Bibliometric Analysis to Recognize Precision Agriculture Research Trends

Tassanee Lunrasri [1*]

[1*] Faculty of Humanities and Social Sciences, Khon Kaen University, Thailand
Corresponding author: tassanee.l@kkumail.com

Abstract

This study presents a comprehensive bibliometric analysis of Precision Agriculture (PA) research from 2000 to 2024, using Scopus database records to examine its evolution, key contributors, influential journals, and leading countries while identifying emerging themes. By applying citation analysis, co-citation networks, bibliographic coupling, and thematic mapping, the study systematically explores PA research trends. Findings indicate a 23.77% annual growth rate, driven by advancements in AI, machine learning (ML), remote sensing, and automation technologies. China and the United States lead global research, with strong international collaborations, particularly with Australia, Canada, and Spain. Key themes include AI-driven decision-making, UAV-based remote sensing, and IoT integration in smart farming, highlighting the role of digital transformation in agriculture. However, critical research gaps persist, especially in smallholder farmer adoption, sustainability assessments, and economic feasibility. Future research should enhance interdisciplinary collaboration, develop cost-effective solutions, and improve technology accessibility in developing regions. By providing a structured overview of research trends and collaboration networks, this study offers valuable insights for policymakers, researchers, and practitioners, shaping agricultural policies, fostering innovation, and accelerating PA technology adoption for sustainable, technology-driven farming.

Keywords: Precision Agriculture (PA), Bibliometric Analysis, AI and Machine Learning, Remote Sensing and UAVs, IoT Integration and Smart Farming.

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1. Introduction

Precision Agriculture (PA) has emerged as a transformative paradigm in modern farming, integrating advanced technologies such as Global Positioning Systems (GPS), Geographic Information Systems (GIS), machine learning, the Internet of Things (IoT), and unmanned aerial vehicles (UAVs). Since its inception in the 1980s, PA has been widely recognized for its ability to optimize resource utilization, enhance crop management, and minimize environmental impacts (Yang, 2018; Padgitt et al., 2001). By addressing critical global challenges, including climate change, food security, and sustainable farming, PA has revolutionized agricultural practices, driving innovation and efficiency through cutting-edge technologies (Fraser, 2018; Knierim et al., 2019).

Over time, PA has expanded its applications, incorporating technologies such as remote sensing, big data analytics, and autonomous systems. These innovations enable real-time decision-making and precision-driven interventions, significantly improving resource efficiency and environmental sustainability through tools like precision irrigation, machine learning, and wireless sensor networks (Sa et al., 2018; Groher et al., 2020). Despite these advancements, there remains a need to understand the trajectory of PA research, identify dominant themes, and highlight emerging technologies and key contributors to guide future innovations and sustainable practices.

Bibliometric analysis has become a crucial methodology for systematically examining the development, structure, and trends within scientific research. By analyzing publication data, citation patterns, and co-authorship networks, bibliometric methods provide valuable insights into the evolution of research fields, reveal emerging themes, and identify gaps in existing knowledge (Donthu et al., 2021b; Zupic & Čater, 2014). In the context of PA, bibliometric analysis has illuminated the progression of research from foundational studies on spatial variability to advanced applications, such as AI-driven crop forecasting and IoT-enabled systems (Triantafyllou et al., 2019; Zhang et al., 2021).

These insights underscore the importance of interdisciplinary collaboration and the integration of diverse technological domains in advancing precision agriculture. Bibliometric analysis is a quantitative method that uses statistical techniques to evaluate publications within a specific research domain, identifying influential papers, authors, journals, and countries, while highlighting emerging research themes. It provides insights into the evolution and structure of Precision Agriculture (PA) research and helps reveal research gaps and trends shaping the field (Aria & Cuccurullo, 2017).

This study comprehensively assesses the current state and future directions of PA research, offering valuable insights for researchers, practitioners, policymakers, and academic institutions. The research conducts a bibliometric analysis of precision agriculture (PA), utilizing data systematically gathered from the Scopus database, to explore recent research trends, prominent themes, and key developments within the field. Additionally, the study highlights significant findings, identifies existing research gaps, and offers recommendations to inform future research directions.

2. Related works

Precision Agriculture (PA) has received significant attention in recent years due to its potential to optimize resource utilization, enhance crop management, and reduce environmental impacts. The integration of advanced technologies such as Global Positioning Systems (GPS), Geographic Information Systems (GIS), machine learning, and the Internet of Things (IoT) has transformed traditional farming into digitalized agricultural systems. This transformation enhances efficiency, reduces costs, and improves productivity (Yang, 2018; Padgitt et al., 2001). PA supports data-driven decision-making, enabling farmers to better adapt to climate variability, a critical global issue emphasized by the United Nations for ensuring food security and sustainability.

Bibliometric analysis has become an essential methodology for examining research trends, citation patterns, and key contributors in the field. Studies by Donthu et al. (2021b) and Zupic & Čater (2014) demonstrate its effectiveness in tracking the evolution of research, identifying key themes, and highlighting gaps in existing literature. Bibliometric studies have documented the shift from early investigations of spatial variability to advanced technologies such as AI-driven crop forecasting and IoT-enabled systems (Triantafyllou et al., 2019; Zhang et al., 2021), underscoring the importance of interdisciplinary collaboration.

Similarly, Pang et al. (2023) identified IoT and machine learning as crucial technologies driving smart irrigation, reflecting their rapid growth in recent years. Armenta Medina et al. (2020) employed bibliometric methods to analyze advanced information and communication technologies (ICT) in agriculture, revealing key research clusters in precision agriculture, smart agriculture, and remote sensing. The integration of AI, big data, and IoT has been recognized as a leading trend, significantly advancing crop yield forecasting, resource efficiency, and decision-making capabilities (Fraser, 2018; Groher et al., 2020).

Recent interest has also grown around Agriculture 4.0, which integrates AI, big data, cloud computing, IoT, and robotics into agricultural practices (Barman et al., 2024). Bibliometric analyses on Agriculture 4.0 highlight its rapid expansion and emphasize the need for further research to improve farmer accessibility (Gupta et al., 2024; Barman et al., 2024). Latino et al. (2022) examined agricultural digitalization, identifying research clusters including technology applications, data modeling, and decision support systems for crop monitoring. Overall, bibliometric analysis systematically assesses research outputs, citation networks, and key themes, offering comprehensive insights into advancements, technological integration, and ongoing challenges in PA research. Building upon existing studies, this research examines PA trends from 2000 to 2024, emphasizing technological advancements, emerging themes, and research gaps.

3. Methodology

This study employs bibliometric analysis, a quantitative approach, to systematically evaluate scientific literature related to precision agriculture (PA). This methodology provides an objective framework to assess research scope and depth, applying fundamental bibliometric techniques such as performance analysis and science mapping (Donthu et al., 2021) based on frameworks by Aria and Cuccurullo (2017), Glänzel and Schubert (2006), and Zupic and Čater (2014). The key methods used include citation analysis, co-citation analysis, bibliographic coupling, co-author analysis, and co-word analysis. These approaches help to systematically identify research gaps, uncover emerging trends, and analyze the intellectual structure of PA research. Overall, bibliometric analysis contributes significantly to understanding core topics, mapping specialized research areas, and clarifying future research directions in precision agriculture.

3.1 Data extraction

Data for this study were systematically collected from the Scopus database to comprehensively address the research question and ensure robust findings (Čater and Zupic, 2015; Gaviria-Marin et al., 2019; Griffith et al., 1974; Jamshed and Majeed, 2022; Mongeon and Paul-Hus, 2016). Scopus, one of the world's largest and most comprehensive databases, provides extensive, reliable academic content across various disciplines, including science, technology, medicine, social sciences, and humanities. Publications were identified through keyword searches for "Precision Agriculture" (PA), an umbrella concept that integrates various Smart Farming technologies, including AI, machine learning, IoT, sensors, UAVs, Big Data, and GIS, all of which collectively enhance agricultural efficiency, optimize resource management, and support climate adaptation (Agustin et al., 2022; Streed et al., 2021; Balafoutis et al., 2020)., resource management, and climate adaptation. The selection criteria limited the dataset to English-language, open-access articles. Initially, 2,078 articles were retrieved, with incomplete metadata filtered out. Data-cleaning procedures adapted from Wang et al. (2020) standardized author keywords, affiliations, and bibliographic details, ensuring consistency and reliability. The final dataset, prepared according to PRISMA guidelines (Liberati et al., 2009; Moher et al., 2009; Page et al., 2021), provides a solid basis for analyzing trends, identifying key contributors, and mapping the evolution of PA research (see Figure 1).

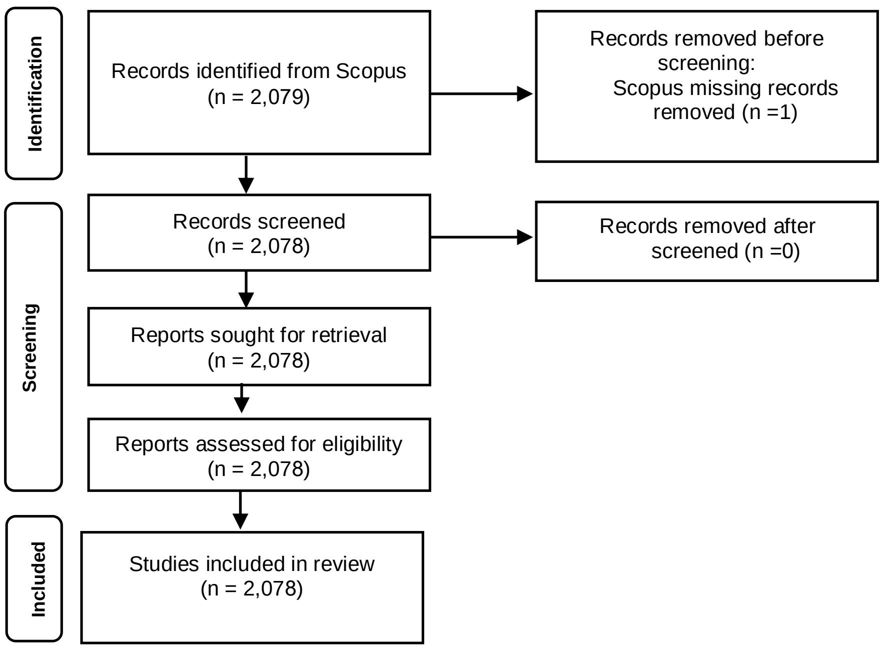

Figure 1. PRISMA flow diagram.

3.2 Data analysis

Bibliometric Analysis in Precision Agriculture Research Bibliometric analysis quantitatively evaluates scientific output through literature, playing a crucial role in tracking Precision Agriculture (PA) research and identifying emerging trends (Donthu et al., 2021). This approach provides insights into publication metrics, geographical distribution, author collaborations, leading institutions, and key journals. By applying statistical and mathematical techniques, bibliometric analysis examines elements such as keywords, article types, authors, publication sources, and abstracts. It primarily measures scientific output in journal articles and conference proceedings and is commonly conducted using RStudio® with Biblioshiny, a widely used tool for bibliometric studies (Aria & Cuccurullo, 2017). Before analysis, the dataset underwent data cleaning and correction to ensure consistency and accuracy, following Van Eck and Waltman (2010). Types of Bibliometric Analysis Conducted

1. Descriptive Analysis: Summarized the growth of PA research, highlighting key contributing countries, prominent authors, and influential journals.
2. Bibliometric Analysis: Employed methods including performance analysis, citation analysis, co-citation analysis, bibliographic coupling, co-word analysis, and co-authorship analysis. Data processing was conducted using Microsoft Excel to ensure accuracy and reliability. Network maps and collaboration structures were generated using Biblioshiny in RStudio, illustrating relationships among core research concepts, author networks, and thematic clusters.

These bibliometric tools provided a structured analysis of PA research, offering deeper insights into its evolution, structure, and future directions.

4. Results

This section presents bibliometric findings on Precision Agriculture (PA), highlighting key research trends, major topics, and gaps for further study. Through a systematic literature assessment, it explores technological advancements and PA's evolving role in modern agriculture. The findings provide a foundation for future research and support agricultural development.

Table1. presents the bibliometric analysis of PA research from 2000 to 2024 examines 2,078 documents from 491 sources, reflecting a 23.77% annual growth rate. With 7,441 unique authors and an international co-authorship rate of 27.91%, the study highlights a strong collaborative trend, averaging 5.17 co-authors per document. The 5,006 author keywords provide insights into key themes, while the 57,847 references may reflect indexing limitations. The field, averaging 3.55 years in age, is young and evolving, with an average citation rate of 27.91 per document, indicating strong academic impact. Table 1 illustrates a rapidly growing research domain with increasing global collaboration and scholarly influence, positioning PA for continued advancement.

Table 1. Main information on the records used for this bibliometric study.

Description	Results
Timespan	2000:2024
Sources (Journals, Books, etc)	491
Documents	2078
Annual Growth Rate %	23.77
Document Average Age	3.55
Average citations per doc	27.91
References	57847
Keywords Plus (ID)	7441
Author's Keywords (DE)	5006
Authors	7861
Single-authored docs	31

Description	Results
Co-Authors per Doc	5.17
International co-authorships %	27.91

Figure 2. presents the publication trends in Precision Agriculture (PA) research from 2000 to 2024 show a steady rise in research output. From 2000 to 2014, publications remained low, with fewer than 10 articles per year. Between 2015 and 2017, output grew steadily, reaching 39 articles in 2017. Since 2018, PA publications have surged, rising from 65 in 2018 to 120 in 2019. The most significant growth occurred between 2020 and 2024, with publications increasing from 218 in 2020 to 501 in 2024. This trend reflects technological advancements and growing academic and industry engagement, particularly in the past five years.

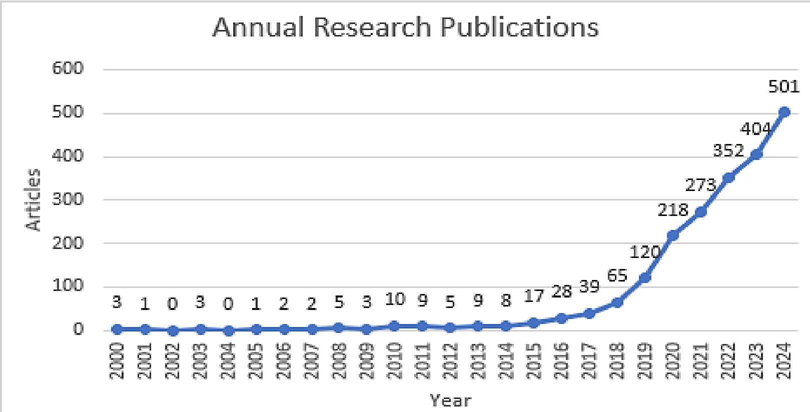

Figure 2. Annual Research Publications

Table 2. Show ten most globally cited Precision Agriculture (PA) papers highlight significant research contributions, especially in remote sensing and UAV applications. The leading paper, "Remote Sensing for Agricultural Applications: A Meta-Review" (Weiss et al., 2020), has 1,156 citations, followed by "DeepFruits: Applications of Remote Sensing in PA" (Sidodia et al., 2016) with 723 citations. Other influential studies include UAV applications (Radoglou-Grammatikis et al., 2020; 667 citations) and deep learning for crop yield prediction (Maimaitijiang et al., 2020; 649 citations). Research focusing on multispectral imaging, biomass estimation, and IoT-based agriculture also stands out, notably "IoT, Big Data, and AI in Agriculture" (Misra et al., 2019) with 478 citations. These works emphasize UAV-based remote sensing, AI analytics, and spectral imaging, reflecting the technological evolution within PA. Citation trends confirm remote sensing and UAV technologies as key drivers in advancing smart agriculture.

Table 2. Top 10 Most Cited Papers Globally

Paper	*DOI*	*TC*	*TCY*	*NTC*
Remote sensing for agricultural applications: A meta-review (Weiss et al., 2020)	10.1016/j.rse.2019.111402	1156	192.67	20.11
DeepFruits: Applications of remote sensing in precision agriculture: A review (Sishodia et al., 2016)	10.3390/rs12193136	723	120.50	12.58
A compilation of UAV applications for precision agriculture (Radoglou-Grammatikis et al., 2020)	10.1016/j.comnet.2020.107148	667	111.17	11.60
Soybean yield prediction from UAV using multimodal data fusion and deep learning (Maimaitijiang et al., 2020)	10.1016/j.rse.2019.111599	649	108.17	11.29

Paper	*DOI*	*TC*	*TCY*	*NTC*
Evaluating multispectral images and vegetation indices for precision farming applications from UAV images (Candiago et al., 2015)	10.3390/rs70404026	619	56.27	3.76
Estimating biomass of barley using crop surface models (CSMs) derived from UAV-based RGB imaging (Bendig et al., 2022)	10.3390/rs61110395	587	48.92	5.87
Intercomparison of UAV, aircraft and satellite remote sensing platforms for precision viticulture (Matese et al., 2016)	10.3390/rs70302971	537	48.82	3.27
IoT, Big Data, and Artificial Intelligence in Agriculture and Food Industry (Misra et al., 2019)	10.1109/JIOT.2020.2998584	478	119.50	22.64
Processing and assessment of spectrometric, stereoscopic imagery collected using a lightweight UAV spectral camera for precision agriculture (Honkavaara et al., 2012)	10.3390/rs5105006	443	34.08	4.48
Sensor Planning for a Symbiotic UAV and UGV System for Precision Agriculture (Tokekar et al, 2017)	10.1109/TRO.2016.2603528	414	41.40	3.90

Remark: TC = Total Citations, TCY= Total Citations per Year, NTC=Normalized Total Citations

Figure 3. Presents the bibliometric analysis, revealing that "Remote Sensing" is the leading journal in Precision Agriculture (PA) research, with 264 published articles, emphasizing the role of UAVs and AI-driven remote sensing technologies. Other key contributors include *Agronomy* (99 articles), *IEEE Access* (88 articles), and *Agriculture (Switzerland)* (85 articles), reflecting the interdisciplinary nature of PA research by integrating agronomy, engineering, and automation. The dominance of AI, IoT, and machine learning in these journals highlights the shift toward data-driven and smart farming solutions, underscoring the need for future research to bridge technological advancements with real-world agricultural applications for sustainable farming.

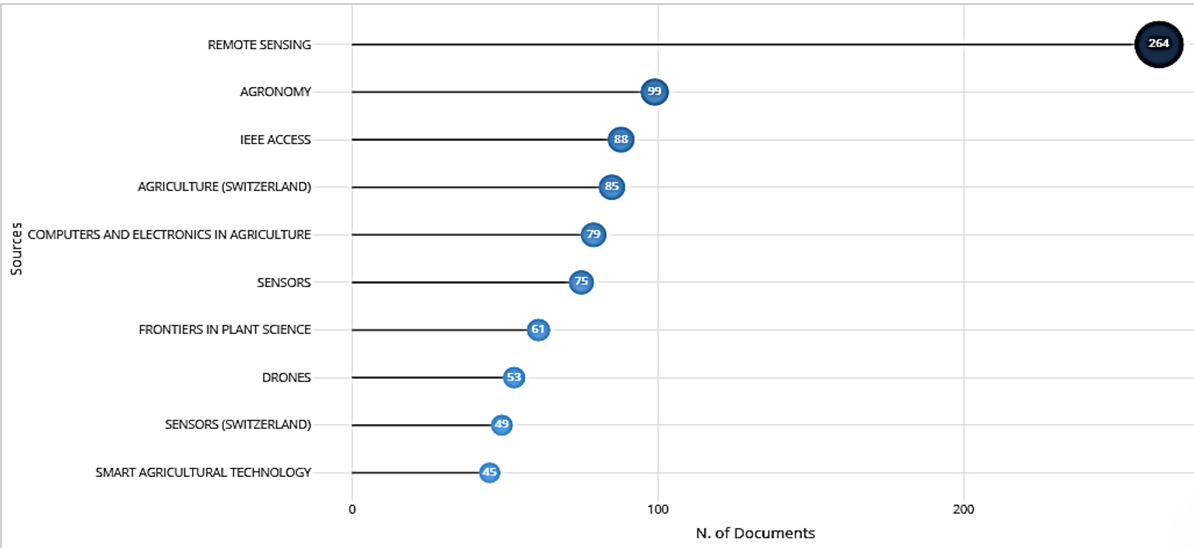

Figure 3. Most Relevant Sources

4.1 Authors

The ranking of the most productive researchers, based on 2,078 published articles, identifies LI Z as the leading author with 31 publications, followed by WANG J (29), LI Y (28), and WANG Y (24). Other notable contributors include ZHANG Y (21), ZHANG Z (20), CHEN Z (18), LI J (18), ZHANG X (18), and LI H (16) (Figure 4). LI Z, WANG J, and LI Y have consistently published, particularly after 2020, demonstrating ongoing contributions to the field (Figure 5). An analysis based on Lotka's Law indicates that 82.4% of researchers have published only one article. In contrast, 10.5% have two publications, with significantly decreasing proportions as publication counts rise. Researchers with five or more articles constitute less than 1% of the total, highlighting that a small group of prolific authors contributes most publications, while most researchers publish infrequently (Table 3).

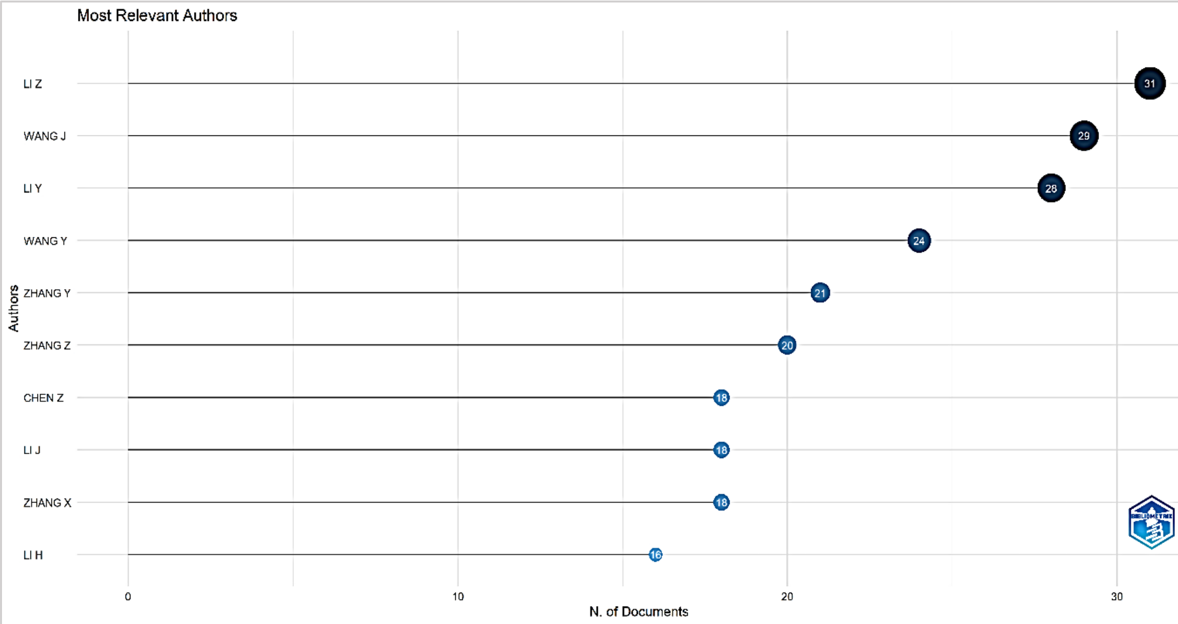

Figure 4. Most influential authors.

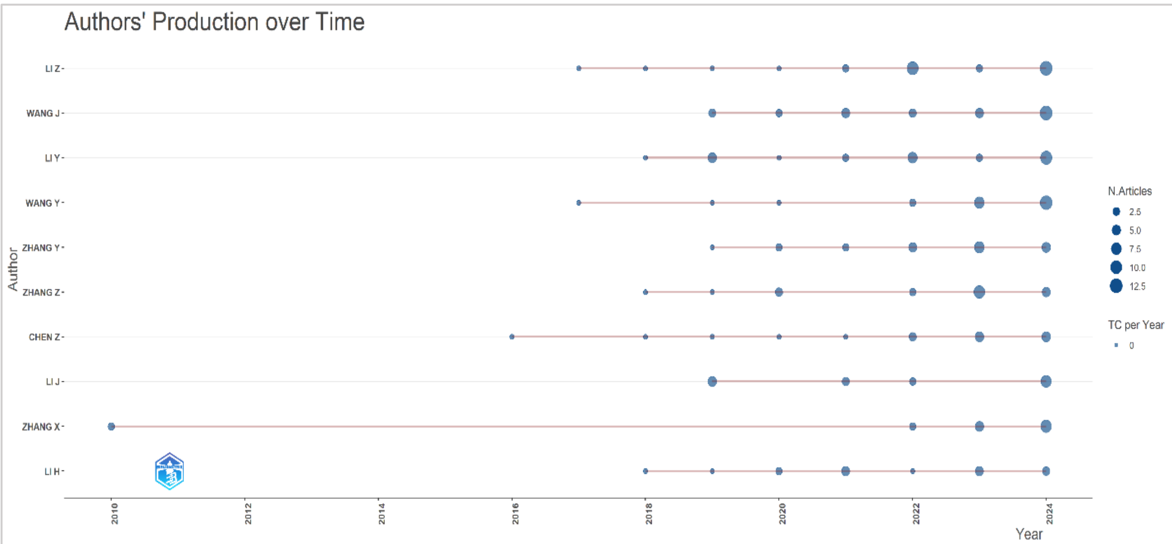

Figure 5. Publication trends of individual researchers over time.

Table 3. Author Productivity through Lotka's Law

Documents written	N. of Authors	Proportion of Authors
1	6477	0.824
2	824	0.105
3	284	0.036
4	105	0.013
5	61	0.008
6	29	0.004
7	20	0.003
8	15	0.002
9	7	0.001
10	13	0.002

4.2 Countries

Figure 6. highlights China and the USA as the top research-producing countries in Precision Agriculture (PA), with China publishing 332 articles (16.0%) and the USA 238 (11.5%). While China focuses on domestic research, the USA leads in international collaboration, partnering with Australia, Canada, and Spain, which have the highest global research partnerships. In PA research output, China ranks first (2,009 publications), followed by the USA (1,339), Italy (816), Brazil (731), and India (670), with Spain, Germany, Greece, Australia, and Canada contributing at moderate levels (see Figures 7). From 2000 to 2024, China experienced the most significant research growth, reaching 1,298 publications in 2023, whereas the USA's growth slowed after 2019, with only 321 publications that year. Meanwhile, Italy (486), Brazil (418), and India (266) in 2022 showed continuous growth, highlighting the rising contributions of emerging nations. This trend underscores China's dominance in research volume, the USA's strong presence, and the growing influence of Italy, Brazil, and India (see Figures 8). The Most Cited Countries chart shows the USA leading in citations (10,269), followed by China (6,436), reinforcing their significant global research impact (see Figure 9).

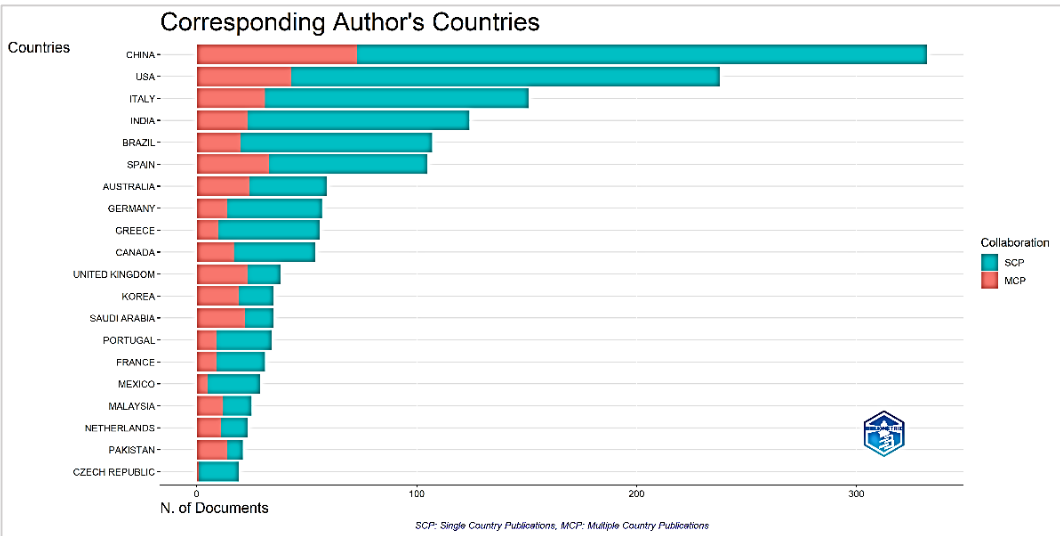

Figure 6. Corresponding Author's Countries

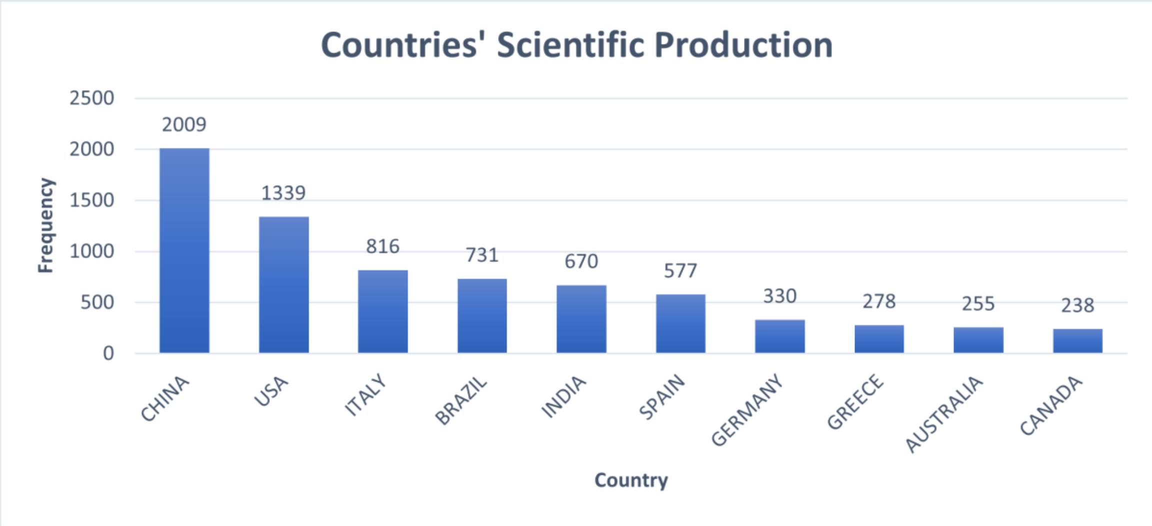

Figure 7. Countries' Scientific Production

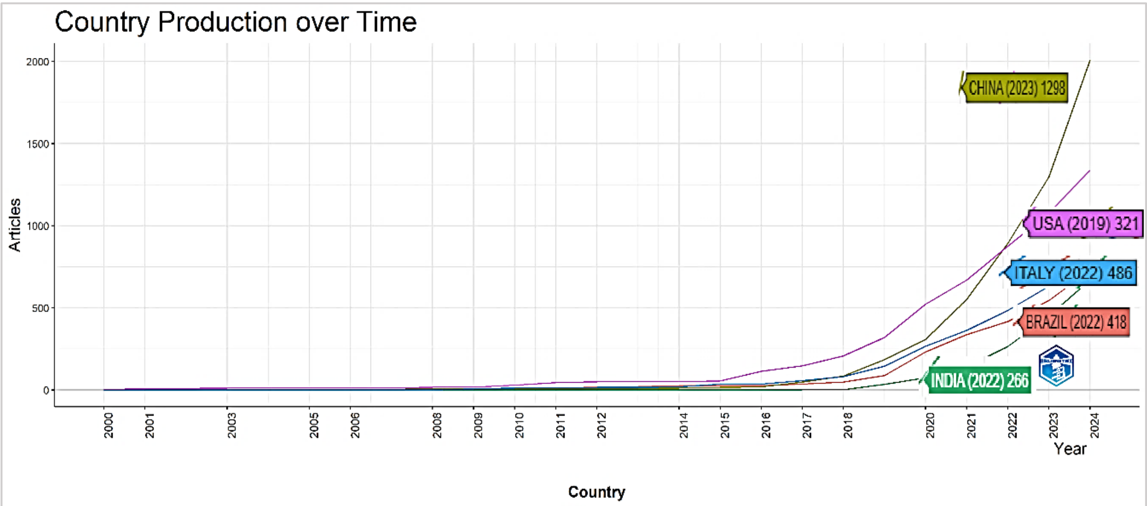

Figure 8. Countries' Production over Time

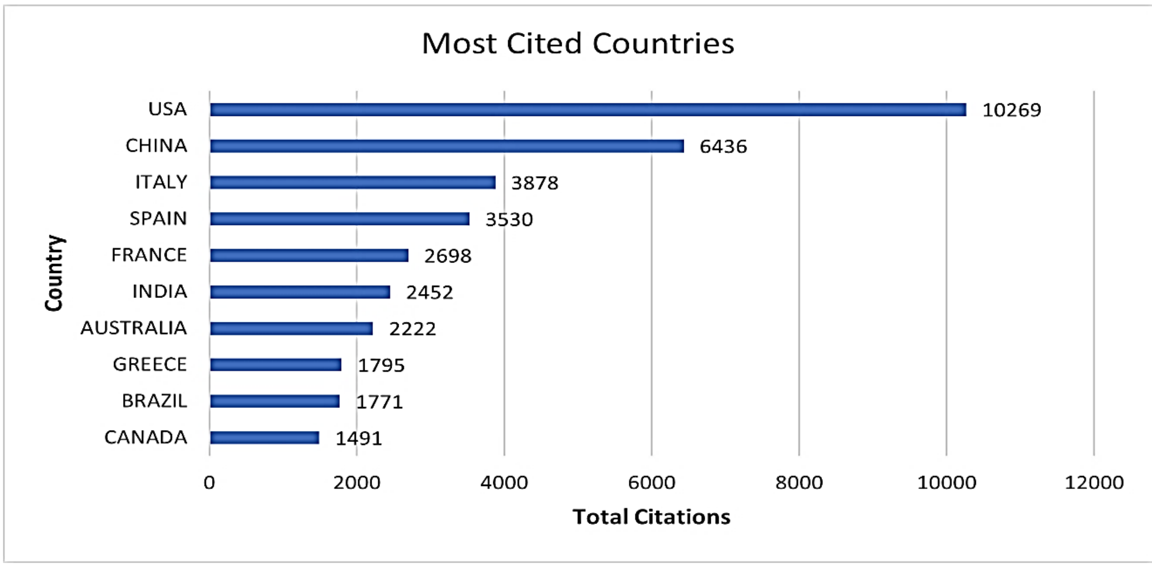

Figure 9. Most Cited Countries

4.3 Words Analysis

This section presents an analysis of the most frequently used words in Precision Agriculture (PA) research, including Most Frequent Words, Word Cloud, Tree Map, Words' Frequency over Time, and Trend Topics. These elements provide valuable insights into research trends and directions within this field. The details are as follows:

4.3.1 Most Frequent Words

Table 4. highlights "Precision Agriculture" as the most frequently occurring term (1,236 times), reinforcing its central role in this research domain. Related terms like "Crops" (377 occurrences) and "Agriculture" (276) emphasize the importance of crop management and cultivation. Technological advancements are evident in "Remote Sensing" (510), "Deep Learning" (336), and "Unmanned Aerial Vehicles (UAVs)" (323), reflecting the increasing reliance on AI-driven analytics and aerial monitoring. The integration of automation and intelligent systems is underscored by "Agricultural Robots" (218) and "Machine Learning" (216), while "Internet of Things" (137) highlights the growing role of connected systems and real-time data collection. Overall, the table illustrates a rapidly evolving research landscape, emphasizing cutting-edge technologies to enhance agricultural productivity and sustainability.

Table 4. Most Frequent Words

Words	Occurrences
precision agriculture	1236
remote sensing	510
crops	377
deep learning	336
unmanned aerial vehicles (uav)	323
agriculture	276
antennas	267
agricultural robots	218
machine learning	216
internet of things	137

4.3.2 Word Cloud

Figure 10. presents Word Cloud visualization highlights the most frequently occurring terms in Precision Agriculture (PA) research, with "***precision agriculture"*** being the most dominant, underscoring its central role in the field. Other frequently appearing terms include "remote sensing," "unmanned aerial vehicles (UAV)," "deep learning," "machine learning," and "agricultural robots," reflecting the growing integration of artificial intelligence, robotics, and remote sensing in PA research. Additionally, terms like "crops," "antennas," and "agriculture" indicate a strong emphasis on crop management and agricultural applications. This visualization effectively captures key themes and emerging technological trends in PA research.

Figure 10. Word Cloud

4.3.3 Tree Map

Figure 11. presents the most frequent keywords in Precision Agriculture (PA) research as a word-tree map. The ten most frequent keywords are "precision agriculture" (1,236 times), "remote sensing" (510 times), "crops" (377 times), "deep learning" (336 times), "agriculture" (276 times), "antennas" (267 times), "unmanned aerial vehicles (UAV) " (323 times), "agricultural robots" (218 times), "machine learning" (216 times), and "internet of things" (137 times). These keywords highlight the dominant research themes, emphasizing the role of advanced technologies such as remote sensing, AI, UAVs, and robotics in modern agricultural practices. The strong presence of terms related to crop management and technological integration indicates the increasing focus on precision farming and smart agriculture solutions.

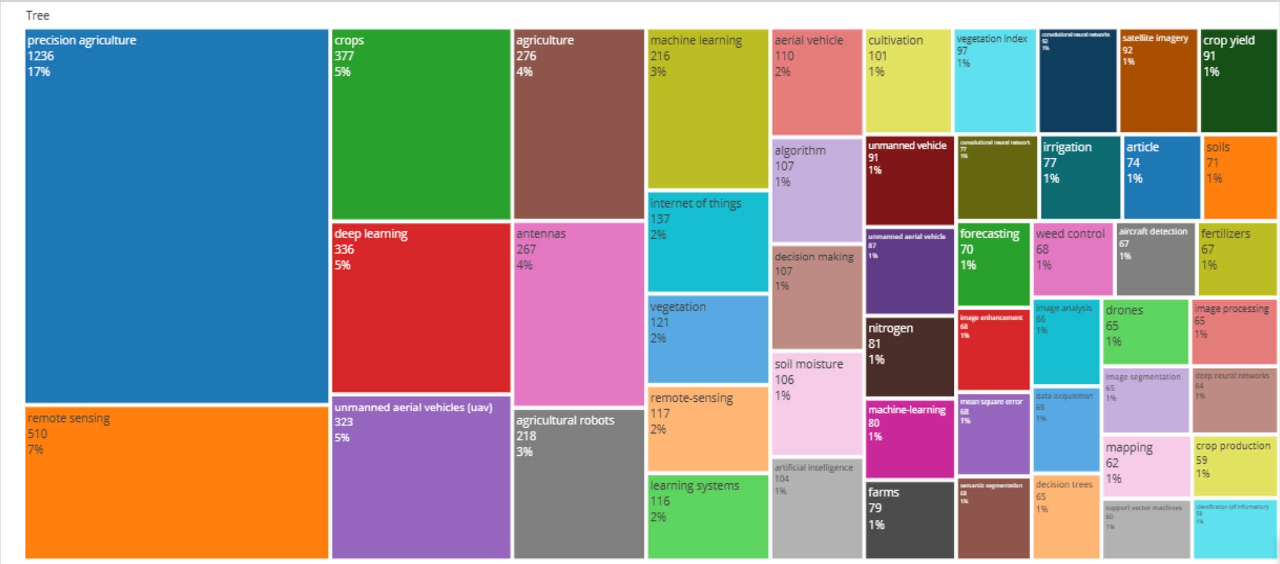

Figure 11. Tree Map

4.3.4 Words' Frequency over Time

Table 5. presents frequency trends of key research terms in Precision Agriculture (PA) from 2020 to 2024, highlighting the increasing adoption of advanced technologies. "Precision Agriculture" saw the most significant growth, rising from 282 occurrences in 2020 to 1,236 in 2024, underscoring its expanding role in modern farming. "Remote Sensing" (202 to 510) and "Deep Learning" (38 to 336) show strong upward trends, reflecting the growing reliance on AI and data-driven decision-making. Automation technologies, including "Unmanned Aerial Vehicles (UAVs)" (118 to 323) and "Agricultural Robots" (82 to 218), continue to rise, indicating a shift toward smart and autonomous farming. "Internet of Things (IoT)" (42 to 137) also shows increased adoption, emphasizing its role in connected agriculture and real-time monitoring. In contrast, traditional terms like "Crops" and "Agriculture" exhibit only moderate growth, suggesting a stable yet evolving focus on fundamental farming practices. These trends highlight the growing impact of AI, automation, and remote sensing, shaping the future of precision agriculture to enhance productivity, efficiency, and sustainability.

Table 5. Words' Frequency over Time

Word	2020	2021	2022	2023	2024
PRECISION AGRICULTURE	282	395	645	946	1236
REMOTE SENSING	202	259	356	432	510
CROPS	131	182	253	327	377
DEEP LEARNING	38	80	130	236	336
UNMANNED AERIAL VEHICLES (UAV)	118	172	229	278	323
AGRICULTURE	131	167	216	239	276
ANTENNAS	90	141	194	237	267
AGRICULTURAL ROBOTS	82	156	163	191	218
MACHINE LEARNING	43	74	113	151	216

Word	2020	2021	2022	2023	2024
INTERNET OF THINGS	42	57	95	122	137

4.3.5 Trend Topics

Figure 12. shown figure illustrates trends in the most relevant topics in Precision Agriculture (PA) research. "Precision Agriculture" appears most frequently (1,236 occurrences), emphasizing its central role in modern agricultural practices. "Remote Sensing" (510 occurrences) and "Unmanned Aerial Vehicles (UAVs)" (323 occurrences) highlight the growing reliance on remote sensing and drones for data collection and farm management. The increasing integration of artificial intelligence (AI) is evident in the occurrences of "Deep Learning" (336 occurrences) and "Machine Learning" (216 occurrences), reflecting its impact on agricultural analysis and decision-making. Additionally, "Agricultural Robots" (218 occurrences) and "Internet of Things (IoT)" (137 occurrences) demonstrate the expansion of automation and smart farming systems. These trends suggest that digital technologies particularly AI, automation, and IoT are driving PA advancements, enhancing efficiency, precision, and sustainability in modern agriculture.

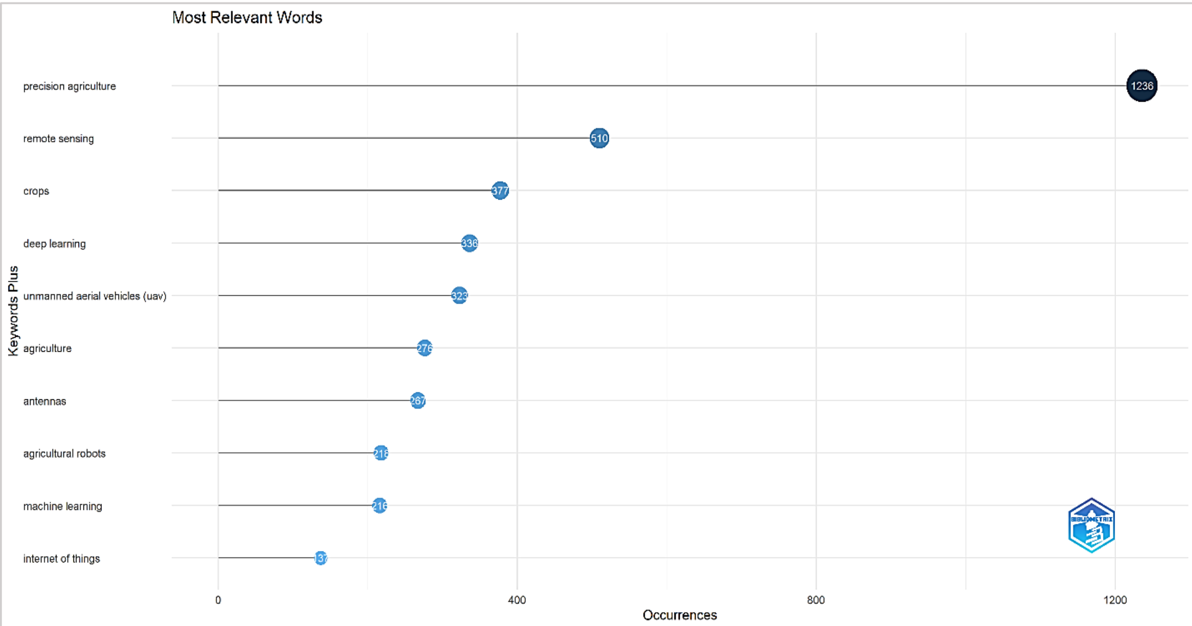

Figure 12. Trend Topics

4.4 Co-occurrence Network

Figure 1 3. presents Co-occurrence Network maps key topics in Precision Agriculture research based on authors' keywords, revealing two primary clusters. The blue cluster focuses on PA technologies like "precision agriculture," "remote sensing," "UAVs," "crops," and "agricultural robots," highlighting their role in smart farming. The red cluster centers on advanced computational techniques, including "deep learning," "convolutional neural networks," and "image processing," showcasing the growing AI integration in agriculture. These clusters are strongly interconnected, reflecting the convergence of automation, data-driven analytics, and precision farming to enhance efficiency and sustainability in modern agriculture.

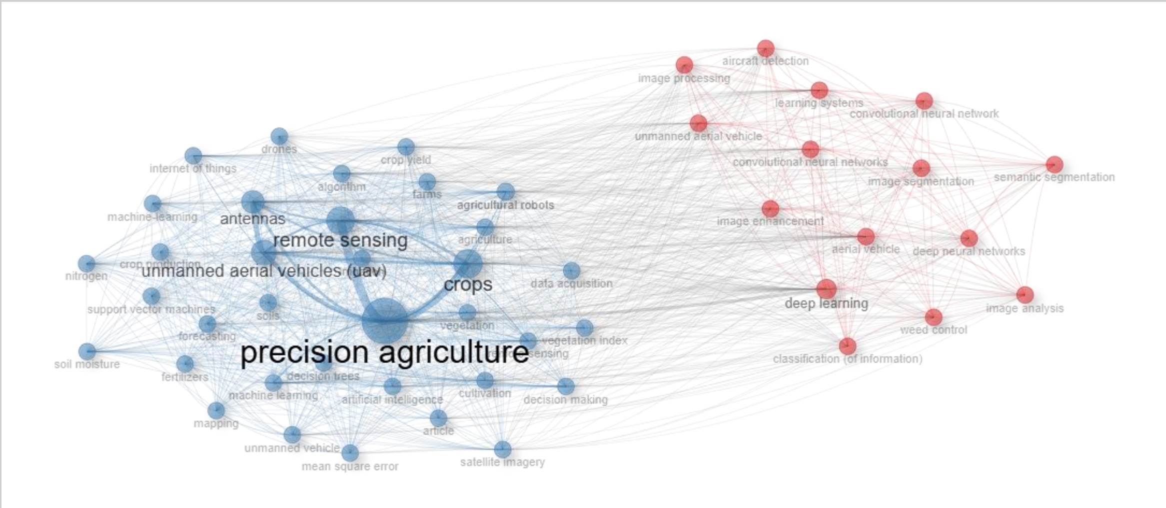

Figure 13. Co-occurrence Network

4.5 Research Thematic Mapping

Figure 14. presents a research theme map in PA, categorizing research topics into four groups based on their importance and development. Basic Themes include Precision Agriculture, Deep Learning, and Agricultural Robots. These topics hold high importance but are still in the early stages of development, indicating strong potential for future expansion. Niche Themes such as Remote Sensing, Crops, and Unmanned Aerial Vehicles (UAVs) have gained significant research attention and extensive studies. However, their applications are often limited to specific areas. Emerging or Declining Themes include Agriculture and the Internet of Things (IoT), which have shown a decreasing trend in research interest but may still hold potential for further development. Motor Themes are not present in this map, indicating that no topics have been fully developed and play a central role in driving research within this field. In summary, research on Precision Agriculture, Deep Learning, and Agricultural Robots remains the core focus in PA studies, while Remote Sensing and UAVs play a specialized yet significant role. Meanwhile, IoT and Agriculture could still be potential areas for future exploration.

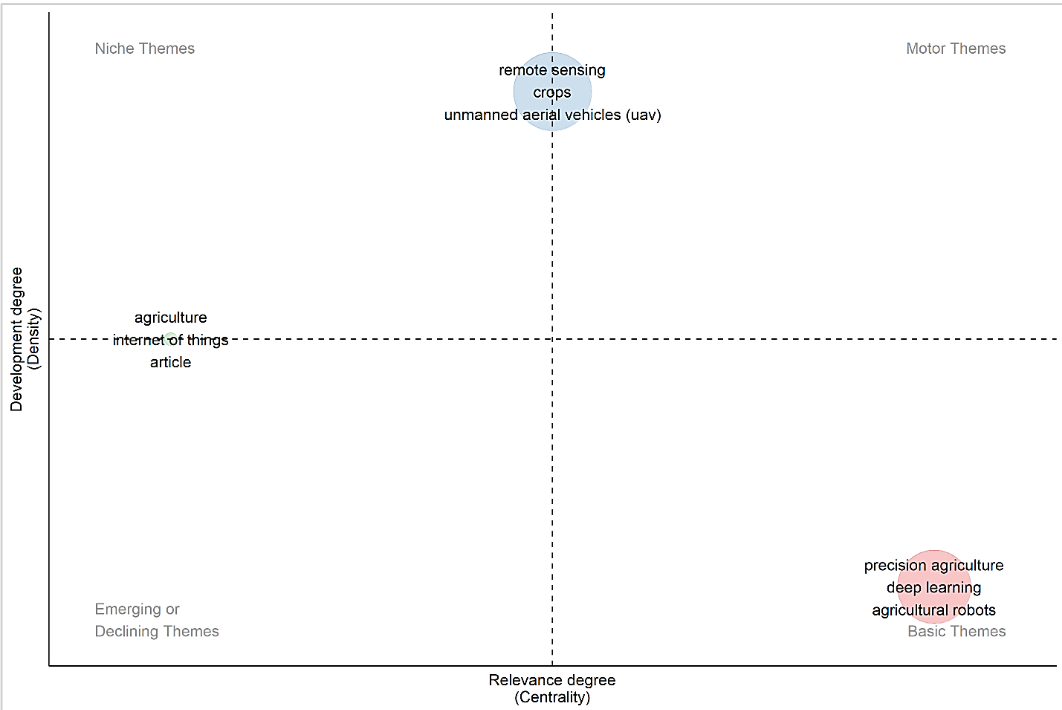

Figure 14. Research Thematic Mapping

4.6 Collaboration Network Analysis

Figure 1 5. presents the Collaboration Network in PA categorizes researchers into primary and secondary networks based on collaboration levels. The blue cluster, including Li Y, Wang J, and Chen Z, is the most interconnected, driving knowledge exchange and academic partnerships. The green cluster (Li Z and Zhang W) interacts with the blue network, showing strong inter-group connections. Smaller red, purple, and orange clusters remain relatively isolated. The red cluster (López-Granados-Sánchez J and Port Jim) has strong internal collaboration but limited external links. Researchers like Bareth G and Matese A appear as isolated nodes, reflecting minimal collaboration with the central network. This analysis underscores key researchers' roles in fostering academic cooperation while highlighting opportunities for integrating smaller clusters into broader networks, essential for advancing PA research.

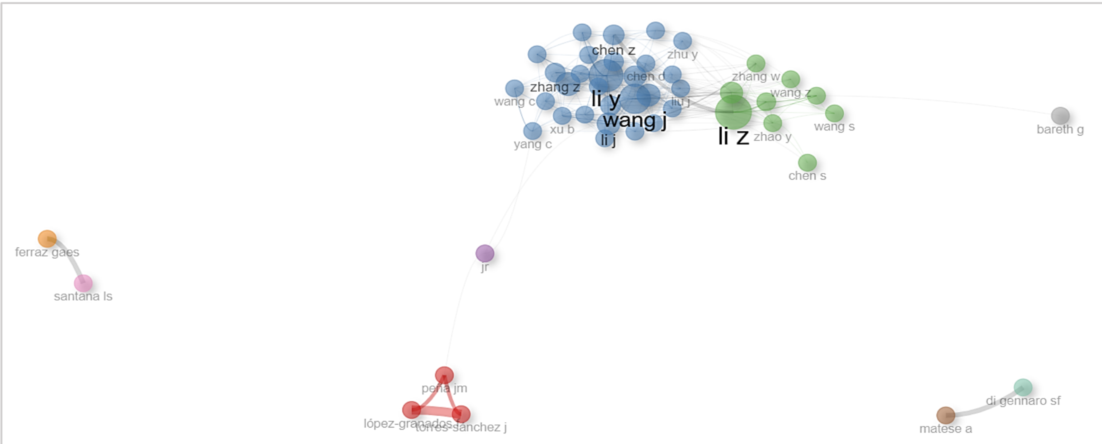

Figure 15. Collaboration Network

4.7 Countries' Collaboration World Map Analysis

Figure 16. illustrates the global research collaboration network in Precision Agriculture (PA), highlighting key international partnerships. The United States (USA) leads in collaboration, working closely with Canada (15 papers), Australia (11), and Saudi Arabia (11). China has extensive ties, particularly with the USA (36), the UK (15), and Pakistan (12), reflecting its growing influence. India maintains strong links with Saudi Arabia (22), Australia (10), and South Korea (8), emphasizing its expanding role in PA research. In Europe, Germany, France, and Italy collaborate closely with the UK, Spain, and EU nations, while in South America, Brazil is a key hub, partnering significantly with Portugal (4), Spain (4), and the UK (3). The global PA research network continues to expand, fostering cross-border knowledge exchange and academic advancements.

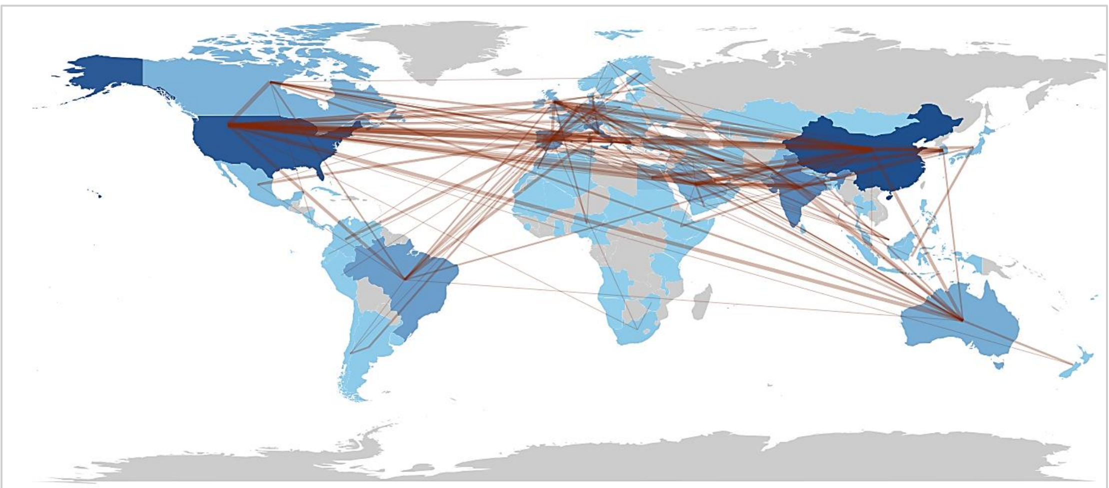

Figure 16. Countries' Collaboration World Map

4.8 Three-Field Plot

Figure 17. presents the Three-field plot (Sankey diagram), illustrating relationships among highly cited references, influential researchers, and commonly used keywords in Precision Agriculture (PA) research, reveals that most studies emphasize advanced technologies such as Precision Agriculture, Deep Learning, Machine Learning, and Remote Sensing, particularly through UAVs and Object Detection techniques. Notably, researchers such as Wang J, Li Z, Li Y, Zhang Z, and Wang Y play a key role in widely applying and integrating these technologies. This highlights the current research trend in PA, emphasizing the integration of digital technologies and artificial intelligence to concretely improve agricultural productivity and management practices.

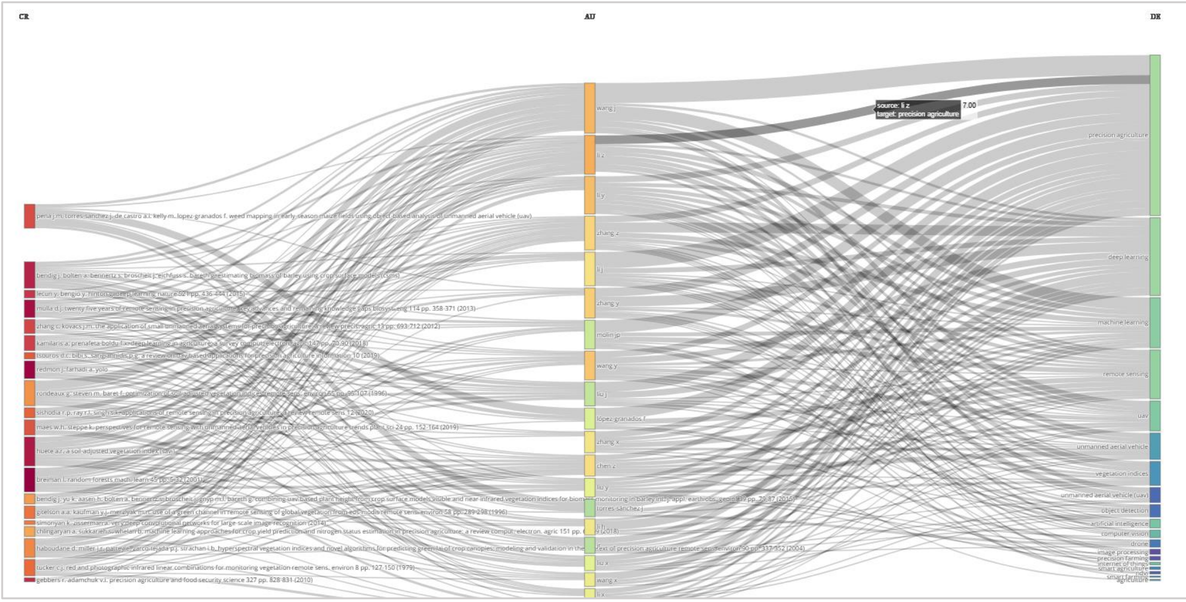

Figure 17. The Three-field plot

4. Discussion

This bibliometric analysis of Precision Agriculture (PA) research provides an insightful overview of the field's progression, highlighting key trends and emerging themes. The findings underscore the substantial growth in PA-related scientific literature, driven by the surge in data-driven agricultural practices. The integration of advanced technologies such as remote sensing, machine learning, artificial intelligence (AI), the Internet of Things (IoT), and unmanned aerial vehicles (UAVs) is pivotal in transforming traditional farming into a more efficient, technology-driven endeavor.

Over the past two decades, PA research publications have seen a significant rise, especially in the last five years. This trend reflects an increasing emphasis on AI, automation, and precision solutions. Judijanto and Lesmana (2024) observed a marked increase in research outputs focused on AI, IoT, and UAVs in PA, demonstrating the crucial impact of automation, machine learning, and real-time monitoring technologies in shaping contemporary farming practices.

Bibliometric analysis also identifies the leading researchers, prominent journals, and top contributor nations in the field, with China and the United States at the forefront of global advancements in PA. These countries are noted for extensive collaborations, as highlighted by Behera and Behera (2025), who illustrate the role of international research networks in driving innovation in precision farming, automation, and AI applications. Key researchers such as Li Z, Wang J, and Zhang X are central figures, contributing significantly to the field within leading institutions.

Thematic mapping indicates that remote sensing, machine learning, and UAV applications dominate current research, reflecting the sector's shift toward automation and real-time analytics. AI-driven techniques, including deep learning and convolutional neural networks, are becoming increasingly integral to PA. Szomszor (2025) emphasizes that AI, IoT, and automation are among the most frequently cited themes in sustainable agriculture, suggesting that AI-enhanced solutions bolster precision agriculture while supporting long-term environmental sustainability.

Despite these advancements, research gaps remain. More studies are needed on the adoption of PA technologies by smallholder farmers and the economic feasibility of these technologies, particularly in developing regions where access may be limited. Sustainability issues, such as resource conservation and environmental impact assessments, also require further exploration. Integrating PA with climate-resilient agricultural practices presents a promising avenue for future research.

Another crucial aspect is the evolving role of IoT and cloud computing in precision farming. While research in these areas has expanded, their full potential is yet to be realized. Expanding studies on IoT-enabled smart farming and exploring blockchain-based data security could further drive innovation.

Although this study provides a comprehensive bibliometric analysis of Precision Agriculture (PA) research, several limitations should be acknowledged. The reliance on Scopus as the sole database may introduce selection bias, potentially omitting relevant studies published in other languages. Additionally, the study depends on metadata accuracy, meaning errors in author affiliations, citation counts, or indexing could distort results. The quantitative approach, which relies on citation metrics and co-authorship networks, may overlook qualitative aspects, such as real-world applicability and interdisciplinary collaborations. Moreover, keyword selection may have excluded emerging research areas, suggesting that Natural Language Processing (NLP)-based techniques could enhance future data retrieval. Another limitation involves temporal bias in projections for 2024, as technological advancements, policy changes, and unforeseen events may alter expected research trends. While the study highlights PA research growth, it does not thoroughly examine practical adoption challenges, particularly for smallholder farmers in developing regions, making case studies, expert analysis, and policy evaluations valuable for future studies. Furthermore, the study focuses exclusively on precision agriculture in crop production and does not extend to precision livestock farming (PLF) due to fundamental differences in methodologies and technologies between crop and livestock systems. As a result, its findings reflect only precision crop agriculture trends and should not be generalized to livestock applications, suggesting the need for future research to expand into precision livestock farming for a more comprehensive understanding of precision agriculture.

In conclusion, this bibliometric study highlights the rapid evolution of PA research, propelled by technological advancements and interdisciplinary collaboration. The increasing adoption of AI, automation, and big data analytics is reshaping modern agriculture, bearing significant implications for food security and sustainability. Future research should aim to bridge the gap between technological advancements and practical implementation by addressing accessibility challenges, sustainability concerns, and integration with emerging digital innovations to ensure a more efficient and resilient agricultural future.

5. Conclusion

The results of the bibliometric analysis reveal that Precision Agriculture (PA) research from 2000 to 2024 has undergone significant growth, with an annual increase of 23.77%, driven by the increasing adoption of digital technologies such as artificial intelligence (AI), machine learning (ML), the Internet of Things (IoT), and unmanned aerial vehicles (UAVs) in modern farming. China and the USA are the leading contributors to PA research, with strong international collaborations facilitating knowledge dissemination. A small number of highly influential researchers and institutions, such as Li Z, Wang J, and Li Y, have played a significant role in shaping the field, confirming the concentration of expertise within specific regions and academic circles. Technological advancements, particularly in remote sensing, deep learning, and automation, have emerged as dominant themes in PA research, underscoring the shift from traditional agronomic approaches to smart farming practices driven by AI-driven analytics and precision-driven decision-making. The study identifies "Remote Sensing" as the most published journal in PA research, followed by Agronomy, IEEE Access, Agriculture (Switzerland), and Computers and Electronics in Agriculture, reflecting the interdisciplinary nature of PA research. Despite these advancements, significant knowledge gaps remain, particularly in the adoption of PA technologies by smallholder farmers, sustainability assessments, and the economic feasibility of large-scale implementation. Future research should focus on addressing these gaps by fostering interdisciplinary collaborations, integrating emerging technologies with real-world agricultural applications, and promoting accessibility for farmers in developing regions. Additionally, further exploration of PA's socio-economic impact and its long-term sustainability is crucial for shaping agricultural policies and practices. Overall, this study underscores the transformative potential of PA in modern farming, emphasizing the need for continued innovation and collaborative efforts to enhance productivity, efficiency, and environmental sustainability in the agricultural sector.

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