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The Development of Precision Agriculture Research in Modern Agriculture: A Bibliometric Study 2010–2024

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ABSTRACT

Precision agriculture has emerged as a transformative approach in modern agriculture by integrating advanced technologies such as remote sensing, artificial intelligence, machine learning, Internet of Things (IoT), robotics, and big data analytics to improve agricultural productivity and sustainability. Given the rapid expansion of research in this field, a comprehensive understanding of its intellectual structure and development trends is essential. This study aims to analyze the evolution of precision agriculture research through a bibliometric examination of global scientific publications indexed in the Scopus database from 2010 to 2024. Bibliometric techniques were employed to evaluate publication trends, influential authors, institutions, countries, and highly cited literature. Furthermore, network visualization analyses using VOSviewer were conducted, including co-authorship, institutional collaboration, country collaboration, co-citation, keyword co-occurrence, overlay visualization, and density visualization. The findings reveal a significant increase in publication output over the study period, reflecting growing academic and practical interest in precision agriculture. India, China, the United States, and the Russian Federation emerged as the most influential contributors in terms of collaboration and research productivity. The most highly cited literature focused on nanotechnology, hyperspectral imaging, sustainable nutrient management, agricultural robotics, and smart farming technologies. Keyword analysis identified precision agriculture, sustainable development, smart agriculture, crops, Internet of Things, machine learning, and artificial intelligence as dominant research themes. Overlay visualization further demonstrated a transition from traditional topics such as soil fertility and crop management toward digitally enabled and sustainability-oriented agricultural systems. The results indicate that precision agriculture has evolved into a highly interdisciplinary field that combines technological innovation and sustainable development principles to address global agricultural challenges. The study provides valuable insights into current research trends and future directions for researchers, policymakers, and practitioners engaged in modern agricultural development.

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1. INTRODUCTION

The agriculture sector continues to be one of the most significant factors in ensuring food security, economic development, and sustainability of the planet. Nevertheless, the agriculture sector faces multiple challenges due to the growing population, climate change, the scarcity of natural resources, and the necessity to boost productivity without harming the environment [1], [2]. The forecast made by international agencies predicts that the number of people living on the planet will increase in the coming years, causing more pressure for food production, water supply, and agricultural resources. Classical farming techniques may be not enough to solve emerging issues because of the poor efficiency in using natural resources and the inability to cope with spatial and temporal variability of agricultural systems. Therefore, modern agriculture becomes a highly technology-driven industry focused on efficiency, sustainability, and making decisions based on data analysis. Among various developments in agriculture, precision agriculture can be viewed as one of the most promising paradigms that involves applying high technologies like GPS, GIS, remote sensing, Internet of Things gadgets, AI, machine learning, drones, robotics, and big data analytics to enhance agricultural production [3]. Precision agriculture seeks to apply the right input, at the right place, at the right time, and in the right quantity, thereby improving productivity while reducing costs and environmental burdens. As digital transformation continues to reshape agricultural practices worldwide, precision agriculture has become a critical area of scientific investigation and technological development [4].

The rapid evolution of digital technologies over the past decade has greatly contributed to the progress of precision agriculture research. Scientists, along with government agencies, companies from the agricultural sector, and other stakeholders who work on developing modern technology, realized the benefits of precision agriculture for improving management practices in farms and contributing to sustainable agricultural development [5], [6]. New technologies like unmanned aerial vehicles (UAVs), wireless sensor networks, satellite images, cloud computing, and deep learning methods have helped precision agriculture extend its scope of application far beyond traditional site-specific management. With the use of modern technologies, farmers can receive real-time data about the state of crops, soil, weather conditions, irrigation, and even insect damage to make better decisions about their crop yields. What is more, the widespread introduction of Industry 4.0 principles in the sphere of agriculture has resulted in the increasing use of smart farming systems that incorporate various kinds of sensors, machinery, and analysis platforms in an integrated agricultural ecosystem [7]. All of that has led to an increase in the number of scholarly articles dedicated to the topic of precision agriculture in agricultural sciences, engineering, environmental sciences, computer science, data analysis, and other fields.

However, despite the growing number of academic studies on the issue, the scientific field continues to evolve dynamically and fragment into numerous sub-areas because of its interdisciplinary character. Scholars have focused their research on various topics, including variable-rate technologies, yield mapping, soil sensing, machine learning, unmanned agricultural machines, climate-smart agriculture, and many others. As a result, new approaches, technologies, and ideas continually reshape the current research framework and facilitate innovations but make it more complex, making it rather challenging for researchers to find out the most significant themes, authors, collaboration trends, and emerging topics in the field. Thus, the identification of the main tendencies and trends in the scientific literature is crucial for further research, for the formulation of evidence-based agricultural policy and technologies. Conducting the scientific evaluation will allow us to explore the evolution of scientific literature on the topic, to find out the most interesting issues that have been studied by scholars before, and to identify promising areas for future research.

Indeed, bibliometrics analysis has proved to be an essential tool used to study the growth of science in a specific subject area. The difference between bibliometric and literature reviews is that literature reviews focus mainly on the synthesis of literature qualitatively while bibliometric analysis focuses on the quantitative study of scientific publications. Using bibliometric techniques and tools like VOSviewer, the researcher can identify knowledge networks, key players within the discipline, collaboration patterns, trends, and thematic structures in large corpora of scientific literature. Bibliometrics analysis has been utilized by researchers extensively in different scientific subjects including sustainability, renewable energy, medicine, education, artificial intelligence, and agricultural science. When it comes to precision agriculture, bibliometric analysis is a useful tool that provides insights into the scientific progress in the field and its significance. Despite the availability of review articles that have highlighted the technological development of precision agriculture, the number of bibliometric studies investigating the global trends in precision agriculture between 2010 and 2024 has not been abundant. Given the significant development in technology that has taken place in recent years, the bibliometric analysis of the research field needs to be conducted to understand current trends and further progress in the field.

Consequently, this research study is focused on analyzing the development of precision agriculture research in contemporary agriculture through the conduct of a bibliometric analysis of the scientific literature published across the globe from 2010 until 2024. More specifically, this research focuses on identifying the publication growth trends, influential authors, productive organizations, top contributing countries, popular journals, and science cooperation patterns in the area under consideration. In addition to this, the study examines the intellectual architecture and evolutionary trajectories of research in precision agriculture using citation, co-citation, and keyword co-occurrence analyses. Through the exploration of the intellectual architecture of precision agriculture research over a period of fifteen years, this study attempts to offer a critical insight into the transformations of research in the area driven by the use of digital technologies. The expected outcomes of this study will be beneficial for academic professionals, policymakers, agricultural practitioners, and innovators in developing innovative strategies in modern agriculture based on technological advances.

2. METHODS

Bibliometric research methodology was chosen to carry out the analysis and identify trends in precision agriculture studies in modern agriculture during the period from 2010 to 2024. This approach was selected due to its potential to conduct a systematic quantitative assessment of scientific publications and their citations, collaborations, and thematic developments within a particular research area. The data set required for the study was collected from Scopus, the leading scientific source that contains the largest volume of peer-reviewed papers. The search was carried out based on the use of the keyword "precision agriculture" and other terms associated with the topic. In addition, the inclusion of papers was restricted to those written during the time frame 2010-2024 and representing various types of academic literature including articles and reviews. After the exclusion of duplicate data, the final database was exported in CSV format.

The gathered data were subjected to bibliometric analysis in order to determine publication trends, important contributors, and the intellectual structure of the research domain. First, descriptive bibliometric measures were adopted to determine annual publication trend, citation activity, prolific authors, institutions, nations, and sources. Afterward, network analysis was performed with the aid of the VOSviewer software tool to map scientific connections and knowledge structures. Co-authorship network analysis was conducted to analyze cooperation among authors and countries, and co-citation analysis was conducted to uncover important citations and intellectual basis of the research. Moreover, keyword co-occurrence analysis was conducted to uncover major themes in precision agriculture research.

The methods that helped in tracking the evolution of research themes were overlay visualization and density visualization methods, which can be used in VOSviewer. The overlay visualization method helped identify the emergence of new themes and changing interests in the course of research, while the density visualization approach revealed the areas of greatest interest among scholars. The findings were analyzed to trace the evolution path of precision agriculture studies and to detect possible directions for further research. Using both descriptive and network-oriented bibliometric approaches, it becomes possible to provide an overview of the scientific achievements made in precision agriculture around the world within 2010-2024.

3. RESULT AND DISCUSSION

3.1 Co-Author Analysis

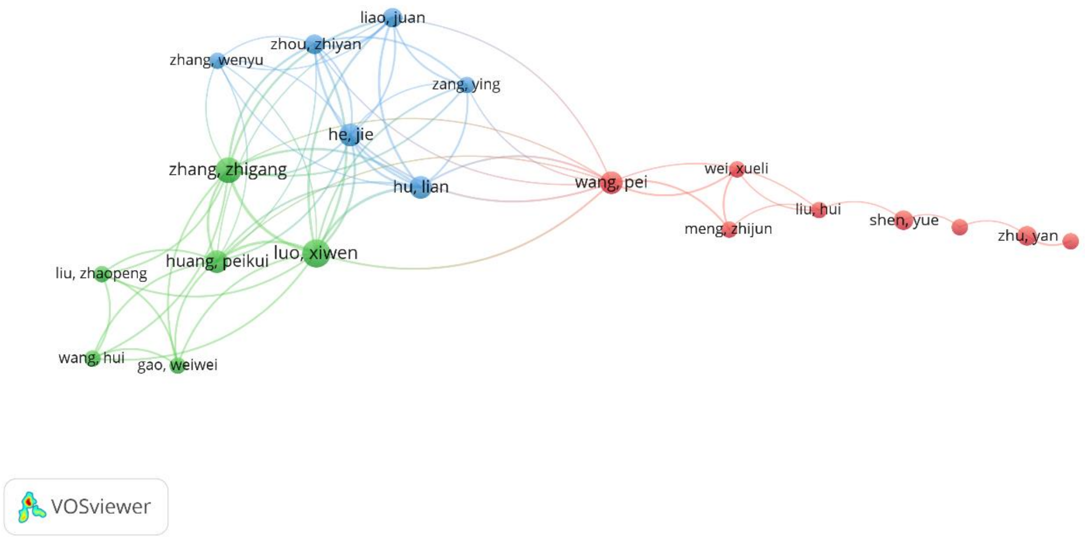

Figure 1. Author Visualization
Source: Data Analysis

The co-authorship network visualization reveals a relatively concentrated collaboration structure in precision agriculture research, consisting of three major author clusters represented by red, blue, and green groups. The blue and green clusters form the core of the network, exhibiting dense interconnections among authors such as He Jie, Hu Lian, Luo Xiwen, Zhang Zhigang, and Huang Peikui, indicating strong collaborative relationships and significant contributions to the field. These authors appear to act as central nodes, facilitating knowledge exchange and research cooperation within the scientific community. In contrast, the red cluster is more linear and less densely connected, with Wang Pei serving as a bridging author linking the core collaboration groups to peripheral researchers such as Wei Xueli, Meng Zhijun, Liu Hui, Shen Yue, and Zhu Yan. The size of the nodes suggests that authors such as He Jie, Luo Xiwen, Wang Pei, and Zhang Zhigang have relatively higher research influence or publication productivity compared to other researchers in the network.

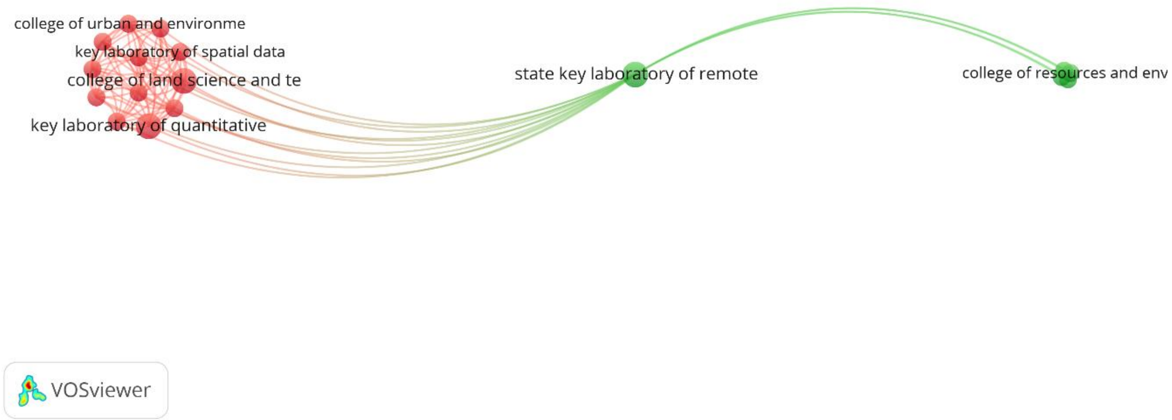

Figure 2. Institution Visualization
Source: Data Analysis

From the institution collaboration graph above, there is a clear indication that the research being done within the domain of precision agriculture follows a pattern where most of the research is being conducted by a few institutions that are closely linked together. The first cluster of institutions represented by the color red indicates that it is the main research group, which is made up of institutions like the College of Land Science and Technology, Key Laboratory of Quantitative Remote Sensing, Key Laboratory of Spatial Data Mining, and the College of Urban and Environmental Sciences. There seems to be a very high degree of internal collaboration among these institutions judging from the interconnecting lines. The second cluster represented by the green color shows the State Key Laboratory of Remote Sensing Science, which is instrumental in bridging the gap between the research groups and the other collaborating organizations, such as the College of Resources and Environmental Sciences.

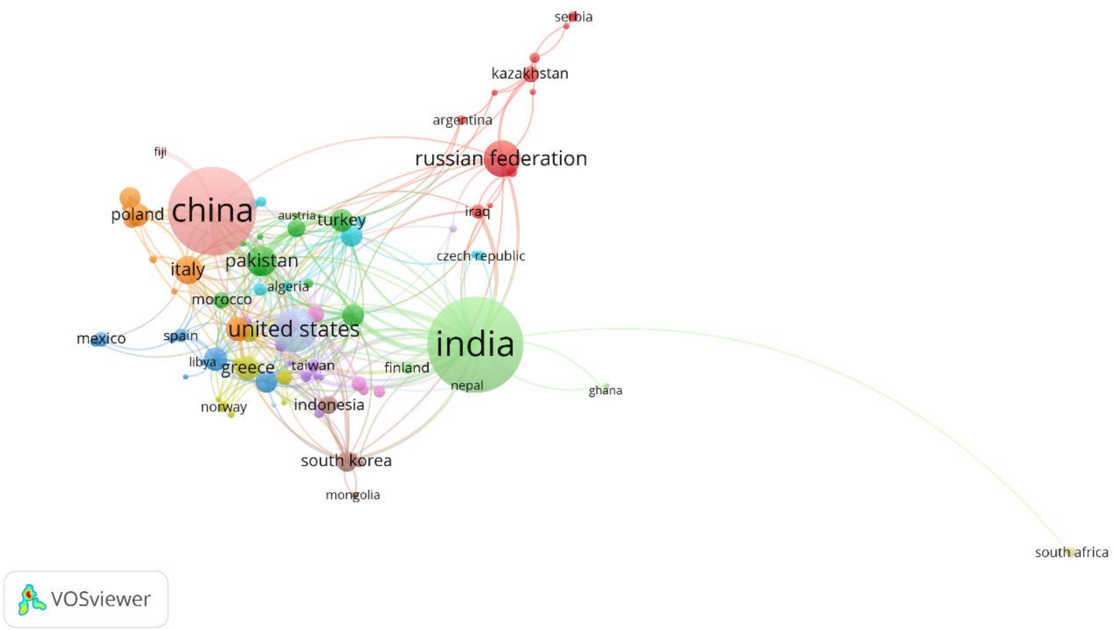

Figure 3. Country Visualization
Source: Data Analysis

The country collaboration network demonstrates that precision agriculture research is supported by extensive international cooperation, with India, China, the United States, and the Russian Federation emerging as the most influential contributors in the field. Among these countries, India occupies the most central position in the network, indicated by its large node size and numerous collaborative links connecting it to countries across multiple clusters. This suggests that India plays a pivotal role in facilitating global research collaboration and knowledge exchange in precision agriculture. China also exhibits a substantial research presence and strong collaborative relationships, particularly with Asian and European countries, reflecting its growing investment in agricultural digitalization and smart farming technologies. The United States serves as another major collaboration hub, maintaining extensive connections with countries such as Spain, Greece, South Korea, and several developing nations, highlighting its longstanding leadership in agricultural innovation and technological research. Meanwhile, the Russian Federation forms a distinct but well-connected cluster linked with countries such as Kazakhstan, Serbia, Argentina, and Iraq, indicating regional and international cooperation in agricultural research. The visualization further reveals participation from both developed and developing countries, including Pakistan, Turkey, Algeria, Indonesia, Nepal, Ghana, and South Africa, illustrating the global relevance of precision agriculture as a solution to agricultural productivity and sustainability challenges.

3.2 Citation Analysis

Table 1. Top Cited Literature

Citations	Authors and Year	Title
911	[8]	Nanotechnology in agri-food production: An overview
820	[9]	Modern Trends in Hyperspectral Image Analysis: A Review
619	[10]	Role of nanotechnology in agriculture with special reference to management of insect pests

508	[11]	Long-term experiments for sustainable nutrient management in China. A review
504	[12]	Genomics, Physiology, and Molecular Breeding Approaches for Improving Salt Tolerance
497	[13]	Environmentally friendly fertilizers: A review of materials used and their effects on the environment
456	[14]	Research and development in agricultural robotics: A perspective of digital farming
326	[15]	Precision agriculture for crop and livestock farming—Brief review
279	[16]	Technological revolutions in smart farming: Current trends, challenges & future directions
265	[17]	Smart Sensors and Smart Data for Precision Agriculture: A Review

Source: Scopus 2026

Table 1 shows that the most cited literature in precision agriculture research is dominated by studies related to advanced agricultural technologies, sustainable input management, and digital farming innovation. The highest-cited work by [8], with 911 citations, indicates the strong influence of nanotechnology in agri-food production, followed by [9], which highlights the importance of hyperspectral image analysis as a key method for agricultural monitoring. Several highly cited studies also focus on nanotechnology, nutrient management, salt tolerance, and environmentally friendly fertilizers, suggesting that sustainability and productivity improvement are central foundations of this research field. Meanwhile, works on agricultural robotics, smart farming, smart sensors, and precision agriculture reviews demonstrate the growing shift toward digitalization, automation, and data-driven farm management.

3.3 Keyword Co-Occurrence

The keyword co-occurrence network shows the intellectual structure of precision agriculture research and points out the main themes in the domain of study from 2010 to 2024. The phrase “precision agriculture” is found at the center of the network, implying its significance as the central idea uniting several technological and agricultural areas of study. The size of the node and the numerous links show that precision agriculture has become a multi-disciplinary area encompassing data analytics, digitization, sustainable practices in agriculture, and agricultural management systems. This also indicates that researchers consider precision agriculture as an approach to achieving higher productivity and sustainability of farms.

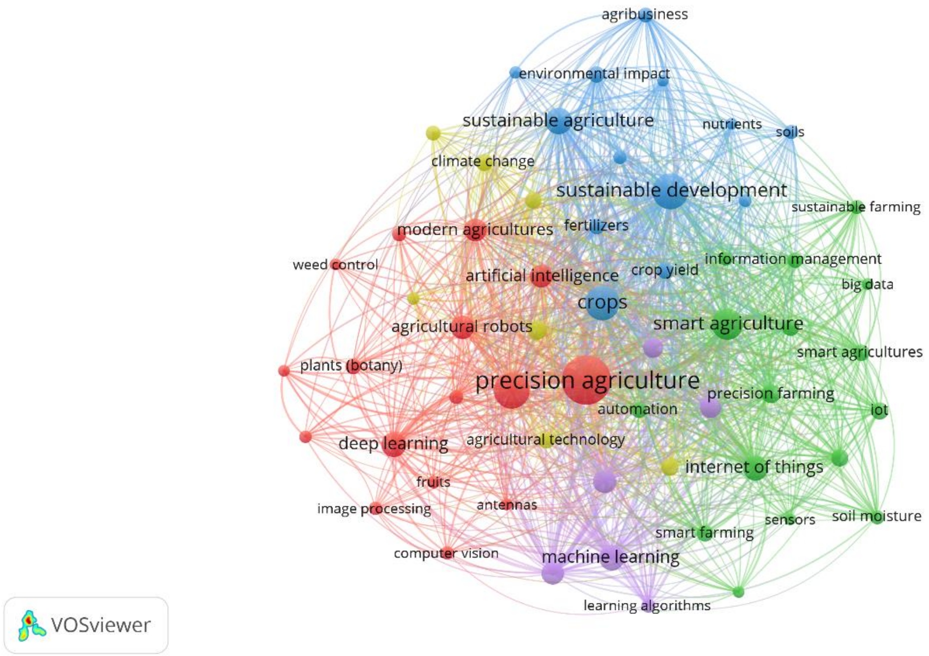

Figure 4. Network Visualization
Source: Data Analysis

This cluster can be considered mostly related to the concept of technology innovation and intelligent agriculture. In particular, keywords including artificial intelligence, deep learning, computer vision, image processing, robots, and automation point to increased usage of highly sophisticated methods that involve computing technologies to facilitate agricultural decision-making. Overall, the high relevance of such terms proves an increased implementation of advanced technological approaches that help to recognize crops, detect diseases, predict yields, control machinery autonomously, and optimize field activities. Thus, this cluster clearly illustrates a role of digitalization in agriculture development.

The green group emphasizes issues related to infrastructure for smart farming and IoT agricultural systems. Keywords of relevance are internet of things, smart farming, smart agriculture, sensors, soil moisture, precision agriculture, big data, and information management. These keywords point out the growing trend towards the use of devices and systems for monitoring in farming activities. The strong connections between these keywords show how the field of precision agriculture is moving more towards the application of sensor networks and IoT for data gathering, monitoring soil moisture levels, optimizing irrigation, and improving the management of resources.

The blue cluster is all about sustainability and environmental management in precision agriculture. Terms like sustainable development, sustainable agriculture, environmental effects, crop production, nutrients, soils, and agribusiness suggest an increased attention to achieving equilibrium between productivity in agriculture and environment protection. The high relevance of sustainable development, which can be seen from the size of this node among the others in the graph, shows that precision agriculture is becoming one of the solutions to the major issues of our time – food safety, resource protection, and climate change. Precision agriculture researchers pay much attention to fertilizers, soil, nutrients, and sustainable farming.

The yellow and purple clusters indicate two key topics relating to technology and sustainable development which have recently emerged as part of an interdisciplinary field. The keywords "climate change," "fertilizer," "machine learning," "learning algorithm," and "crop management" point towards the intersection of sustainability issues and modern methodologies. This indicates that predictive analysis, adaptive measures in response to climate change, and decision support systems are key areas of interest for recent studies.

From the overlay visualization, it can be noted how research themes have changed over time in relation to precision agriculture since all keywords have been colored according to their average year of publication. The early research themes, colored dark blue and purple (circa 2019-2020), involved the traditional agricultural production process and resource management. This can be noted from some of the keywords like soil fertility, nitrogen, manure, soil quality, crop production, organic farming, and agriculture, which suggest that the first efforts involved the improvement of agricultural production using effective methods of soil and nutrient management.

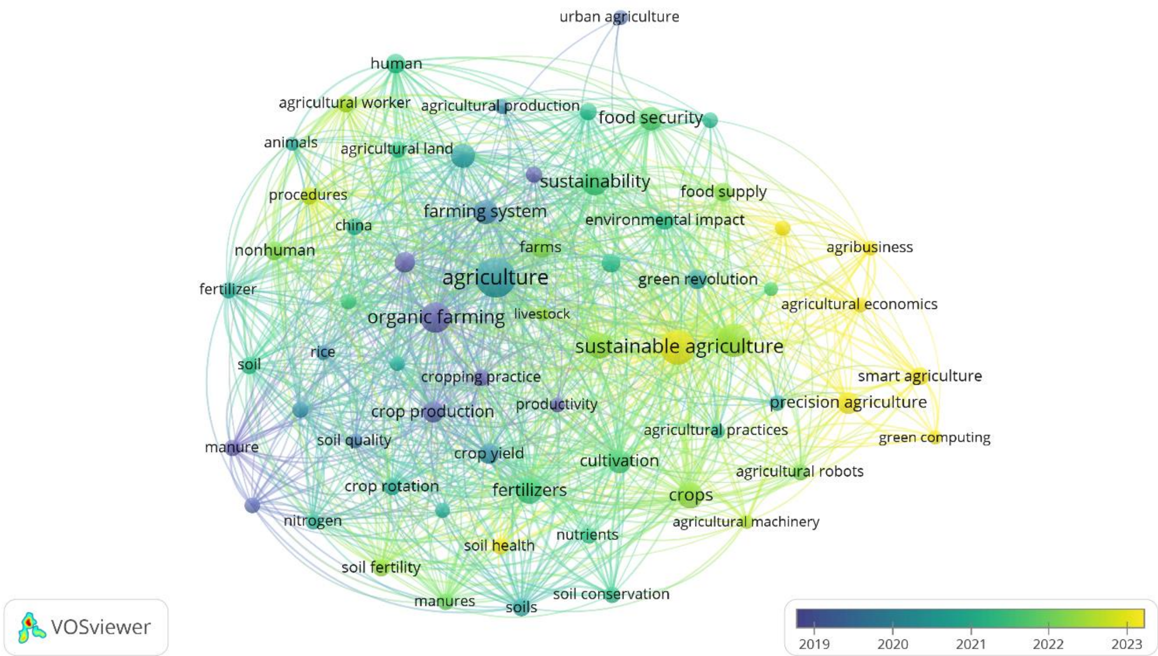

Figure 5. Overlay Visualization

Source: Data Analysis

With the advancement of research in this field over the 2020-2022 period, which is marked with green-colored nodes, the research areas have broadened to sustainability issues. The key terms associated with this expansion include sustainability, sustainable agriculture, food security, food supply, environment effects, farming systems, agricultural production, and crops. These topics indicate the changing research focus on agricultural productivity not only as an issue of improving the yield but also considering the sustainability aspect. Specifically, researchers began to address agricultural productivity in light of environmental conservation and sustainable development goals against the background of climate changes, population growth, and resource pressures.

However, more contemporary areas of research in terms of the yellow-colored nodes (2022-2023) demonstrate a clear inclination towards digitalization and intelligent agriculture systems. Key words such as precision agriculture, smart agriculture, green computing, agricultural robots, agricultural machinery, agribusiness, and agricultural economics become the representatives of the new and rapidly developing themes. Such tendency clearly illustrates the development of precision agriculture as an area evolving from the traditional agronomic approaches to the ones associated with using advanced technological means that include automation, analytics, robotics, etc. The use of key words related to economy and agribusiness becomes one more proof of the same idea.

Density visualization shows the most researched and highly connected topics in precision agriculture studies. Those areas that are depicted in bright yellow indicate the most dense part of research, and precision agriculture turns out to be the leading keyword in the map. Related words like sustainable development, crops, and smart agriculture are also shown to have a dense cluster; this means that they are the fundamental knowledge areas of precision agriculture research. The importance of these topics in relation to precision agriculture shows the main direction for researchers – to use innovations for agricultural purposes, as well as promote sustainability goals.

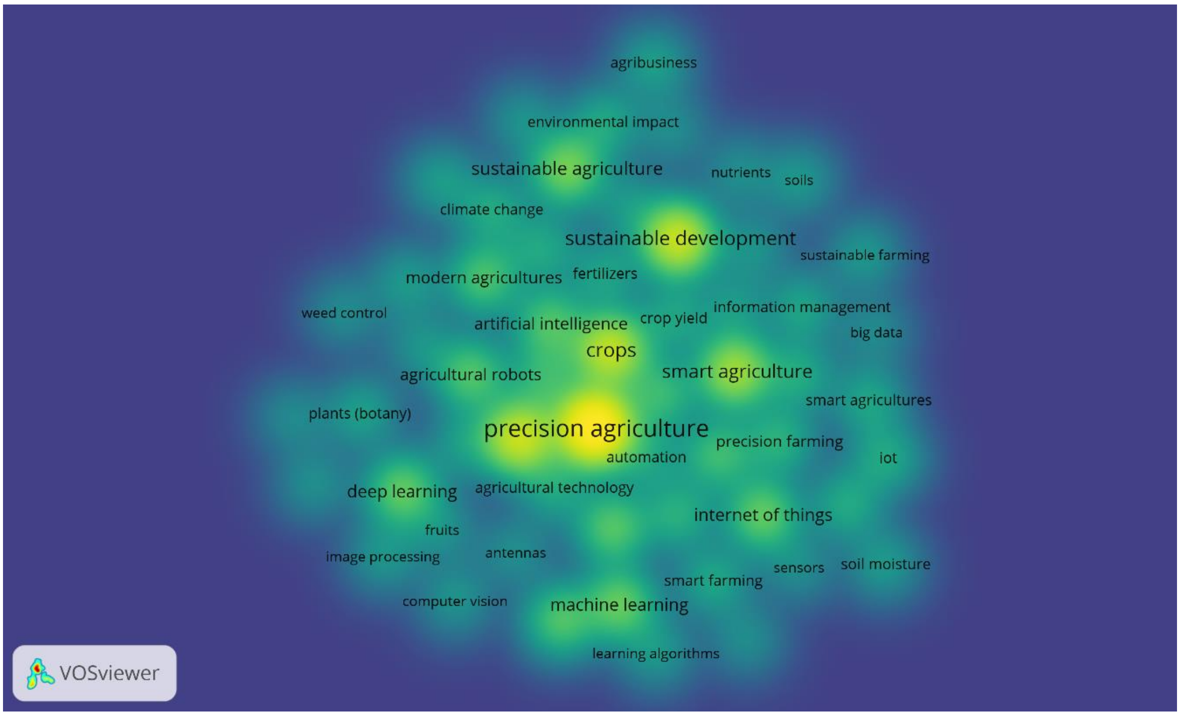

Figure 6. Density Visualization
Source: Data Analysis

Apart from the above, some additional important areas of research that have high relevance to the study can be observed in green areas, which include IoT, machine learning, artificial intelligence, precision agriculture, information management, crop production, environmental impact, and sustainable agriculture. This highlights the importance of precision agriculture as an interdisciplinary area, where the use of data analysis, intelligent systems, sensing technology, and environmental science comes together for efficient solutions. Some other research areas, however, such as computer vision, image processing, deep learning, soil moisture, and agricultural robots, have been found in less dense regions of the map.

4. CONCLUSION

This bibliometric study provides a comprehensive overview of the development of precision agriculture research in modern agriculture during the 2010–2024 period. The findings reveal a substantial growth in scientific publications, reflecting increasing global interest in the application of advanced technologies to improve agricultural productivity, efficiency, and sustainability. The collaboration analyses indicate that research activities are concentrated among several influential authors, institutions, and countries, with India, China, the United States, and the Russian Federation playing prominent roles in international scientific cooperation. Citation analysis demonstrates that the intellectual foundation of the field is built upon studies related to nanotechnology, remote sensing, sustainable nutrient management, agricultural robotics, smart farming, and digital agriculture technologies. Furthermore, keyword co-occurrence, overlay, and density visualizations reveal a clear evolution of research themes from traditional concerns such as soil fertility and crop management toward sustainability-oriented agriculture and, more recently, toward the integration of artificial intelligence, machine learning, Internet of Things (IoT), smart agriculture, and agricultural automation. These findings suggest that precision agriculture has transformed into a highly interdisciplinary research domain that combines digital innovation with sustainable development objectives. Future research is expected to further explore intelligent decision-support systems, autonomous agricultural technologies, climate-resilient farming practices, and data-driven agricultural management solutions to address the growing challenges of global food security and environmental sustainability.

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