraniliprole, and lufenuron achieved the most effective control, resulting in a 94.86% reduction in the population and an efficacy rate of 94.94% (Song et al., 2020). The average percentage of efficacy in killing pesticides, as presented in Table 7, falls within the specified range.

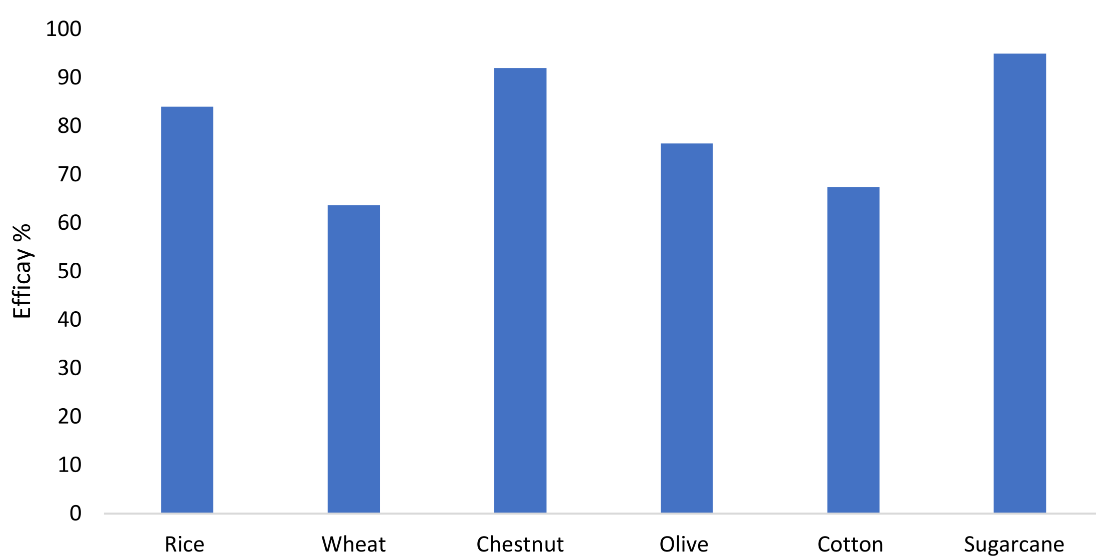


Fig. 8 Efficacy to kill insecticides/pesticides using drone spraying

Table 7 List of different crops considered for insecticide reduction analyses

Crops	Authors
Rice (84%)	Qin et al., 2016
Wheat (63.7%)	Lou et al., 2018
Chestnut (92%)	Arakawa & Kamio, 2023
Olive (76.4%)	Xu et al., 2023
Cotton (67.42%)	Parmar et al., 2021
Sugarcane (94.94)	Song et al., 2020

Operational Time

By modifying the spray method, incorporating adjustments in swath width and flight pattern, Unmanned Aerial Systems (UAS) spray applications can achieve work rates within the range of 2.0 to 4.5 hectares per hour. (Giles & Billing, 2015). An important parameter in pesticide spraying is the spraying speed, which, depending on the drone type, can cover 6 to 7 hectares in an hour, a significant improvement over the more common 1 to 2-hectare coverage (Shahrooz et al., 2020). The performance of the drone can vary between 5 and 7 hectares per hour when it comes to pesticide spraying (Simula, 2021). The employed UAV covers an area of about 5 hectares per hour during a single flight mission. Each mission requires approximately 8000 mAh at 22.2 V, resulting in a total energy consumption of 177.6 Wh. (Sacco et al., 2021). UAV field coverage typically ranged from 4 to 10 hectares per hour, representing a significant improvement over manual spraying, which is 30 to 100 times less efficient (Hussain et al., 2019; Parmar et al., 2021). The average coverage area for UAVs is presented in Fig. 9. Table 8 listed of different crops considered for reduction analysis.

Conclusions

In conclusion, the research conducted in the field of agricultural spraying drones, as summarized through bibliometric methods and adherence to PRISMA guidelines, sheds light on the promising potential of drone technology in revolutionizing modern farming practices. Agriculture, a sector crucial for economic productivity, faces environmental challenges exacerbated by climate change. Farmers grapple with time-consuming crop damage assessment. The accessibility of technology, particularly drones, has offered a solution to this problem, though comprehensive research on their impact on farmers' cost and time management remains limited.

The integration of drones into agriculture presents multiple advantages. Precise targeting through drone technology reduces pesticide usage, benefiting the environment. Drones also optimize water distribution and enhance efficiency, potentially reshaping contemporary farming practices. The rapid response to pest-related issues improves

Table 8 List of different crops considered for reduction in crops

Crops	Authors
Vineyard (3.25 h)	Giles and Billing 2015
Olive (6.5 h)	Shahrooz et al., 2020
Rice (6 h)	Simula 2021
Maize (4 h)	Hussain et al. 2019
Cotton (7 h)	Parmar et al., 2021

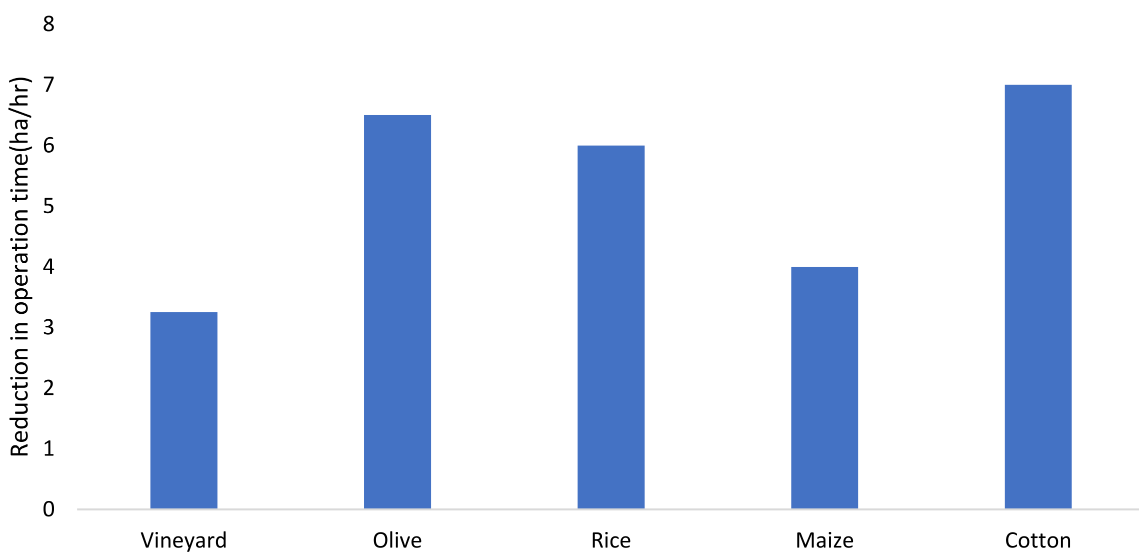


Fig. 9 Area of coverage per ha by drone

crop protection and yields. Notably, drone spraying achieves uniform pesticide dispersion, minimizing coverage gaps in pest and disease management. Thus, the adoption of drones in agriculture holds promise for sustainable and efficient farming practices, mutually benefiting farmers and the environment.

Over the past decade, the literature in this field has grown substantially, with a noticeable increase in publications post-2015. While this knowledge domain is still evolving, numerous unanswered questions remain, such as the effectiveness of drones in indoor farming etc.

A comprehensive analysis of research clusters from 2015 to 2023 highlights the evolution of the domain, expanding its focus beyond previous studies. Researchers highlight the synthesis of UAV applications in agriculture, with numerous studies delving into drone uses for imaging tasks, precision agriculture, and pesticide spraying.

During the same period, an examination of research topics reveals "Pesticide spraying" as the dominant subject, with 617 occurrences, followed closely by "Unmanned aerial vehicle" and "Deep learning" with 393 and 302 occurrences, respectively. These findings underscore the significant emphasis on pesticide spraying technology, UAVs, and advanced machine-learning techniques within agricultural research.

The integration of drones in agricultural practices has showcased substantial benefits, particularly in pesticide application and crop management. Reports indicate a noteworthy reduction in pesticide usage, ranging from 30 to 65%, compared to traditional knapsack spraying methods. This signifies a more efficient and targeted approach to pest control and underscores the potential environmental impact through reduced chemical exposure. Additionally, drones have demonstrated a positive influence on crop yields, with reported increases ranging from 3.6% to 9.7% compared to knapsack methods. The efficiency in eliminating insecticides and pesticides further supports the effectiveness of drone spraying, varying from 63.7% to an impressive 94.94%. Beyond pest management, drones contribute significantly to sustainable agriculture by conserving water resources, potentially reducing water usage by up to 90%. The versatility of drone technology is evident in its coverage capacities, ranging from 2 hectares per hour at a minimum to an impressive 6–7 hectares per hour at maximum capacity. As these findings suggest, the adoption of drones in agriculture holds promise for enhancing efficiency, reducing environmental impact, and optimizing resource utilization in modern farming practices.

In summary, the research in agricultural spraying drones indicates a bright future for sustainable and efficient farming practices. With the potential to reduce environmental impact and enhance crop yield, drones are emerging as a crucial tool for modern agriculture. However, there is still much to explore in this evolving field, with room for further investigation and development in the years to come.

Limitations

Nevertheless, drones come with certain limitations, including a limited frequency range, low battery life, high initial costs, and limited tank capacity. Advancements in Unmanned Aerial Vehicle (UAV) technology for plant protection show promise in addressing these challenges, as indicated by current research. Despite these advancements, the adoption of drone technology in agriculture remains limited, primarily due to these technical constraints. Additionally, regulatory hurdles and the need for skilled operators present further obstacles to widespread implementation. Furthermore, in some regions, including parts of India, the readiness of farmers to adapt to this technology is relatively low, which further hampers its broader acceptance. Overcoming these limitations and addressing these concerns will be crucial in realizing the full potential of drone technology in agriculture.

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Declarations

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