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TRENDS AND PATTERNS IN THE RESEARCH DEVELOPMENT OF AGRICULTURAL DRONES, A BIBLIOMETRIC ANALYSIS FROM 2000 TO 2023

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Abstract: The incorporation of robotics in agriculture embodies a major advancement in information and communication technologies, which addresses critical challenges such as promoting sustainability, Labor shortages, and increasing efficiency. This bibliometric analysis explores the trends and patterns in the research development of agricultural drones from 2000 to 2023, against the backdrop of their increasing integration into modern agricultural practices. Agricultural drones, also known as unmanned aerial vehicles (UAVs), have emerged as transformative tools in precision farming, offering capabilities such as crop monitoring, pest management, and soil analysis with unprecedented efficiency and accuracy. This study employs the R-bibliometrics package, Vos Viewer, and Excel for comprehensive analysis, leveraging these tools to examine publication trends, citation impacts, author collaborations, and keyword co-occurrences across a diverse range of journals and disciplines. Findings reveal a steady growth in research output, punctuated by significant peaks in interest, particularly following advancements in artificial intelligence applications within the field. This analysis not only highlights the pivotal role of agricultural drones in shaping modern agriculture but also identifies critical areas for future research and innovation, including AI integration, environmental sustainability, and the optimization of drone technologies for enhanced agricultural productivity and sustainability.

Keywords: Agricultural drones, Precision Agriculture, UAVs, Artificial Intelligence, remote sensing

1. Introduction

Agriculture is the basis of human civilization, providing food, fiber, and other key resources. With the increase in the global population, the demand for agricultural products is intensifying [1], [2]. This rising demand places immense pressure on agricultural systems to increase productivity, enhance sustainability, and reduce environmental impacts [3]. Therefore, the introduction of robotic systems in the agricultural sector which are crucial in ending hunger and malnutrition sustainably by conserving and restoring ecosystems and natural resources [4].

The literature review aims to offer a wide-ranging overview of robotics in agriculture, emphasizing its scope and importance, historical developments, current advancements, and the benefits and challenges related to its adoption. Besides, the review will briefly examine the Technology Acceptance Theory (TAT). Overall, this review seeks to highlight the transformative potential of robotics in shaping the future of agriculture.

2. Robotics in agriculture

Robots are important to precision agriculture, also referred to as precision farming, which comprises of data-driven techniques to enhance field-level management. Furthermore, farmers can make informed decisions about planting, fertilizing, and irrigation by collecting and analysing data on soil conditions, crop health, and weather patterns [5], [6]. Its main objective is to enhance crop performance while improving environmental quality [7]. Additionally, it leverages various technologies to address the spatial and temporal variability inherent in agricultural production. Autonomous tractors and machinery equipped with machine learning algorithms, AI, and GPS can perform various tasks like ploughing, planting, and spraying with little human intervention [8]. Other high technologies, like wireless measuring networks, can increase the efficiency of complex systems. For example, smart irrigation can operate in this way [9]. Furthermore, modern technologies ensure that seeds are planted at ideal depths and distances, also ensuring the application of fertilizers and pesticides is accurate as a study by Thomas et al. highlighted [6]. Additionally, they can be utilized to capture and process large volumes of data, offering the capabilities needed to operate effectively at both the individual plant level and the entire field level [10].

2.1. History of robotics in agriculture

The origin of agricultural robots can be traced to the early 1900s. However, the use of advanced robotics in agriculture is a more recent development [11]. Furthermore, during the 1980s, the introduction of microprocessors and sensors created a way for the initial automation of agricultural tasks. The Primary robotic systems were mainly designed to perform simple repetitive tasks like milking cows and picking fruits [12].

Significant advancement came in the 1990s with the development of more polished robotic systems that performed complex tasks. The initiation of GPS technology and AI further improved the capabilities of agricultural robots [13]. Various researchers embarked on exploring the potential of autonomous vehicles for soil preparation, harvesting, and planting [14]. The turn of the 21st century marked the beginning of precision agriculture, where robots became an integral part of farming and crucial for optimizing various agricultural processes.

2.2. Current developments in agricultural robotics

Recent developments in agriculture are immensely reshaping how to produce and consume food. A significant development is the integration of digital technologies. Field-level management is being optimized using GPS, IoT sensors, and data analytics in crop farming [13]. Through this technology, the farmer can easily monitor soil conditions, weather patterns, and crop health, and ensure efficient use of resources such as fertilizers, pesticides, and water. Biotechnology is another transformative force which has come in handy [15]. The incorporation of genetic engineering has enabled the development of crops that are resistant to pests, diseases, and extreme weather conditions [16]. Many farmers have embraced genetically modified organisms (GMOs), which has significantly enhanced food security in regions with agricultural challenges [17]. Practices such as cover cropping, no-till farming, and agroforestry reduce soil and improve water retention, leading to reduced climate change [18]. Therefore, the emphasis on regenerative agriculture has been embraced to restore soil health, increase biodiversity, and enhance ecosystem services.

2.3. Benefits and challenges

The development of robotics in agriculture has brought numerous benefits and challenges. On the positive side, robotics have increased efficiency [19]. Automated machines perform tasks such as weeding, planting, and harvesting which has minimized manual labour and increased yields [20], [21]. Therefore, robotics have led to Labor saving which has exceptionally filled the gap of agricultural labour shortage.

Robotics in agriculture have also led to Improved crop quality and enhanced sustainability [22]. Drones and robotic sensors have come in handy since they provide real-time data on crop health and soil conditions [18]. Farmers use the information to optimize resources and make informed decisions leading to cost-saving and environmental sustainability [23], [24].

These agricultural advancements come with challenges. The cost of robotics technology can be relatively high, preventing their use by small-scale farmers [25]. Furthermore, technical expertise is needed to operate and sustain the machines, as Cheng et al found [20]. Additionally, the adoption of robotics has led to the displacement of the workforce, creating a large population of unemployed communities [26]. On the other side, robots can be applied to that segment of agricultural production where the workforce is demanding, like horticulture [27]. Another important question is how can the utilisation of new technology support the efforts for sustainability. In a study, Valle and Kinzle tried to give an adequate answer for this when investigating the application possibilities of robots and automated equipment for sustainable crop production [28].

Overall, the use of autonomous systems in agriculture has raised regulatory, safety, and ethical issues [29], [30].

2.4. The technology acceptance theory (TAT)

The technology acceptance theory provides a framework for understanding how users come to accept and use new technologies. In this case, we can highlight that robots and drones can be used successfully not only in agriculture but e.g. in environmental management [31], [32]. An upcoming field of application is security technology where robots and drones fulfil tasks well [33]. TAT suggests that technology adoption is influenced by perceived usefulness and perceived ease which are the primary factors [6]. Subeesh & Mehta in their research found that farmers are more likely to adopt robotic systems if they perceive these technologies will improve productivity, minimize costs, and enhance crop quality [8]. Bechar and Vigneault highlight that the complexity of operating and maintaining robotic systems can hinder their adoption, therefore the need for providing adequate training and ensuring user-friendly technologies can ease this concern [11]. Continued research and development, with the inclusion of supportive policies, are essential for realizing the full potential of robotics in agriculture [34].

The research questions for this study are:

RQ1: What are the publication trends in agricultural drones?

RQ2: What are the most prolific scholars, articles, journals, and countries contributing to agricultural drones?

RQ3: What are the research directions for future research?

3. Materials and methods

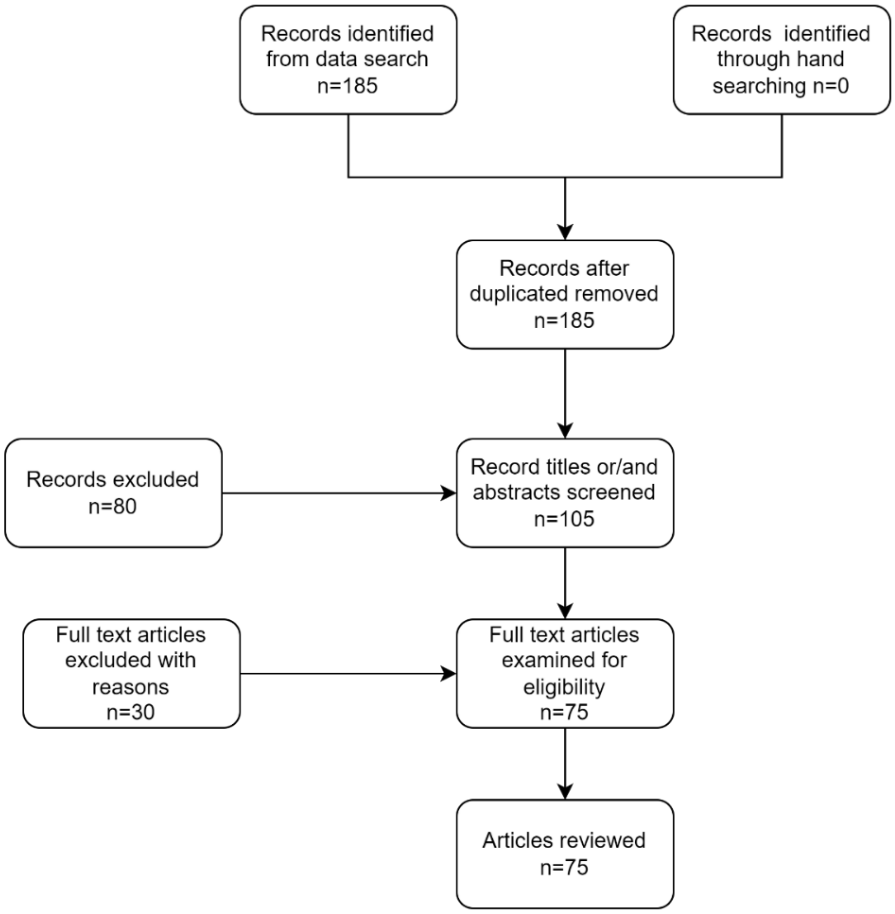

Figure 1. PRISMA Flow Diagram for Study Selection Process

This research drew data from Scopus. SCOPUS is a widely used and reliable source for scientific publications. The keywords ("agricultural drone") OR ("drones in agriculture") OR ("crop monitoring drones") were used only articles written in English were reviewed. Figure 1. shows the search methodology. Data was analysed using the R-bibliometric package, Excel, and NVIVO, and the results are shown in section 4.

4. Results

4.1. Most relevant sources

The study examined the most relevant sources of the period examined by the research. The results are shown in Table 1.

Table 1. Most relevant sources of the research

Sources	Articles
Drones	4
IEEE Access	4
Applied Sciences (Switzerland)	3
Computers And Electronics In Agriculture	3
Journal Of Biosystems Engineering	3
Agriculture (Switzerland)	2
Agronomy	2
Chemical Engineering Transactions	2
Revista De La Facultad De Agronomia	2
Agricultural Engineering International: Cigr Journal	1

The results show that the Journal of Drones and IEE ACCESS had the most publications, 4, while Applied Sciences (Switzerland), Computer and Electronics, and the Journal of Biosystems Engineering, had the second largest number of publications on agricultural drones, 3. Agriculture, Agronomy, Chemical Engineering, and Revista de had 2 articles each, while Agricultural engineering had only 1 article. The wide range of articles implies that agricultural drones have been studied across different disciplines and therefore, a multidisciplinary approach should be embraced to fully understand, improve, and advance agricultural drones.

4.2. Annual production

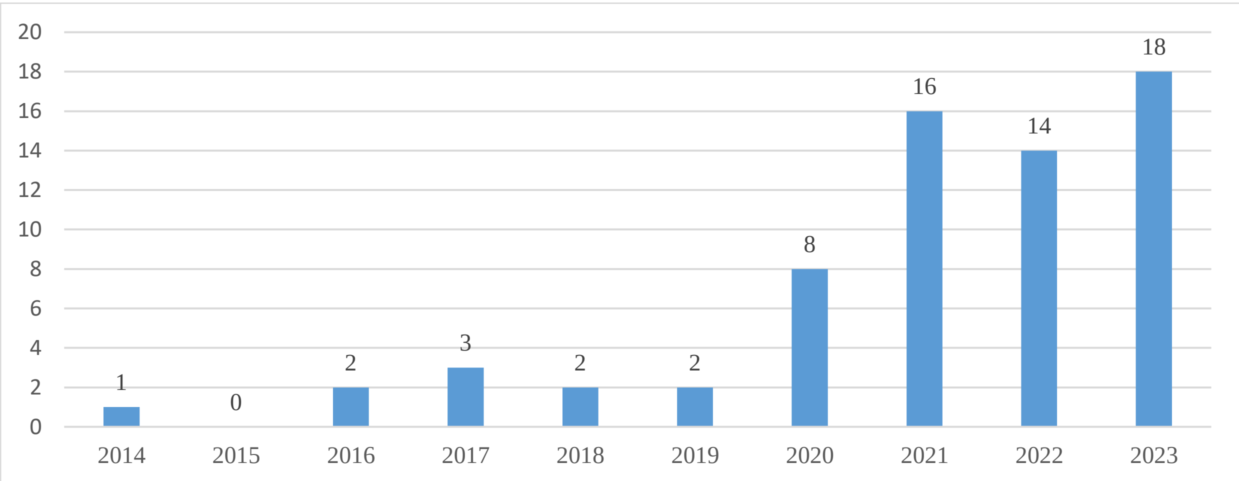

Figure 2. Articles published annually

The study further examined the annual production of research articles to obtain a general overview of the scientific publications on agricultural drones and the results are shown in Figure 2 below.

Figure 2. shows an overall rise in publications since 2014, albeit a decline in 2015, 2018, and 2022. There were the fewest publications between 2014 and 2019, where 2017 recorded the highest, 3, while 2015 had the least, 0. There was a sporadic rise in publications between 2019 and 2021, where publications rose from 2 in 2019 to 16 in 2021. This shows a rise in interest in agricultural drones as artificial intelligence gained traction. There was a slight decline in 2022 to 14 articles followed by a sudden rise to 18 in 2023. Despite variations in publications across the period, the study shows that agricultural drones have gained interest since 2014.

4.3. Source local impact

The study further examined the local impact of the journals based on their h-index. The h-index is a metric designed to measure both the productivity and citation impact of the publications within a journal. The results are shown in Table 2.

Table 2. Sources h-index

Journal	h-index
IEEE Access	4
Drones	3
Journal of Biosystems Engineering	3
Agriculture (Switzerland)	2
Agronomy	2
Applied Sciences(Switzerland)	2
Chemical Engineering Transactions	2
Computers and Electronics in Agriculture	2
Agricultural Engineering International CIGR Journal	1
Basrah Journal of Agricultural Sciences	1

Table 2. shows that IEE Access has the highest h-index of 4. On the other hand, Drones and Journal of Biosystems Engineering had an index of 3, while Agriculture, Agronomy, Applied Sciences, Chemical Engineering Transactions, and Computer and Electronics in Agriculture journals had and index of 2. Lastly, Agricultural Engineering International CIGR Journal and Bashah Journal of Agricultural Sciences had and index of 1. These findings imply that the journal's h-index of 4 means that the journal has published at least four articles, each of which has been cited at least four times. In other words, four is the maximum number such that the journal has at least 4 papers with 4 citations each. Similarly, journals with an h-index of 1, imply that the journal has published at least 1 article and has been cited at least once. Therefore, articles on agricultural drones have been fairly cited over time.

4.4. Most productive authors – all publications

The study further examined the authors with the most publications and the results are shown in Figure 3.

Figure 3. shows that the top ten authors had at least 6 articles and utmost 10. Huang Y and Ramasamy M have the highest publications, 10. Michels had 9, while Tang 8, Faical B, Fritz B, and Murugan D, had 7 articles each. Lastly, Belforte G, Qing T, and Zhang C, had 6 articles each. These findings imply that the top ten authors have published at least 6 papers, which explains the spontaneous rise in annual production over time as shown in Figure 2.

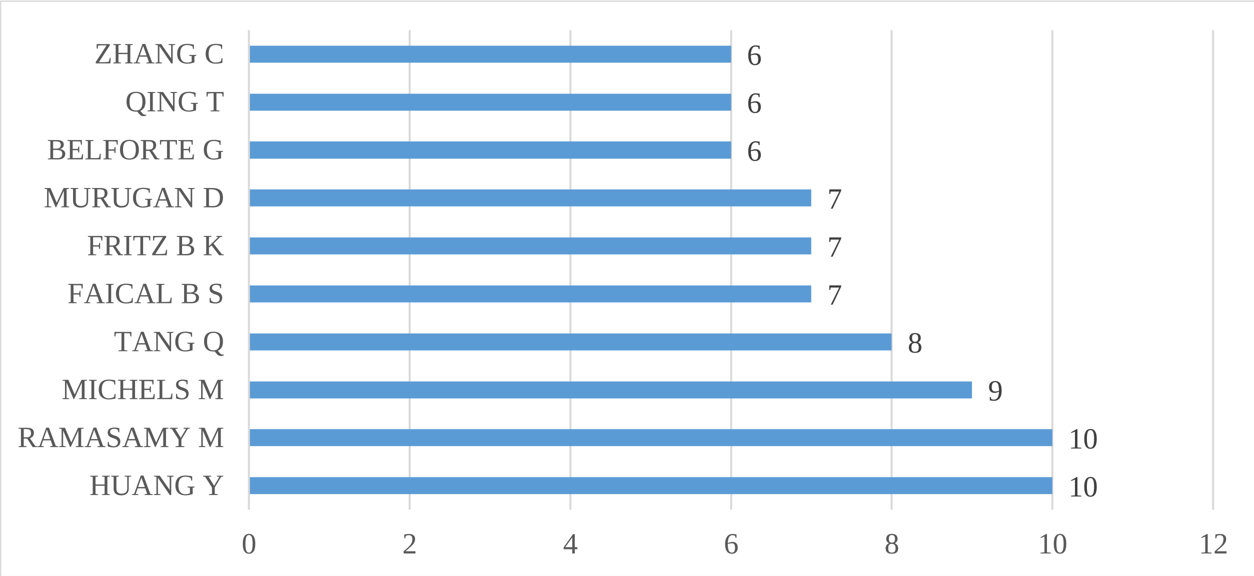

Figure 3. Most productive authors

4.5. Most productive authors - annually

The study further examined the most productive authors, which measures the average number of publications per year. The results are shown in Figure 4.

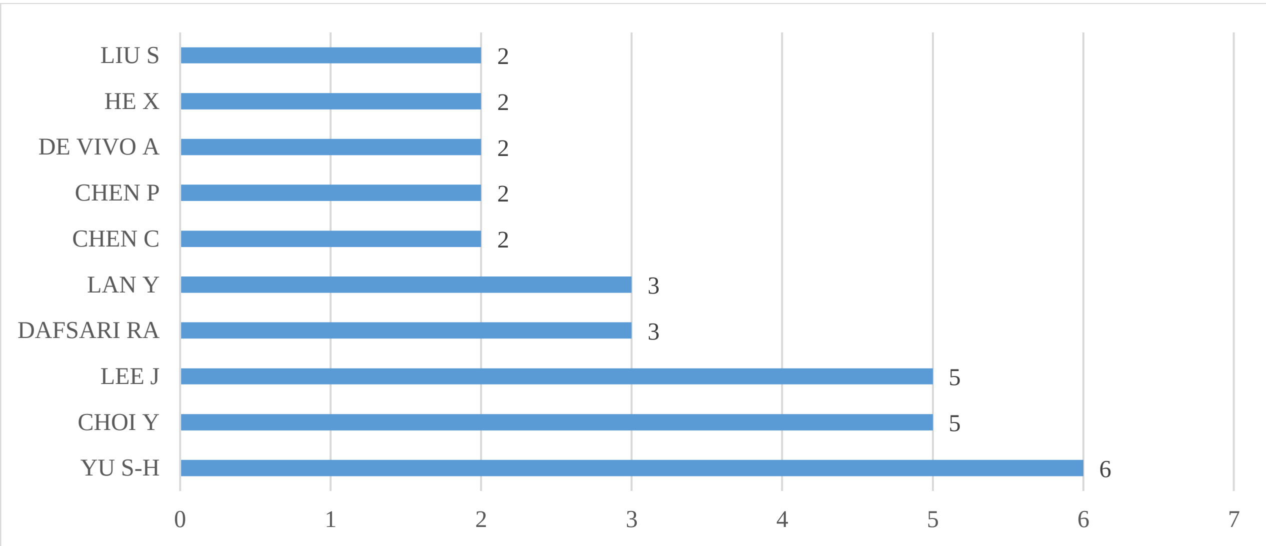

Figure 4. Most productive authors per year

Figure 4. shows that Yu S-H has the highest average publications (6). Choi Y and Lee J had 5, while Dafsari RA and Lan Y had 3. The rest had 2. These results differ from the findings on most local citations. The most productive authors are not the most cited. This implies that productivity does not imply impact even though it increases the chances of more citations.

4.6. Co-authorship

The study explored the co-authorship between researchers in agricultural drones and the results are shown in Figure 5.

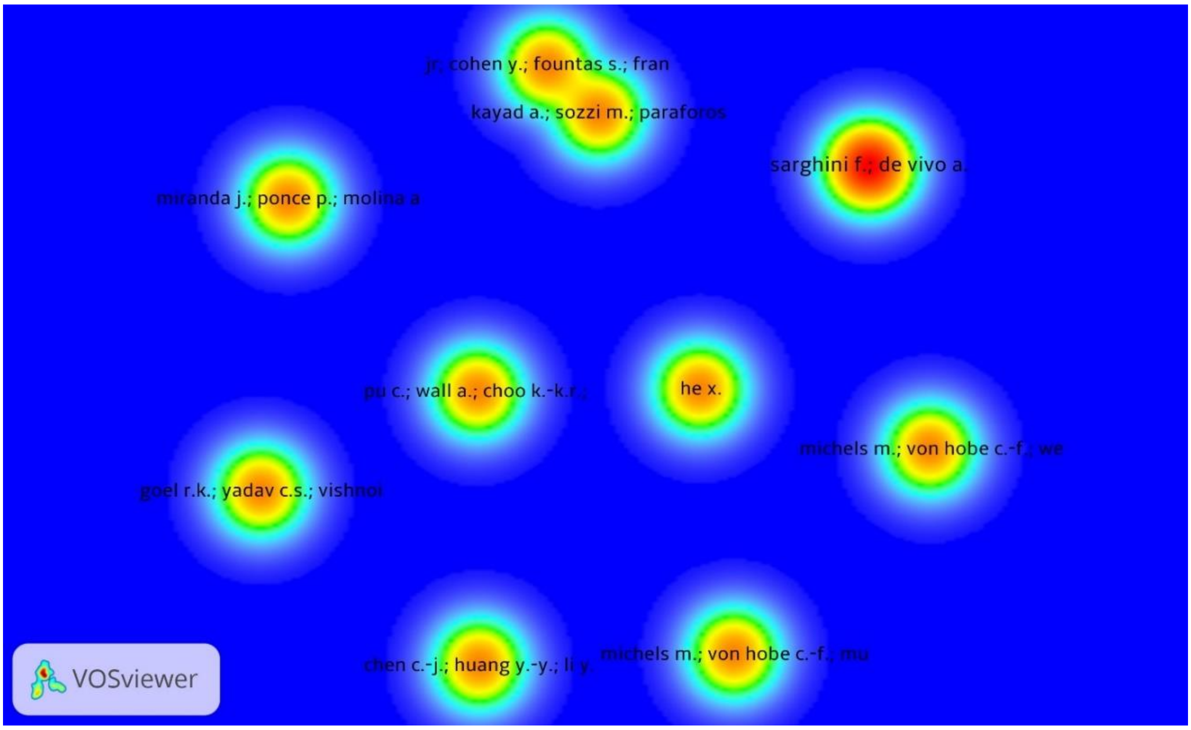

Figure 5. Co-authorship

The study results show that researchers in agriculture have collaborated. The main collaborators are Cohen and Fountas, Kayad, Sozzi, Paraforos, Sarghini and De Vivo, Michels and Von, Chen and Huang, Goel, Yadav, Vishnoi, and Pu and Choo. Michels and Von have collaborated twice. Collaboration is essential as it brings together diverse expertise, perspectives, and resources, enabling researchers to tackle complex problems that are often beyond the scope of a single individual or institution. Collaborative efforts can lead to more comprehensive and robust studies, as they use different methodologies and insights from various disciplines.

4.7. Most relevant keywords

The study examined the most relevant keywords and the occurences as the results are shown in Figure 6. Analyzing the most relevant keywords helps in identifying research trends and influential topics, and mapping the intellectual structure of a field.

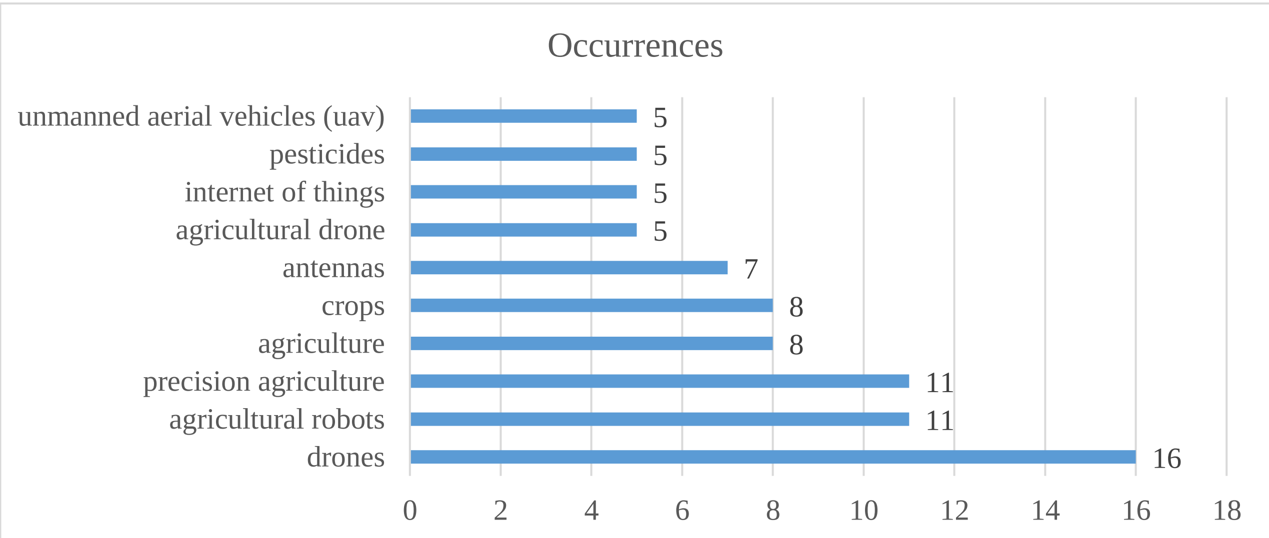

Figure 6. Occurrences of the Most Relevant Keywords

Drones had the highest occurrence, 16, while precision agriculture and agricultural robots had 11. This is because they were the keywords. Agriculture and crops occurred 8 times, while antennas had 7. Agricultural drones, the Internet of Things, pesticides, and unmanned aerial vehicles had 5. These keywords imply that agricultural drones have been examined in the context of precision agriculture, robots, and unmanned aerial vehicles. Agricultural drones are widely applied in spraying pesticides and have been advanced to unmanned aerial vehicles. Data is mainly transmitted through the antennas and scientific advancements have been made constantly to enhance their effectiveness.

4.8. Co-occurrence of keywords

The study further examined the co-occurrence of keywords and the results are shown in Figure 7. Examining the co-occurrence of keywords is essential because it helps in identifying relationships between concepts, uncovering research trends, and mapping the intellectual structure of a field, thereby providing insights into how different topics are interconnected and evolving.

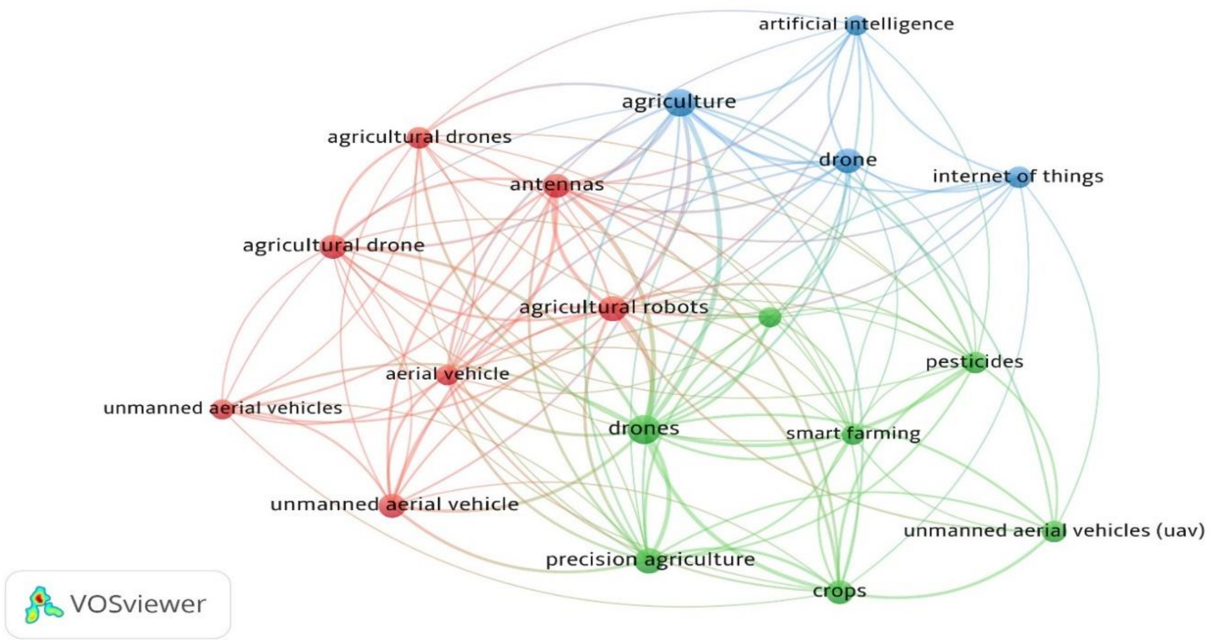

*Figure 7***.** Co-occurrence of Keywords

Figure 7. shows the interconnection between numerous keywords, which are in three clusters, green, blue, and red. The red cluster consists of keywords related to aerial vehicles namely agricultural drones, aerial vehicles, unmanned aerial vehicles, antennas, and agricultural robots. These cover the mechanical aspects of agricultural drones, which consist of the application of unmanned aerial vehicles in agriculture. The blue cluster consists of agriculture, artificial intelligence, drones, and the Internet of Things. These keywords are related to the key sources of data that are integrated into the drone's software. The last, green cluster consists of pesticides, crops, unmanned aerial vehicles, precision agriculture, and smart farming. The application of drones and artificial intelligence in agriculture has helped to advance it into smart farming and precision agriculture, which is more accurate, efficient, and has high yields.

5. Discussion

The bibliometric analysis of agricultural drones reveals significant trends and patterns in research publications, highlighting the multidisciplinary nature and evolving interest in this field. The findings indicate that journals such as the Journal of Drones and IEEE Access are leading in the number of publications, with Applied Sciences (Switzerland), Computers and Electronics in Agriculture, and the Journal of Biosystems Engineering following closely. This broad range of journals suggests that agricultural drone research spans multiple disciplines, from engineering and computer science to agronomy and biosystems engineering, underscoring the necessity for a multidisciplinary approach to fully leverage and advance the technology. The analysis of publication trends since 2014 shows a general increase in research output, with notable fluctuations in specific years. The highest number of publications was recorded in 2021, with 16 articles, reflecting a surge in interest likely driven by advancements in artificial intelligence and its applications in agriculture. Despite occasional declines, the overall upward trend indicates growing recognition of the importance and potential of agricultural drones. The slight dip in 2022 followed by a sharp increase in 2023 further emphasizes the dynamic nature of this research area. The h-index analysis reveals that IEEE Access has the highest impact, with an h-index of 4, indicating that it is a significant source of influential articles in the field. Other journals with moderate h-indices, such as Drones and the Journal of Biosystems Engineering, also contribute substantially to the literature. This citation pattern suggests that while many journals publish on agricultural drones, only a few achieve a high level of impact and influence within the academic community.

Author productivity analysis shows that top contributors like Huang Y and Ramasamy M have published extensively, with each having ten publications. However, the most productive authors are not necessarily the most cited, indicating that high productivity does not always equate to high impact. This highlights the importance of quality and relevance in research outputs over sheer quantity. Collaboration among researchers is evident, with notable partnerships between Cohen and Fountas, Michels and Von, and others. These collaborative efforts enhance the quality and breadth of research by integrating diverse expertise and methodologies, leading to more comprehensive and robust studies. The co-occurrence of keywords such as "drones," "precision agriculture," and "agricultural robots" further illustrates the interconnection between various aspects of agricultural drone research. The keyword clusters reveal distinct areas of focus, from the mechanical aspects of drones to their applications in precision agriculture and smart farming.

6. Areas of further research

Based on the bibliometric analysis of agricultural drones, future research should focus on several key areas. Firstly, integrating Artificial Intelligence (AI) to enhance drones' capabilities in real-time data processing and decision-making represents a significant opportunity. Research should also expand into precision agriculture applications, refining sensor technologies and optimizing resource management based on drone-derived data. Environmental sustainability needs further exploration, particularly in assessing and mitigating drones' ecological impacts and optimizing energy use. Technological advancements, including improving drone endurance and payload capacities, are crucial for expanding their operational efficiency. Addressing regulatory challenges, evaluating economic feasibility, and fostering interdisciplinary collaborations across engineering, agronomy, and policy-making are essential to advancing drone adoption in agriculture. Lastly, exploring emerging applications like urban agriculture monitoring and disaster response will broaden the scope of drone technology's contributions to sustainable agricultural practices.

7. Conclusion

The bibliometric analysis underscores the growing and multidisciplinary interest in agricultural drone research. The increasing number of publications and the involvement of diverse journals and authors reflect the expanding scope and potential of this technology. The impact of key journals and the productivity of top authors highlight important contributors to the field, while the collaboration between researchers signifies the collective effort to advance agricultural drones.

The analysis of keyword co-occurrence reveals critical areas of research focus, such as precision agriculture, unmanned aerial vehicles, and smart farming, demonstrating the integration of advanced technologies in agricultural practices. These insights provide a comprehensive overview of the current state of research on agricultural drones and suggest that continued multidisciplinary collaboration and focus on high-impact research are essential for further advancements.

In conclusion, agricultural drones have seen a significant rise in research interest and application since 2014, driven by technological advancements and the need for efficient agricultural practices. The findings emphasize the importance of a multidisciplinary approach and collaborative efforts to fully realize the potential of agricultural drones in enhancing productivity and sustainability in agriculture.

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