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Efficiency of Water and Fertilizer Use in Agriculture: A Global Bibliometric Study

Loso Judijanto
IPOSS Jakarta, Indonesia

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ABSTRACT

This study presents a comprehensive bibliometric analysis of global agricultural research on the efficiency of water and fertilizer use. As agricultural systems face increasing pressure to meet the growing global demand for food while minimizing environmental impacts, understanding the optimal use of water and fertilizers has become crucial. Through bibliometric techniques, this study analyzes key trends, influential publications, and research clusters that explore the intersection of water and fertilizer use efficiency, sustainable agriculture, and environmental concerns. The findings highlight the evolving nature of research, with significant contributions from major research hubs such as China, India, the United States, and Europe. Additionally, the study reveals the increasing importance of technological innovations and international collaboration in advancing sustainable agricultural practices. The research serves as a valuable resource for scholars and policymakers seeking to foster innovation and sustainability in the agricultural sector.

Corresponding Author:

Name: Loso Judijanto
Institution: IPOSS Jakarta, Indonesia
Email: losojudijantobumn@gmail.com

1. INTRODUCTION

Agriculture remains one of the most essential sectors for global food security, economic stability, and rural livelihoods. As the global population continues to grow, agricultural systems are under increasing pressure to produce higher yields with limited natural resources [1], [2]. Water and soil nutrients particularly nitrogen, phosphorus, and potassium are fundamental to crop growth and productivity. However, the conventional use of these inputs often leads to inefficiencies, where excessive application does not translate into proportional yield increases and can instead contribute to environmental degradation [3]. Given that agriculture accounts for approximately 70% of global freshwater withdrawals and a significant share of fertilizer consumption, understanding how efficiently these inputs are used has become critical for achieving both food security and sustainability goals [4], [5].

The disparity between input use and output efficiency has significant implications for environmental health. Inefficient irrigation systems result in water losses through evaporation, deep percolation, and runoff,

which diminish the water available for productive use and stress freshwater ecosystems [6]. Similarly, when fertilizers are applied in excess of crop needs, nutrients can leach into groundwater, volatilize into the atmosphere, or run off into surface water bodies, leading to eutrophication and greenhouse gas emissions [7], [8]. These challenges are not only ecological but also economic—wasted inputs increase production costs for farmers and reduce the economic viability of agricultural enterprises, particularly in regions where water and fertilizers are costly or scarce [9].

Global interest in resource-use efficiency in agriculture has surged as researchers, policymakers, and practitioners recognize the dual mandate of enhancing food production while minimizing environmental footprints. Efficient use of water and fertilizers is frequently linked with sustainable intensification—the concept of increasing agricultural output from the same land area with fewer external inputs and reduced environmental harm [10]. Numerous studies have explored strategies for optimizing irrigation scheduling, adopting precision agriculture technologies, implementing soil testing, and using enhanced-efficiency fertilizers to improve input efficiency [11]. Yet, the diffusion of such practices varies widely across regions, crops, and farming systems, underscoring the need for comprehensive assessments that can integrate findings across disciplines and geographies.

Bibliometric analysis provides a quantitative approach to mapping the evolution, structure, and trends in scientific literature on a given topic. By analyzing publication output, citation networks, keyword co-occurrence, and collaborative patterns, bibliometric studies can reveal how research attention has shifted over time and where future research opportunities may exist [12]. In the context of water and fertilizer use efficiency, bibliometric studies can help identify key research themes—such as precision irrigation, remote sensing, nutrient use efficiency, and policy frameworks—as well as influential authors, institutions, and countries shaping the discourse. Such insights are invaluable for researchers seeking to position their work within existing knowledge and for funding agencies aiming to allocate resources toward impactful research areas.

Despite the growing body of research on sustainable agriculture, there has been limited synthesis of how the academic conversation around water and fertilizer efficiency has developed on a global scale. Research outputs are dispersed across agronomy, environmental science, engineering, economics, and policy journals, making it challenging to discern overarching trends without systematic analysis. Moreover, as global challenges like climate change and resource scarcity intensify, stakeholders require a clear understanding of where the scientific community stands in addressing efficiency issues, which topics are emerging, and what gaps remain. A bibliometric perspective can thus serve as a foundational step toward building coherent research agendas and informing evidence-based policy formulation.

While individual studies have investigated aspects of water and fertilizer efficiency in specific crops, regions, or technologies, there is a lack of comprehensive synthesis that examines global research trends, collaborations, and thematic priorities within this field. Without such synthesis, it is difficult to assess how scientific knowledge has evolved, where research concentrations and gaps lie, and how different disciplines and regions contribute to the broader understanding of efficient resource use in agriculture. This fragmentation limits the ability of researchers and policymakers to coordinate efforts toward solving pressing sustainability challenges linked to water scarcity, nutrient loss, and climate change impacts on agricultural systems. The objective of this study is to conduct a comprehensive global bibliometric analysis of research on the efficiency of water and fertilizer use in agriculture.

2. METHODS

This study employed a bibliometric research design to systematically analyze global scientific literature related to the efficiency of water and fertilizer use in agriculture. Bibliometric analysis is a quantitative approach that enables the evaluation of large volumes of academic publications to identify patterns, trends, and intellectual structures within a research field. The analysis focused on peer-reviewed journal articles and review papers published in international scientific outlets. Relevant publications were retrieved from a major bibliographic database widely recognized for its comprehensive coverage of agricultural, environmental, and multidisciplinary research. A structured search strategy was developed using carefully selected keywords and Boolean operators related to water use efficiency, fertilizer or nutrient use efficiency, and agricultural production. Only publications written in English and published within a defined time frame were included to ensure consistency and comparability of the data.

After data collection, the retrieved records were screened to remove duplicates and irrelevant documents. Bibliographic information such as authors, publication year, journal name, country of affiliation, keywords, abstracts, and citation counts was extracted for analysis. Descriptive bibliometric indicators, including annual publication trends, document types, and citation performance, were used to evaluate the growth and impact of research in this field. In addition, productivity and collaboration patterns among authors, institutions, and countries were examined to understand the global distribution of research efforts and international cooperation. These indicators provide insights into how scientific attention to water and fertilizer efficiency has evolved and which actors have played central roles in advancing knowledge.

To explore the intellectual structure and thematic evolution of the research field, science mapping techniques were applied. Keyword co-occurrence analysis was conducted to identify dominant research themes and emerging topics related to water and fertilizer use efficiency. Co-authorship and co-citation analyses were also performed to reveal collaborative networks and influential publications shaping the field. Specialized bibliometric software was used to visualize networks and clusters, enabling clearer interpretation of complex relationships among research themes and contributors. The combined use of performance analysis and science mapping ensured a comprehensive understanding of both the quantitative growth and conceptual development of global research on efficient water and fertilizer use in agriculture.

3. RESULTS AND DISCUSSION

3.1 Keyword Co-Occurrence Network

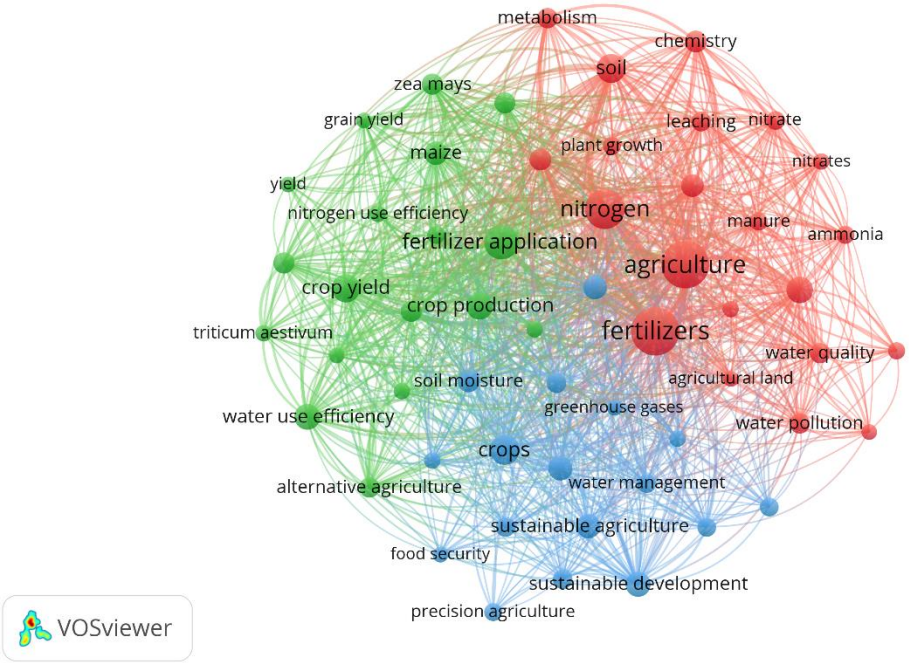

Figure 1. Network Visualization
Source: Data Analysis Result, 2026

Figure 1 shows the interconnections between key topics in the global research on the efficiency of water and fertilizer use in agriculture. The map is color-coded to indicate the different thematic clusters that emerge from the analysis of publications and their keywords. These clusters represent the major areas of focus in the literature on agricultural efficiency, with each color highlighting a particular theme. The red cluster, positioned at the top-right, is heavily focused on fertilizers, with keywords like "fertilizer application," "nitrates," "nitrogen," "ammonia," and "manure" forming key nodes in this cluster. These terms suggest that a significant portion of the research is concerned with understanding the role of fertilizers in agricultural production, particularly nitrogen fertilizers, which are known to impact both crop yield and environmental health. The connections to "water quality" and "water pollution" in this cluster also indicate the environmental concerns linked to fertilizer use, such as nutrient runoff and water contamination.

In the green cluster, which is located on the left side of the map, there is a clear emphasis on water use efficiency and crop yield. Keywords like "water use efficiency," "soil moisture," "crop yield," and "irrigation" point to research that explores how water can be used more effectively in agriculture to improve productivity. The presence of terms like "maize" and "triticum aestivum" (wheat) suggests that much of the research in this cluster focuses on staple crops and their water requirements, highlighting the importance of optimizing water resources for sustainable crop production.

The blue cluster, located towards the bottom, is linked to sustainable agriculture and agriculture management. Keywords like "sustainable agriculture," "precision agriculture," and "sustainable development" suggest that researchers are increasingly focusing on approaches that balance agricultural productivity with environmental sustainability. Terms such as "food security" and "alternative agriculture" also point to a growing interest in practices that can support long-term agricultural productivity while addressing broader global challenges like climate change and resource scarcity.

The connections between these clusters reflect the growing interdisciplinary nature of research in this field. For example,

the overlap between the fertilizer-focused red cluster and the water-focused green cluster demonstrates how research on fertilizer efficiency is closely tied to water management strategies. This suggests that scholars are investigating ways to optimize the use of both water and fertilizers to enhance agricultural productivity while minimizing environmental impacts. This interconnectedness highlights the complexity of achieving sustainable agriculture, where efficient resource use is critical to addressing both environmental concerns and global food security needs.

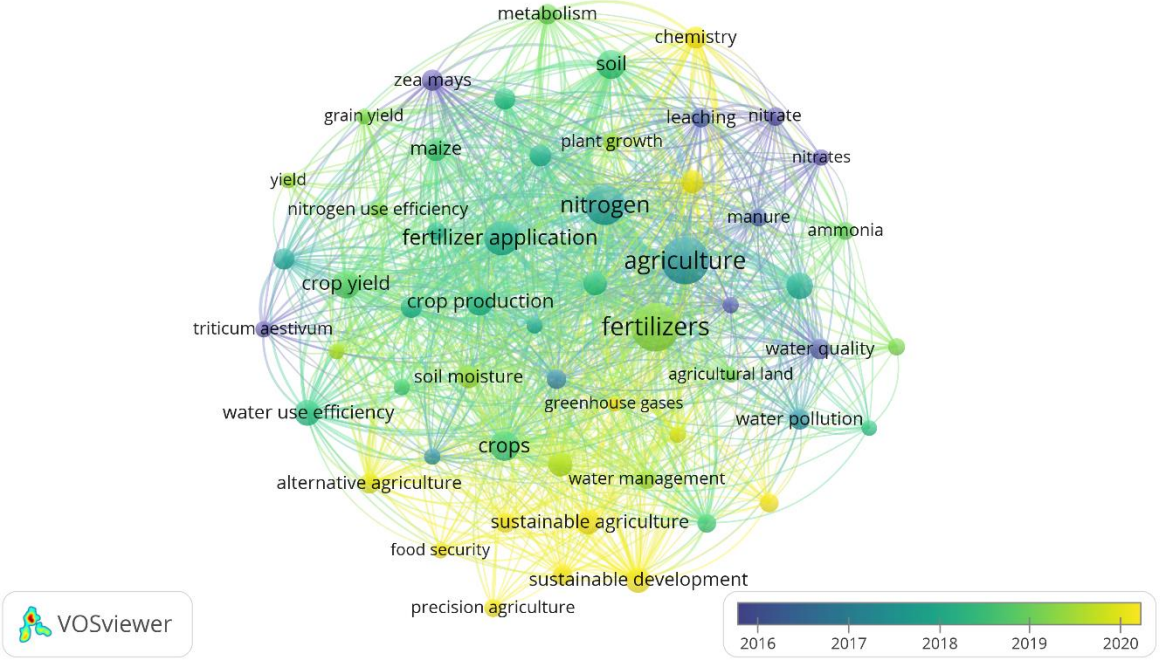

Figure 2. Overlay Visualization
Source: Data Analysis Result, 2026

Figure 2 shows the evolution of research topics related to the efficiency of water and fertilizer use in agriculture, with a focus on the years 2016 to 2020, as indicated by the color gradient. The map highlights how various themes in agricultural efficiency, particularly concerning water, fertilizer, and crop management, have developed over the past few years. The colors range from purple (representing 2016) to yellow (representing 2020), suggesting the shifting focus and growing research interest in these areas.

The fertilizer and water use efficiency clusters, which were prominent in earlier years (2016-2017), seem to have continued their growth, as evidenced by the transition towards green and yellow shades. This indicates increasing research into how fertilizers, especially nitrogen, are applied efficiently in agriculture while mitigating their environmental impact. There is a clear trend toward integrating these topics with sustainable practices such as sustainable agriculture and precision agriculture, which have gained more traction in recent years (2019-2020). These developments are supported by the overlap of themes like water management, soil moisture, and agriculture productivity.

In addition, the shift towards research on environmental impacts, such as water quality and water pollution, is evident, especially in the more recent years. The increasing overlap of these topics with fertilizer application and nitrogen use efficiency suggests that researchers are focusing on finding solutions to reduce the negative consequences of fertilizer use, such as nutrient runoff into water bodies. The presence of greenhouse gases and alternative

agriculture in the later years highlights the growing intersection of agricultural practices with climate change mitigation and the need for sustainable development, showing a more integrated approach to addressing global food security challenges while minimizing environmental footprints.

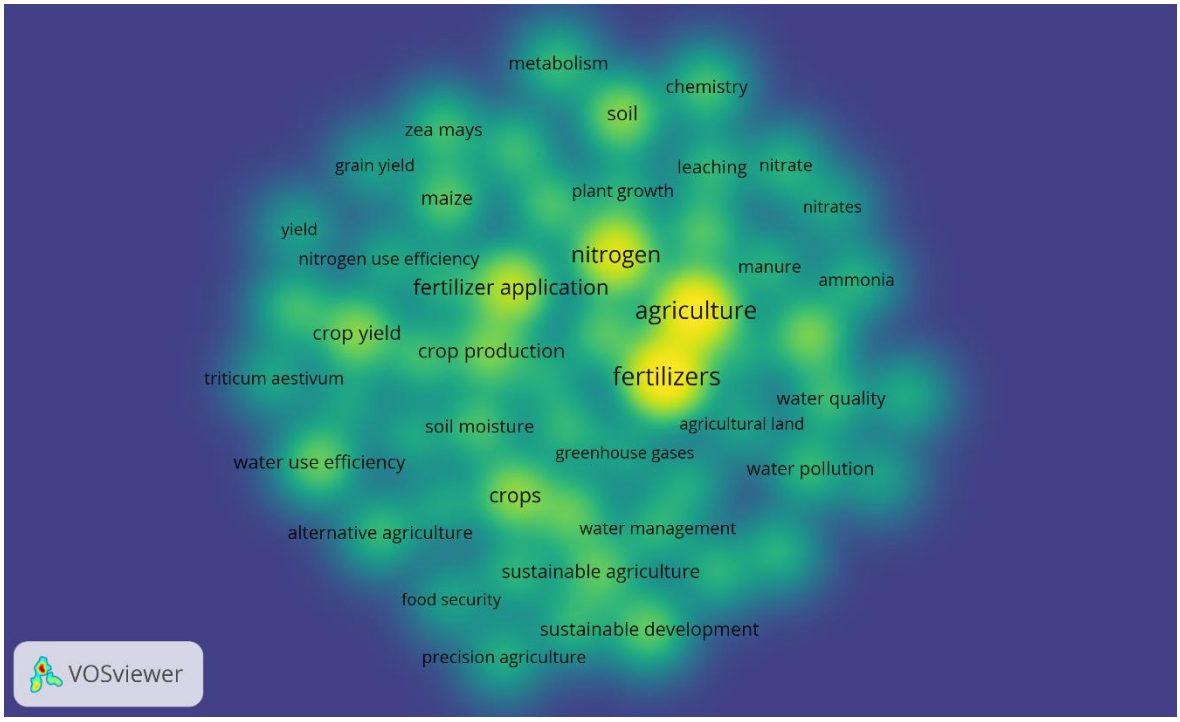

Figure 3. Density Visualization

Source: Data Analysis Result, 2026

Figure 3 presents the distribution and intensity of research topics related to the use of water and fertilizers in agriculture. The central cluster, marked by a bright yellow hue, indicates the high frequency of research around fertilizers, especially topics like nitrogen, fertilizer application, and nitrogen use efficiency. This suggests that fertilizers, particularly nitrogen-based ones, are at the core of the research on improving agricultural efficiency. The proximity of terms like crop production and crop yield indicates that much of the research focuses on how fertilizers influence agricultural productivity, with a strong connection to improving both the quantity and quality of crops.

In contrast, the surrounding areas of the heatmap show a broad interest in the environmental impacts of fertilizer use, as seen in terms like water quality, water pollution, and greenhouse gases. These terms, along with sustainable agriculture and precision agriculture, highlight the growing concern with minimizing the environmental footprint of agricultural practices. The sustainable development and food security keywords suggest an emerging focus on integrating efficient resource use with broader goals of long-term food security and environmental sustainability.

3.2 Co-Authorship Network

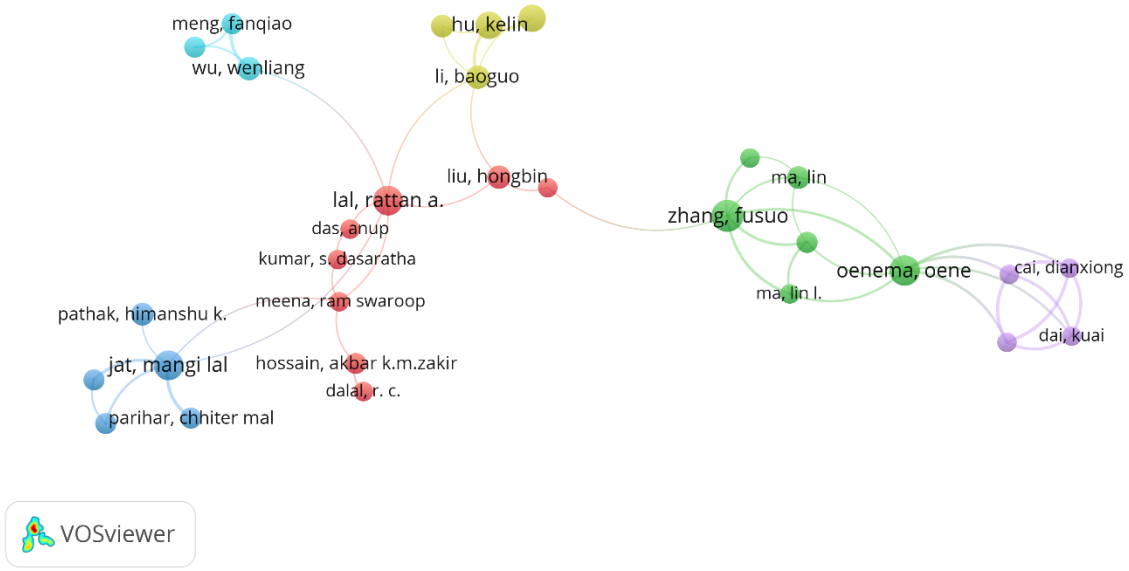

Figure 4. Author Collaboration Visualization

Source: Data Analysis Result, 2026

Figure 4 represents the co-authorship relationships between researchers in the field related to your study. Each node represents an individual researcher, and the links between them indicate collaborations on research papers. The color-coding and grouping of nodes show distinct research clusters, with some well-defined groups of co-authors such as those in the red, green, and blue clusters, suggesting frequent collaboration within those groups. Notably, Rattan A. Lal is at the center of the largest cluster, indicating a prominent role in the research community. The clusters are loosely connected, with various co-authorship patterns suggesting collaboration between specific researchers in subfields, likely related to soil science, nitrogen management, and sustainable agricultural practices. This map helps to visualize how research ideas spread across the academic community and how various scholars are interlinked based on their joint publications.

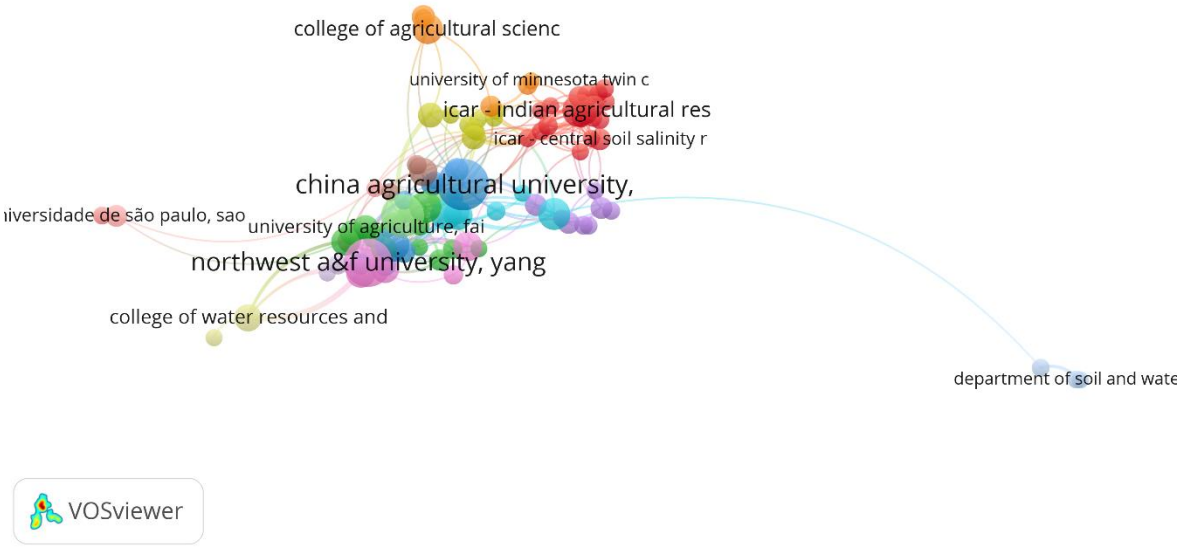

Figure 5. Affiliation Collaboration Visualization
Source: Data Analysis Result, 2026

Figure 5 illustrates the collaborations between different research institutions in the field of agricultural studies, with a focus on soil and water resources. Each node represents a university or research institution, and the links between them indicate co-publications or collaborative research efforts. Notably, institutions such as China Agricultural University, Indian Agricultural Research Institute (ICAR), and University of Minnesota are central, suggesting active participation and research output in this field. The colorful clusters represent distinct groups of institutions that are closely connected, indicating strong academic ties and collaborative networks. The presence of institutions like the University of São Paulo and Northwest A&F University further emphasizes the global nature of research in agricultural sciences, especially those related to soil and water management. This map highlights the international collaboration in addressing agricultural challenges, particularly in soil and water resource management.

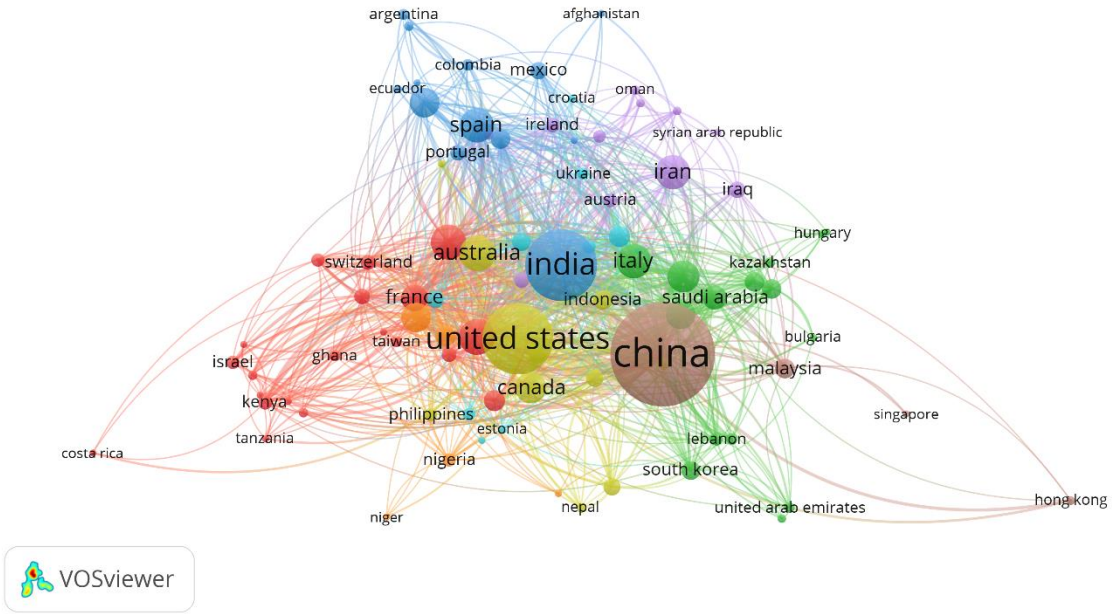

Figure 6. Country Collaboration Visualization
Source: Data Analysis Result, 2026

Figure 6 represents the global collaboration in agricultural research based on country affiliations. Each node represents a country, and the connections between them show the frequency and strength of collaborations in the research domain. The map reveals several distinct clusters, with countries like China, India, United States, and Australia forming the largest and most interconnected groups. These central nations likely have a high volume of international collaborations in agricultural research. Countries in Europe, such as Spain, France, and Italy, form another significant cluster, with close ties to countries in Africa and Asia. Smaller, peripheral clusters, including countries like Nigeria, Kenya, and Ghana, indicate regional collaboration but with fewer global connections. The map highlights the global nature of agricultural research, with particular emphasis on collaborations between key agricultural research hubs across continents.

3.3 Citation Analysis

Table 1. Top Cited Research

Citations	Authors and year	Title
3110	[13]	A global perspective on the use, sales, exposure pathways, occurrence, fate and effects of veterinary antibiotics (VAs) in the environment
2353	[14]	Managing nitrogen for sustainable development
1045	[15]	Lost food, wasted resources: Global food supply chain losses and their impacts on freshwater, cropland, and fertiliser use
996	[16]	50 year trends in nitrogen use efficiency of world cropping systems: The relationship between yield and nitrogen input to cropland
975	[17]	Nitrogen fertilizer use in China - Contributions to food production, impacts on the environment and best management strategies
936	[18]	Nutrient use efficiency in plants

Citations	Authors and year	Title
898	[19]	Review on materials & methods to produce controlled release coated urea fertilizer
820	[20]	Improving agricultural water use efficiency in arid and semiarid areas of China
775	[21]	Towards global phosphorus security: A systems framework for phosphorus recovery and reuse options
768	[22]	Phosphate nutrition: Improving low-phosphate tolerance in crops

Source: Scopus, 2025

Discussion

The bibliometric analysis of global agricultural research reveals a significant degree of international collaboration, with key countries like China, India, United States, and Australia at the center of extensive research networks. These countries play a pivotal role in driving agricultural innovation, particularly in areas related to soil and water management. The close-knit clusters around these nations suggest that they not only lead in research output but also collaborate extensively across borders, sharing knowledge and resources to tackle global agricultural challenges. The geographic distribution of research partnerships underscores the growing importance of agricultural sustainability in both developed and developing nations, with countries such as Brazil, Kenya, and Mexico contributing to the broader dialogue on food security and environmental management.

The presence of European countries, notably France, Germany, and Spain, within the research network highlights the significant role of the European Union in shaping agricultural policies and innovations. These countries often lead in research on sustainable agriculture, biodiversity conservation, and climate change mitigation. Their collaborative efforts, particularly with Asian and African countries, signal the importance of knowledge transfer between regions. Notably, the inclusion of countries like Israel and Singapore indicates the growing influence of technological advancements and innovation in agricultural practices, such as precision farming, in enhancing food production and resource management. These collaborative efforts are essential in addressing global challenges like climate change, water scarcity, and soil degradation.

Furthermore, the analysis reveals the expanding role of emerging economies, particularly China and India, in agricultural research. These nations are becoming key players not only in research but also in the implementation of sustainable agricultural practices due to their large agricultural sectors and the need to feed their growing populations. The growing network of collaborations with countries in Africa, Latin America, and Southeast Asia reflects the increasing focus on addressing local agricultural challenges through shared global knowledge. The interconnectedness of research institutions across these regions suggests a global commitment to improving agricultural efficiency while ensuring long-term environmental sustainability. These trends underscore the importance of international cooperation in advancing agricultural research and practices.

4. CONCLUSION

The bibliometric analysis of global agricultural research highlights the extensive international collaboration that is essential for addressing the complex challenges faced by the agricultural sector, particularly in areas like soil and water management, sustainable farming, and climate change mitigation. Key research hubs, such as China, India, the United States, and Australia, play a central role in fostering these collaborations, connecting with countries across Europe, Africa, and Latin America. This network of partnerships underscores the importance of knowledge exchange and collective action in advancing agricultural innovation. The growing participation of emerging economies

in this global network further emphasizes the need for shared solutions to improve food security and environmental sustainability on a global scale, ensuring that agricultural research continues to evolve to meet the demands of a rapidly changing world.

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