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Bibliometric analysis of 'precision agriculture' in the Scopus database

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Abstract

This bibliometric analysis explores the rapid growth and evolving research dynamics of precision agriculture (PA) from 1999 to 2023 based on data from the Scopus database. Analyzing 1,219 publications, the study identifies a substantial global collaboration and an annual growth rate of 7.97% in PA research. Key findings highlight advancements in artificial intelligence and remote sensing technologies and significant contributions from leading institutions such as Nanjing Agricultural University, the University of Florida, and the University of Bonn. Notably, the study underscores the prominent role of institutions from Germany, the USA, and China in shaping PA research. The insights gained emphasize the critical role of interdisciplinary research in fostering sustainable agricultural practices. Precision agriculture demonstrates the potential for enhanced yields, reduced environmental impacts, and increased efficiency by addressing resource management and food security challenges, particularly in regions like Bangladesh. However, challenges such as high implementation costs and the need for technical expertise persist. This analysis underscores the importance of continued research, policy support, and global interest in advancing precision agriculture, providing a foundation for future innovations and policy development in sustainable agriculture systems worldwide.

Keywords: Precision Agriculture; Smart Agriculture; Agricultural Management; Sustainable Farming; Bibliometric Analysis**.**

1. Introduction

Precision Agriculture (PA) leverages temporal, spatial, and specific data to enhance the efficient use of agricultural inputs—such as water, fertilizers, and pesticides—thereby improving productivity, yield quality, and agricultural sustainability. Originating in the 1980s with the pioneering work of Dr Pierre Robert, PA has progressively evolved from basic practices like grid sampling and soil pH mapping to advanced yield monitoring and crop management systems. Early applications of PA focused primarily on mapping and yield monitoring, which expanded in 1992 when the International Conference on Precision Agriculture (ICPA) introduced "Soil Specific Crop Management" in conjunction with the first yield monitors [1]. In 1994, PA took another leap forward by introducing GPS and variable-rate technology, enabling farmers to implement spatially precise farming practices with unprecedented accuracy [2].

As PA technologies have developed, they have helped address critical issues in sustainable agriculture by supporting ecologically friendly and highly efficient farming methods, a practice increasingly recognized as essential to sustainable intensification [3]. PA operates on the principle of observing, measuring, and responding to field-level variability, offering farmers the ability to apply inputs in a targeted manner, a capability that conventional approaches could not achieve [4]. This paradigm shift in crop management allows farmers to treat fields as heterogeneous entities and manage them selectively based on intra-field variability.

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The ongoing technological advancements in PA—ranging from digital sensors, GPS systems, and ICTs to the Internet of Things (IoT)—have driven an agricultural revolution worldwide, empowering farmers to make precise, data-driven decisions [5]. With these tools, farmers can automate tasks, monitor crop and livestock performance, and reduce their reliance on inputs, thereby lowering costs, enhancing yield quality, and minimizing environmental impacts. For example, the removal of Selective GPS Availability in 2000 allowed GPS applications to be used more accurately in non-military contexts, leading to the widespread adoption of variable-rate applications (VRA) and other innovative PA practices in open-field crops, particularly in countries like the United States, Australia, and Italy [6].

The rapid development of PA has catalyzed socioeconomic changes, prompting legislative decisions that address new issues, such as data management, data ownership, and open data access [7]. Additionally, recent research initiatives continue to explore new PA technologies, aiming to improve farm management holistically and promote sustainable practices. Despite significant progress, PA studies often concentrate on major issues, overlooking smaller but equally relevant topics, such as the use of VRA in speciality crops.

Bibliometric analysis provides a valuable tool for quantifying and evaluating scientific contributions within a field, such as PA, by examining patterns and trends in published research [8]. As an analytical approach, bibliometrics enables researchers to assess the scientific output, trace the evolution of research areas, and inform science policy and planning. Recently, bibliometric mapping—an approach that combines bibliometric analysis with term mapping in titles, abstracts, and keywords—has gained traction across various research domains, such as climate science, chemistry, and Mediterranean ecosystems. Through this approach, researchers can explore large datasets in bibliographic databases, gaining insights into the main research themes and their interconnections.

Given the growing importance of PA, this study employs a science mapping approach to examine the distribution, interrelations, and scientific impact of PA research topics within the Scopus database. The analysis highlights the research trajectories of several geographic regions, including Italy, and identifies changes in the structure of PA research over the past 17.

The objectives of this study are threefold: (1) To identify and analyze the prominent themes in PA research, (2) To visualize their interconnections and trends, and (3) To provide insights for researchers, students, and policymakers interested in the evolving field of Precision Agriculture.

2. Precision Agriculture (PA)

Precision Agriculture (PA) is a technologically advanced management approach to enhance crop production by observing, measuring, and responding to field variability [9]. Also known as site-specific crop management (SSCM), PA leverages technologies such as GPS, remote sensing, and variable rate application (VRA) to optimize input use, thereby improving crop yield and minimizing waste. This data-driven method enables farmers to administer nutrients, water, and treatments, enhancing sustainability and profitability.

The primary objectives of PA include enhancing crop yields, reducing input costs, and promoting sustainability by minimizing the environmental impact of farming practices [10]. PA employs advanced tools like drones, sensors, and data analytics to facilitate efficient resource use. This targeted approach allows for precise interventions, reducing waste and improving productivity while supporting data-driven decision-making.

PA technologies like GPS and remote sensing offer solutions to improve resource allocation and boost productivity [11]. However, barriers such as high costs, limited technical expertise, and access to tools hinder full adoption. Policy and institutional support are crucial for overcoming these challenges and facilitating the broader implementation of PA. PA significantly enhances operational efficiency and decision-making by providing real-time data on factors influencing crop productivity. It reduces costs, improves crop quality, and minimizes environmental impact by aligning inputs with crop needs. PA also fosters sustainable practices by conserving resources and reducing environmental degradation [12].

The widespread adoption of PA is constrained by high initial costs, making it less accessible to small-scale farmers [13]. Additional challenges include data privacy concerns, lack of standard procedures, and insufficient technical support. Addressing these barriers requires financial assistance, improved data governance, and enhanced training programs to implement PA technologies effectively.

3. Methodology

This study employs comprehensive scientific mapping techniques to conduct a bibliometric analysis of "Precision Agriculture" using the Scopus database. The analysis spans a decade, covering publications from its first publication in 1999 to 2023. Scopus, a widely recognized source of bibliographic information, provides a reliable foundation for this research.

3.1. Data Collection

The initial data collection was conducted using the keywords "Precision" AND "Agriculture" within the Scopus database, resulting in 1289 publications. Each publication's complete record, including references, was exported for bibliometric analysis. After removing duplicates, the dataset comprised 1219 unique articles. The search was finalized on September 26, 2023.

3.2. Analytical Tools

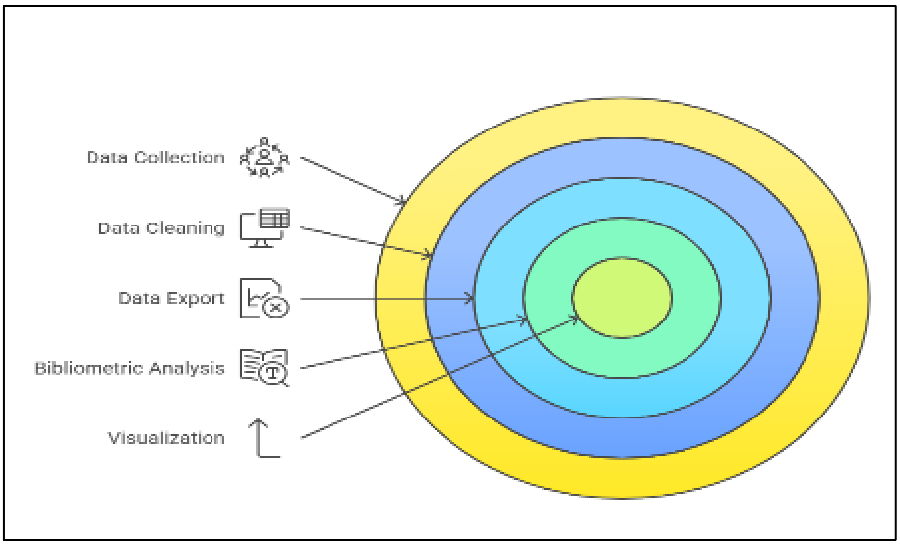
The bibliometric analysis was performed using the Bibliometric package in the R programming environment, a robust scientific mapping and analysis tool. VOSviewer, a sophisticated visualization tool, created and visualized bibliometric networks, offering insights into co-authorship, keyword co-occurrence, and citation patterns [14]. The R package Bibliophagy, known for its user-friendly online applications, was utilized to enhance data handling and visualization [15].

3.3. Research Procedure

The research methodology followed a structured five-step process:

a. **Data Collection**: Articles were retrieved from Scopus using specified keywords.
b. **Data Cleaning**: Duplicate entries were removed to ensure the dataset's integrity.
c. **Data Export**: Complete records of articles were exported for analysis.
d. **Bibliometric Analysis**: Using the Bibliometric R package, data were analyzed to identify trends, key contributors, and research hotspots.
e. **Visualization**: VOSviewer was used to create visual representations of the bibliometric networks.

This systematic approach allows for a thorough examination of precision agriculture's evolution and research dynamics, providing valuable insights for future research and policy development in this field. Figure 1 illustrates the detailed research procedure followed in this study.



Source: Original material of the study

Figure 1 The steps in research methodologies

4. Results and discussion

4.1. Primary data-related information

Figure 2 describes a dataset of scientific publications published between 1999 and 2023. With 1,219 documents, it shows a 7.97% yearly growth rate. The average age of 8.34 years and the average number of citations per document (30.48) indicate the academic merit of these works. The collection has a substantial number of references—39,173 in total.

The substance of the papers is shown by the 3,420 Author's Keywords (DE) and 1,896 Keywords plus (ID), which show the range of concerns and subjects addressed in the articles. With 3,862 authors overall—34 single-authored pieces and an average of 4.72 co-authors per document—the collection has many writers. Notably, 23.95% of these partnerships had foreign co-authors, indicating a worldwide perspective on the study.

The bulk of the document categories in this dataset are articles (1,094), although there are also conference papers (64), editorials (17), errata (12), reviews (31), and one brief survey (1). These document types demonstrate a diversity of scholarly contributions. Scholarly production in this particular topic throughout the specified period can interest scholars and institutions, and this table offers a thorough summary of the dataset's features.

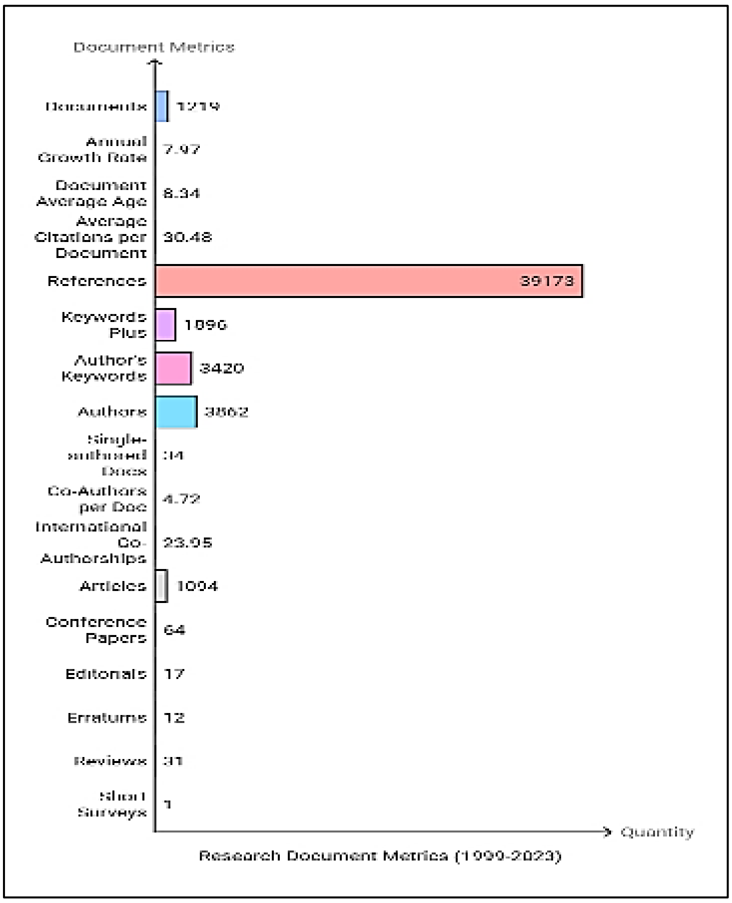


Figure 2 Descriptive statistics for the data

4.2. Publication progression

An annual count of scientific publications published between 1999 and 2023 is shown in Figure 3, "Annual Scientific Production". The number of publications was low initially, declining in 2001 and then increasing again in 2002. The number of articles increased steadily from 2003 to 2006, with small oscillations in between. Between 2007 and 2010, there was a discernible increase in scientific output, which peaked in 2011. Following this high, the number of articles somewhat declined before staying mostly constant from 2011 to 2014 with a few slight variations. There was a notable rising trend starting in 2015, and the number of publications increased significantly, especially between 2018 and 2023.

The graph shows rising interest and scientific output in the topic throughout the specified period, with a notable uptick in recent years.

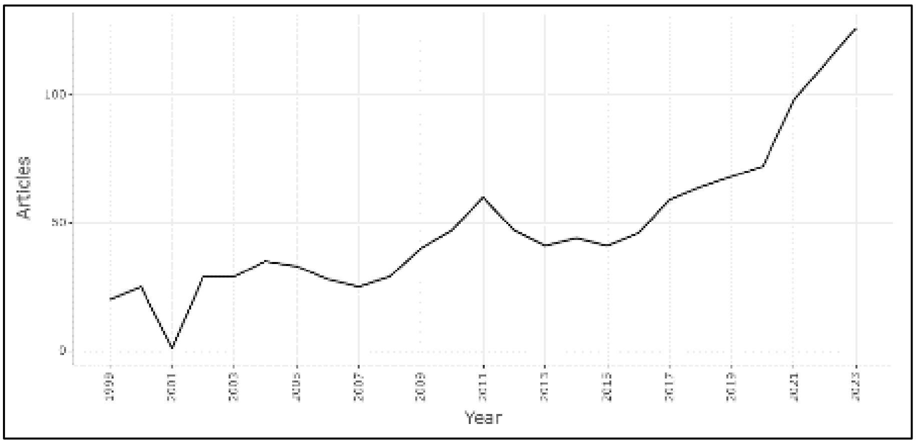


Figure 3 Annual progression of publication (1999-2023**)**

4.3. Citation

Figure 4, "Average Citations per Year," from 1999 to 2023, shows how many citations there were. Over the years, the line varies, showing a general increasing tendency with notable peaks and dips. There is a noticeable peak in citations between 2013 and 2014, followed by a fall and a rise in 2021–2022.

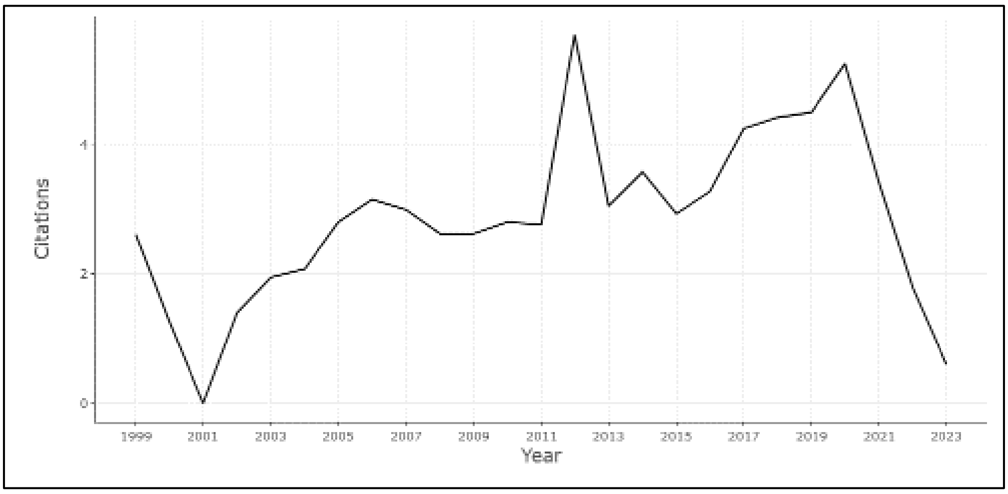


Figure 4 Average citation per year

4.4. Author's Outputs

Figure 5 shows the "Most Relevant Authors." The total number of articles published, which varies from 0 to 20, is shown, along with the names of each author. Each author is shown as a horizontal bar, the length of which reflects the total number of papers to which they have contributed. The authors are ordered according to document count, with TISSERVRE B at the top with 29 documents. Based on their document output, the authors' productivity is visually compared in this chart.

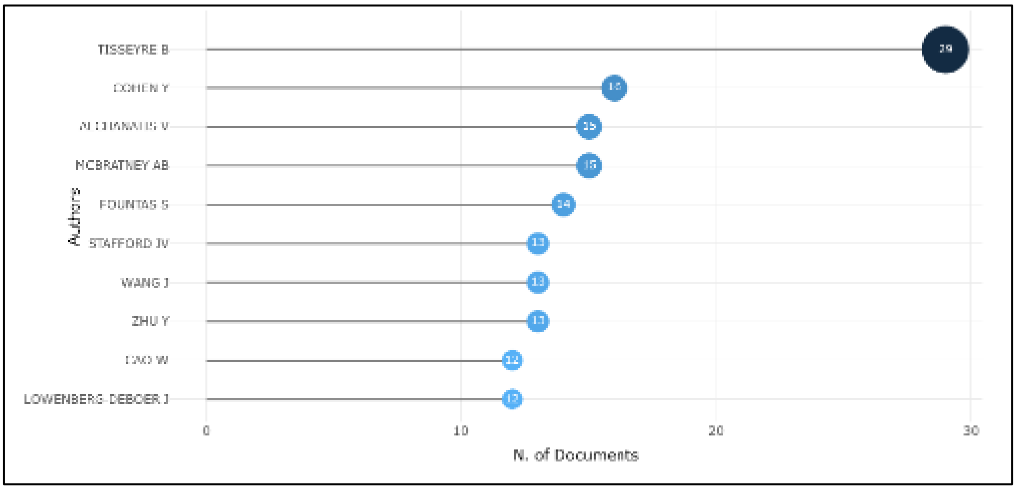


Figure 5 Author's publication

4.5. Author Efficiency using Lotka's Law

Figure 6 shows a graphic depiction of Lotka's Law that displays the distribution of author production throughout a field. The figure represents the total number of articles authored by the author and the proportion of writers who have written that many papers. The solid line displays the actual data, while the dotted line represents the theoretical distribution according to Lotka's Law. The distribution is power-law, as shown by the graph, where a few prolific writers account for a disproportionately significant part of all publications.

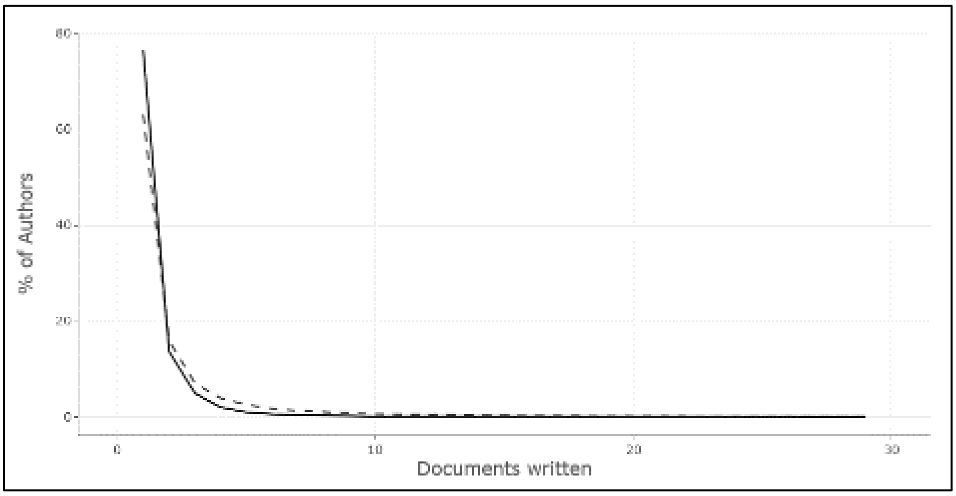


Figure 6 Author productivity through Lotka's law

4.6. Corresponding Authors' Countries

A horizontal bar chart depicting the distribution of multiple-country publications (MCP) and single-country publications (SCP) across different nations is shown in Figure 7. The y-axis displays the list of countries, while the x-axis displays the quantity of papers. Each country is shown by two horizontal bars, one for SCP and one for MCP. The length of the bar indicates how many papers are in each category. The countries are ranked according to the total number of documents (SCP+MCP). The graphic illustrates the trends in patterns of international research partnerships.

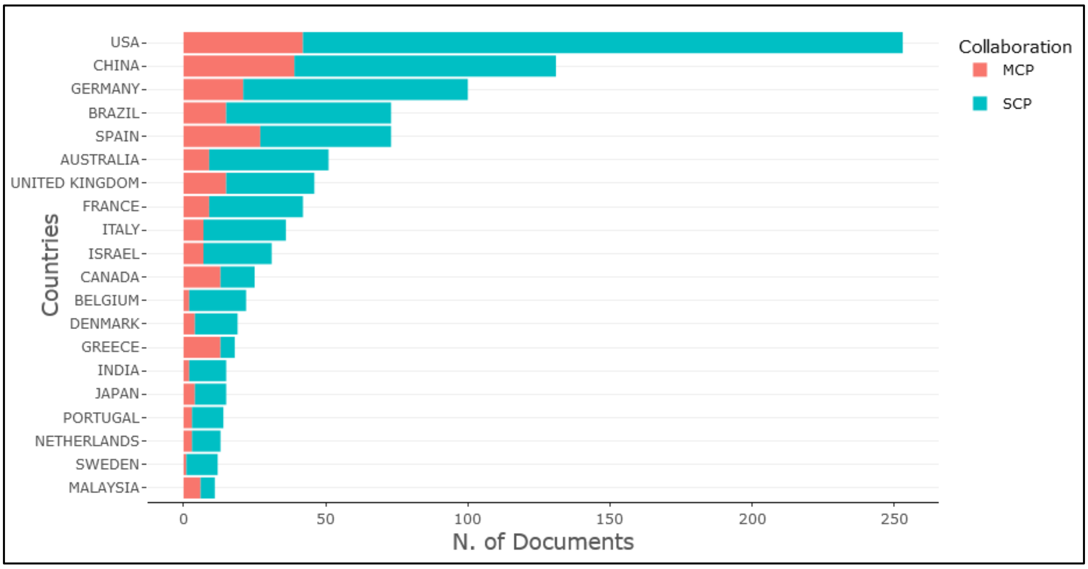


Figure 7 Corresponding authors' countries

4.7. Country Collaboration

Figure 8 shows a network visualization of trends in international research collaboration. Nodes represent countries, and larger nodes denote higher levels of research production. Thicker lines linking the nodes indicate stronger cooperation linkages, which indicate joint research activity across national boundaries. Key research hubs with many international linkages, such as the US, China, and Europe, are highlighted on the map. Regional collaboration clusters are also visible in the picture, especially in North America, Europe, and Asia.

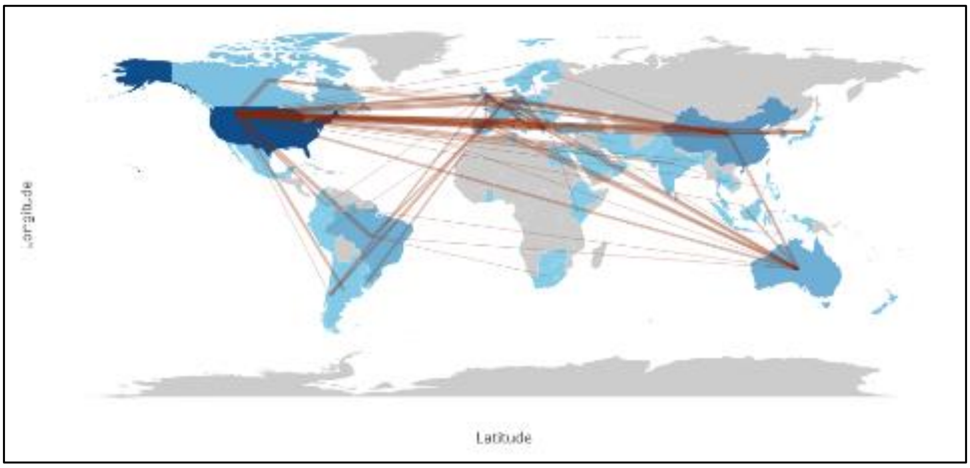


Figure 8 Collaboration among the countries

4.8. Active Institutions

The top 10 universities are shown in Table 1 according to the overall number of published publications. With 95 publications, Nanjing Agricultural University is the most prominent university, with 73 and 72 articles, respectively; the University of Florida and the University of Bonn rank second and third. Other notable universities that have contributed more than fifty publications are the University of Nebraska–Lincoln, South China Agricultural University, China Agricultural University, and Oklahoma State University. An overview of the most active universities in the subject is given in this table.

Table 1 Key Institutions and their Productions

Affiliation	Articles
NANJING AGRICULTURAL UNIVERSITY	95
UNIVERSITY OF FLORIDA	73
UNIVERSITY OF BONN	72
SOUTH CHINA AGRICULTURAL UNIVERSITY	67
CHINA AGRICULTURAL UNIVERSITY	64
OKLAHOMA STATE UNIVERSITY	63
UNIVERSITY OF NEBRASKA-LINCOLN	51
UNIVERSITY OF GEORGIA	49
GHENT UNIVERSITY	48
INSTITUTE OF AGRICULTURAL ENGINEERING	42

4.9. Network Analysis and Trend Word Analysis

4.9.1. Cluster analysis

Figure 9 presents a Clustering by Coupling visualization of the links between essential articles in the precision agriculture sector. Nodes represent individual research; more prominent nodes denote more frequent citations. Edges joining the nodes indicate co-citation links, which imply intellectual ties between the cited works. The network is segmented by discrete clusters, which correspond to study themes. The graphic provides a thorough synopsis of the body of knowledge and conceptual framework in the precision agriculture field.

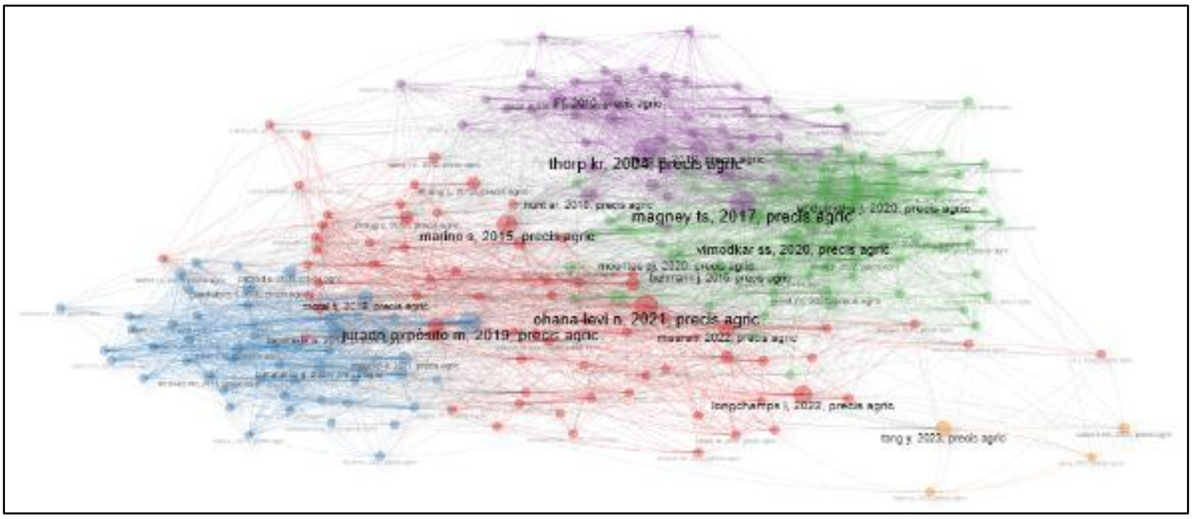


Figure 9 The clusters in precision agriculture research

4.9.2. Network of co-occurrence for the terms

Figure 10 illustrates a co-occurrence network that connects essential phrases in precision agriculture. Nodes represent individual keywords; more prominent nodes denote more frequent occurrences. Co-occurrence, or the frequency with which specific terms appear in the literature, is shown by edges linking the nodes. The network is split into two discrete clusters: one for precision agriculture, crop yield, and nitrogen control, and another for remote sensing. This graphic depiction sheds light on the connections between ideas in the discipline and offers suggestions for future lines of inquiry and areas of incomplete knowledge.

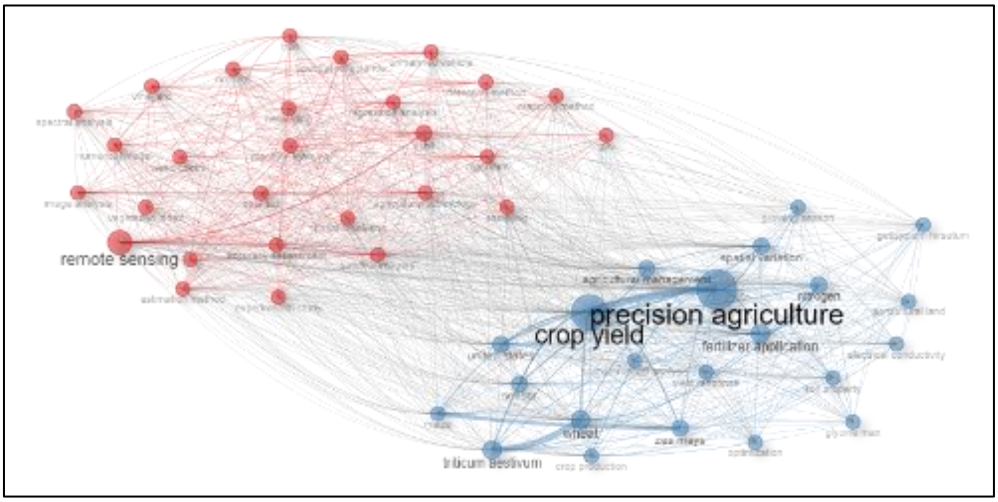


Figure 10 Co-occurrence network of the keywords

4.9.3. Trend topics

A dynamic representation of keyword trends within the research field from 2001 to 2023 is shown in Figure 11. Each horizontal line represents a word, and the size of the circle markers indicates how often a term occurs in the literature throughout a given year. Many phrases, including "artificial neural network," "machine learning," and "remote sensing," have an upward trajectory, which indicates that they are becoming more and more popular over time. On the other hand, words like "education" and "soil survey" show relatively steady or decreasing tendencies. This graphic depiction provides insights into the field's changing research environment and the rise of fresh emphasis points.

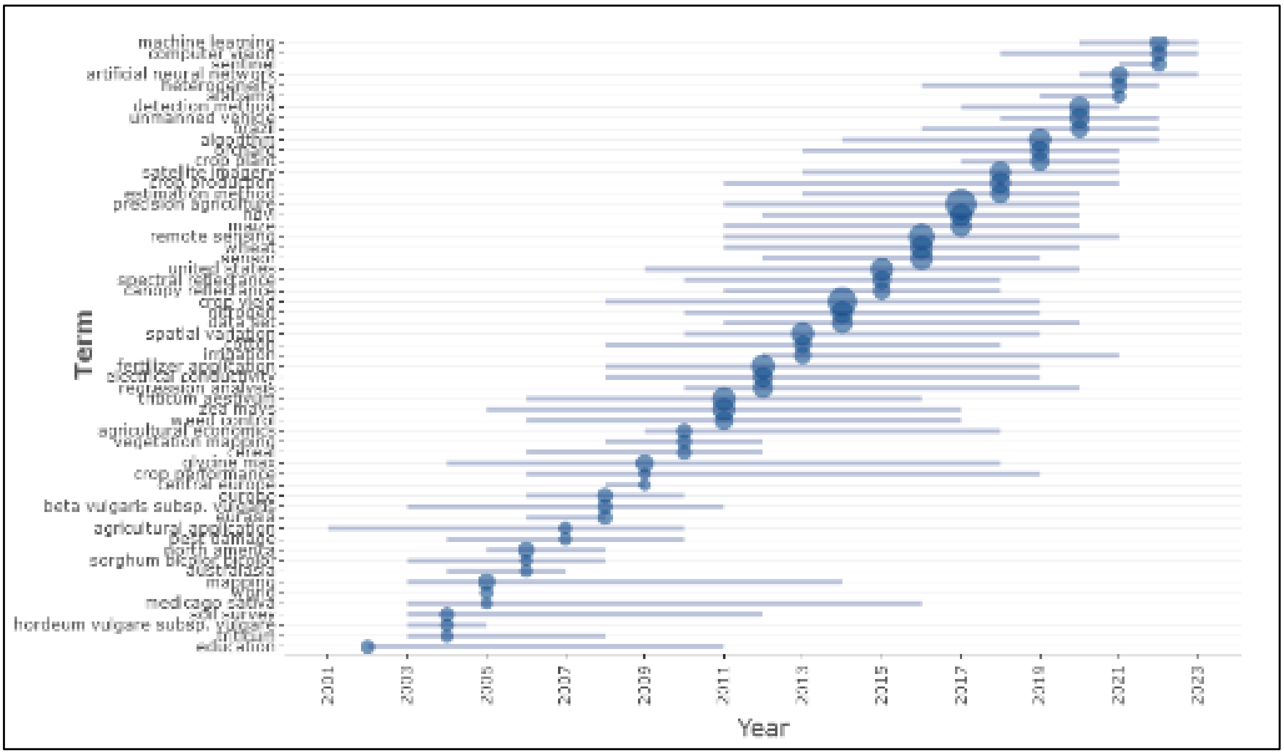


Figure 11 Trend topic in precision agriculture

5. Discussion

This bibliometric analysis covers precision agriculture research indexed in the Scopus database from 1999 to 2023, giving a meaningful overview of the field's development, leading contributors, and future directions. Because of the continued technological advances and challenges to sustainable agricultural production systems, precision agriculture is becoming increasingly significant academically and practically (every model, algorithm, and application computer code being developed represents a knowledge base for subsequent researchers).

This dataset of 1,219 documents reveals an annual growth rate of 7.97%, which shows the increasing interest in precision agriculture. The average citation count of 30.48 per document highlights the strong academic impact of this research, along with two peaks in citations during 2013–2014 and 2021–2022. The peaks correspond to critical technological innovations like remote sensing and machine learning adoption in agricultural practices [16]. Precision agriculture is a cross-disciplinary field since the number of references (39,173) was also huge and many themes were involved, including agronomy, computer, and environmental engineering.

In total, there were 4.72 authors on average for each document, and 23.95% of documents had international collaboration, which makes a great degree within each discipline. This global view is in agreement with that provided by Li et al. 2020), who said that active participation in international collaboration enhances the quality and innovation of research. Effective publishing in each discipline and the load to come from Lotka's Law, with only few highly productive authors producing most of the works in the discipline.

The geographical variety of analysis output demonstrates the dominance of such international locations as the United States, China, and Europe. These areas are also central nodes for cross-border cooperation, as shown by the network map in Figure 8. Some of the highly active institutions, like Nanjing Agricultural University, the University of Florida, and the University of Bonn, have significantly contributed to the field. This is consistent with the study of Wang et al. leading agricultural research and innovating institutions (2021).

5.1. Emerging Research Themes

The co-occurrence network of keywords (Figure 10) and trend analysis (Figure 11) indicate the dynamic of precision agriculture research. These include terms like "artificial neural network", "machine learning," and "remote sensing", all indicators that advanced technologies are becoming increasingly prominent in all aspects of agriculture. Our findings align with previous studies highlighting the importance of AI and big data as essential strategies for maximizing crop management and input use [17]. In contrast, more traditional topics, e.g., "soil survey" and "education," exhibit relatively flatter or decreasing trajectories, indicating a discernible cultural shift in research priority.

The clustering by coupling (Figure 9) reveals specific precision agriculture research themes, such as crop yield optimization, nitrogen management, and remote sensing use. These have been combined into clusters that serve as the conceptual backbone for interpreting the domain's intellectual structure and for identifying areas for future development. Integration of machine learning with remote sensing for real-time monitoring and agricultural decision-making [18].

5.2. Implications for Future Research

This study has several implications for researchers, policymakers, and practitioners. The growing attention to advanced technologies, including machine learning and remote sensing, highlights the importance of interdisciplinary teamwork and capacity building within (or beyond) computing and data science. Second, certain countries and institutions have great dominance, so we must establish partnerships with institutions across the globe to tackle issues in precision agriculture. Finally, recognizing emerging trends and research opportunities directs the focus of future research lines, particularly sustainable resource use and agriculture under climate change scenarios.

This bibliometric analysis provides insights into precision agriculture research's development and current status. These insights underscore the field's maturation, pivotal actors, and innovative trends, establishing a bedrock for future inquiries and advancements. The future of precision agriculture can revolutionize how we approach farming, paving the way toward a more sustainable and efficient global food system.

6. Conclusions

This bibliometric analysis offers an extensive review of the research scenario, leading contributors, and emerging trends in precision agriculture, as outlined in the Scopus database between 1999 to 2023. The study unveiled the intellectual landscape and research dynamics within the field by employing scientific mapping, bibliometric analysis, and network visualization.

6.1. Key Findings

The analysis showed that scientific output on precision agriculture increased steadily through the years, especially after 2015, indicating an increasing significance of related technical advancements in agriculture. As Figure 3(b) shows, research impact as measured through citation analysis dropped after the rigorous time points in 2013–2014, but also recovered in subsequent years. The authorship analysis revealed a variety in the research community, showing a wide range of international cooperation demonstrated by MCPs as well as extended research partnerships.

The study also revealed the dominant research institutes in the field, with the Nanjing Agricultural University, University of Florida, and University of Bonn having the most publications. The presence of a robust network of educational institutions and research collaborations has they have helped create channels for knowledge dissemination and research and innovation for precision agriculture.

6.2. Research Implications

The clustering analysis and co-occurrence networks of keywords emphasized fundamental research themes with dominant production areas (e.g. remote sensing, machine learning, artificial intelligence, crop yield enhancement) and with dominant receiving areas. Data-driven decision-making, sustainable agricultural practices, and a significant emphasis on digital technologies are some of the emerging trends. Taken together, this evidence indicates that the future developments in precision agriculture would be powered predominantly by advances in automation, big data analytics, and climate-smart agriculture.

Together, the discoveries from the study hold essential ramifications for policymakers, agronomists, and agricultural extension professionals. This bibliometric analysis reveals crucial stakeholders, current institutes and nascent research domains that can facilitate research-linked collaboration development and strategic funding decision-making to sustain precision farming advancements.

6.3. Well-established Limitations and Research Directions

To what we know, and this study offers some very useful insights, there are a couple of limitations. But first, it was only based on Scopus data, which isn't comprehensive as it misses relevant publications indexed in other databases (Google Scholar, Web of Science, etc.). In a future study, a more widespread analysis might be conducted by using multiple databases. Moreover, although bibliometric approaches highlight quantitative trends, they cannot capture qualitative perspectives centered around methodologies or practical applications in research. Integrating bibliometric findings with a more in-depth content analysis could yield richer perspectives on how precision agriculture has evolved.

Given that your data goes only until October 2023, we will help you know what more can be done with the research on the future of precision agriculture with emerging events; for example, we have the ever-growing technologies of AI, IoT, and Blockchain changing the face of the world of precision agriculture. In addition, multidisciplinary research across agronomy, computer science, and environmental studies can yield synergetic solutions to the challenges of sustainable food production.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare no conflict of interest.

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