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A Decade of Scientific Publications on Microbial Biotechnology for Sustainable Agriculture

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ABSTRACT

The increasing demand for sustainable agricultural practices has driven significant scientific interest in microbial biotechnology over the past decade. This study presents a scientometric analysis of global research on microbial biotechnology for sustainable agriculture from 2014 to 2024, using data retrieved from the Scopus database and analyzed through VOSviewer software. The results reveal major thematic clusters centered around soil health, plant growth-promoting microbes, rhizosphere dynamics, bioremediation, and microbial metabolism. India, China, the United States, and Brazil emerged as leading contributors, supported by strong international collaboration networks. Keyword co-occurrence, institutional collaboration, and country mapping analyses indicate a growing integration of microbial research with broader environmental and sustainability agendas. Furthermore, the study identifies recent shifts in focus toward climate resilience, microbiome-based approaches, and ecological intensification. The findings offer valuable insights for academic researchers, policymakers, and agricultural stakeholders, highlighting both the intellectual development of the field and its practical applications for addressing global agricultural and environmental challenges.

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1. INTRODUCTION

Over the past decade, the global agricultural sector has been facing unprecedented challenges arising from climate change, land degradation, biodiversity loss, and increasing food demands driven by a rapidly growing population. These complex issues have strained conventional agricultural practices, which often rely heavily on synthetic inputs such as chemical fertilizers and pesticides [1], [2]. While these inputs have historically boosted yields, they have also contributed to significant environmental problems, including soil depletion, water contamination, and greenhouse gas emissions. As a result, there is a growing consensus among scientists, policymakers, and practitioners that a shift toward more sustainable agricultural systems is not only desirable but necessary for ensuring long-term food security and ecological balance [3], [4].

In this context, microbial biotechnology has emerged as a promising avenue for addressing the sustainability crisis in agriculture. Microbial biotechnology refers to the strategic use of beneficial microorganisms such as bacteria, fungi, and actinomycetes for agricultural purposes. These microbes play crucial roles in nutrient cycling, nitrogen fixation, disease suppression, and organic matter decomposition [5]. In particular, plant growth-promoting rhizobacteria (PGPR), mycorrhizal fungi, and biocontrol agents have gained increasing attention as eco-friendly alternatives to synthetic agrochemicals. The use of microbial biofertilizers and biopesticides has been shown to enhance soil health, crop productivity, and resilience to environmental stress, aligning well with the goals of sustainable agriculture [6], [7].

Scientific research in microbial biotechnology has accelerated over the last ten years, driven by advances in genomics, metagenomics, and high-throughput sequencing technologies. These innovations have enabled researchers to explore the diversity, functionality, and interactions of soil microbial communities at unprecedented scales and resolution [8]. As a result, new microbial strains with agricultural benefits are continuously being discovered, characterized, and applied. Simultaneously, the interdisciplinary nature of microbial biotechnology has fostered an expanding body of scientific literature. This growing volume of publications reflects not only scientific curiosity but also urgent practical demands to deploy microbial solutions in sustainable farming systems [1], [2].

Despite this surge in interest, the literature on microbial biotechnology for sustainable agriculture is often dispersed across various journals, fields, and thematic areas. This fragmentation can make it difficult for researchers, practitioners, and policymakers to obtain a comprehensive overview of the key developments, dominant trends, research hotspots, and gaps in knowledge. Bibliometric and scientometric analyses offer valuable tools for addressing this problem by providing quantitative insights into the evolution and structure of scientific research. By systematically mapping publication patterns, citation networks, and keyword co-occurrences, researchers can uncover the intellectual landscape of a field and identify promising directions for future investigation.

Given the central role of microbial biotechnology in transitioning toward more sustainable agricultural systems, a thorough scientometric review of this field is both timely and essential. Such a review would not only synthesize the contributions of the past decade but also provide strategic intelligence for future research agendas. In doing so, it would support more effective integration of microbial solutions into mainstream agricultural practices, contributing to the broader goals of environmental sustainability, food security, and climate resilience.

Despite the significant growth in scientific publications on microbial biotechnology in agriculture, there remains a lack of structured understanding of how this research has evolved over the past decade. The existing body of literature is vast and multidimensional, making it difficult to discern core themes, influential authors or institutions, and emerging research frontiers. Without a systematic scientometric assessment, stakeholders may struggle to grasp the dynamics, maturity, and interdisciplinary nature of this rapidly developing field. This limitation hinders the optimal utilization of scientific knowledge in policy-making, innovation, and sustainable development strategies. The objective of this study is to conduct a comprehensive scientometric review of scientific publications on microbial biotechnology for sustainable agriculture over the past decade.

2. METHODS

This study adopts a scientometric review approach to analyze the landscape of scientific publications on microbial biotechnology in the context of sustainable agriculture from 2014 to 2024. Scientometric analysis is a quantitative method used to assess the development, trends, and structural patterns within a specific body of scientific literature. The method is particularly suitable for mapping the evolution of interdisciplinary research fields such as microbial biotechnology. For this study, the Scopus database was chosen as the primary source of bibliographic data due to its extensive coverage of peer-reviewed scientific journals and its compatibility with bibliometric software tools. The search strategy used a combination of controlled keywords and Boolean operators, including terms such as "microbial biotechnology", "biofertilizer", "biocontrol", "PGPR", and "sustainable agriculture", to ensure comprehensive retrieval of relevant documents.

Once the data were retrieved from Scopus, they were exported in RIS and CSV formats, which include essential metadata such as author names, article titles, abstracts, publication years, journals, keywords, affiliations, and citation counts. The final dataset consisted of original research articles and review papers published in English within the defined time window (2014–2024). Editorials, conference papers, and short communications were excluded to maintain the academic rigor and consistency of the analysis. Duplicates and irrelevant entries were manually screened and removed. This refined dataset was then imported into VOSviewer where further analysis was conducted.

Using VOSviewer, the study generated a series of visual maps that illustrate co-authorship networks (authors and institutions), co-citation relationships (sources and references), and keyword co-occurrence patterns. These maps enabled the identification of dominant research clusters, core themes, emerging topics, and knowledge gaps within the field. The co-occurrence analysis of author keywords was especially useful in detecting thematic hotspots and shifts in research focus over the decade. Clustering algorithms within VOSviewer grouped related terms and research areas, allowing for the classification of subfields and trends in microbial biotechnology.

3. RESULTS AND DISCUSSION

Co-Authorship Network

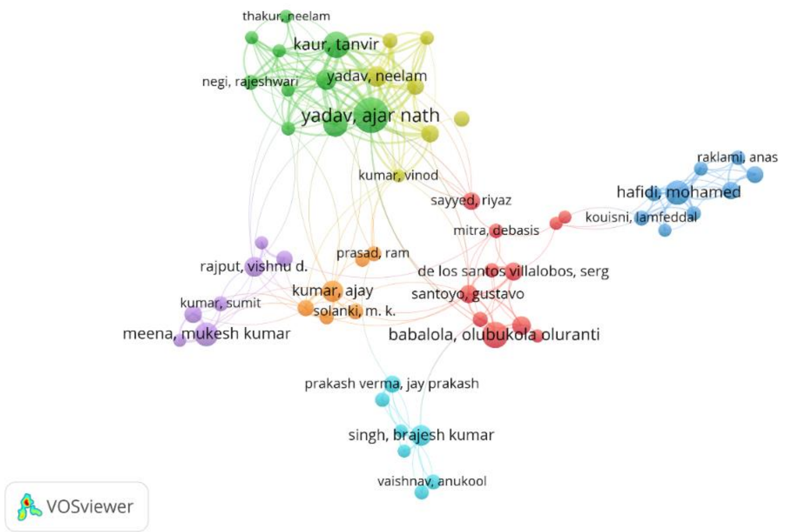

Figure 1. Author Visualization
Source: Data Analysis

Figure 1 above shows a co-authorship network of microbial biotechnology for sustainable agriculture authors in the past decade. Each node is an author, and the edges between them signify co-authorship relationships. The nodes are proportional to the number of documents the author has published, and colors show different clusters of collaborations. Interestingly, Yadav, Ajar Nath (in green) heads the biggest and most integrated cluster, collaborating extensively with authors like Kaur, Tanvir and Yadav, Neelam, suggesting a strong research group most likely based in India. Another bigger and well-known cluster (in red) is centered around Babalola, Olubukola Oluranti, suggesting a separate but effective research group, most likely from Africa. Meanwhile, Hafidi Mohamed leads the blue cluster, likely representing contributions from the North African region.

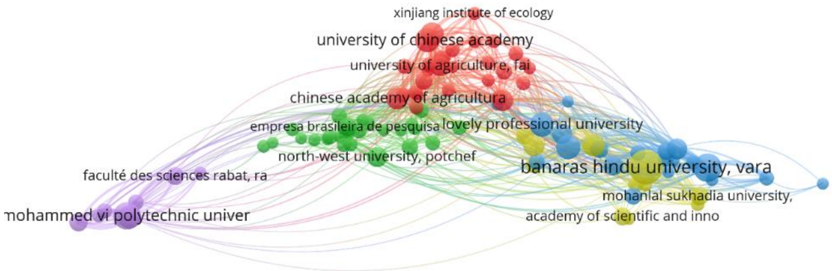

Figure 2. Affiliation Visualization
Source: Data Analysis

Figure 2 shows the institutional network of collaboration in microbial biotechnology for sustainable agriculture between the period 2014 and 2024. Each node represents an institute or research group and the line connecting them (edges) as co-authorship or collaborative research collaborator. Banaras Hindu University (in blue) is depicted as a huge hub of the network, indicating extensive collaboration with other institutes, particularly within India and across the world. Right next to it are Mohanlal Sukhadia University and the Academy of Scientific and Innovative Research as a closely integrated regional cluster. The University of Chinese Academy of Sciences, Chinese Academy of Agricultural Sciences, and the University of Agriculture, Faisalabad form another highly integrated collaborative cluster (in red) and likely represent a large hub of microbial agricultural science activity in East and South Asia. Universities such as Mohammed VI Polytechnic University and Faculté des Sciences Rabat form a smaller but distinct cluster (in purple), representing higher contributions from North Africa.

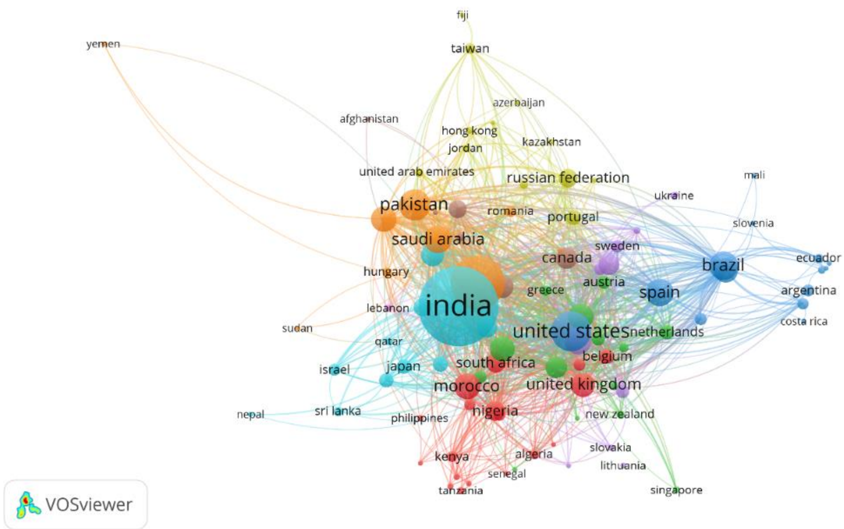

Figure 3. Country Visualization
Source: Data Analysis

Figure 3 displays a country cooperation network in the field of microbial biotechnology for green agriculture during the last decade. Every node is a country, and the node size is proportional to the number of publications, with international co-authorship expressed by the links between nations. India dominates the picture with the biggest node, denoting its leading position and high production in the research field. It is strongly connected to countries such as the United States, United Kingdom, Saudi Arabia, Pakistan, and Nigeria, depicting its extensive global alliances, with a strong focus on Asia and Africa. Brazil, Spain, and Morocco also depict extensive contributions and regional power with close clusters with European and Latin American allies. The advanced interconnectivity among countries like Canada, South Africa, China, and Australia only adds to the global and multi-disciplinary nature of microbial biotechnology studies. Yemen, Afghanistan, and Fiji, however, are located at the periphery, indicating either increasing interest or minimal participation.

Citation Analysis

Table 1. Top Cited Literature

Citations	Author	Title
862	[9]	Siderophores in environmental research: Roles and applications
308	[10]	Microbial protein: future sustainable food supply route with low environmental footprint
176	[11]	Future challenges and perspectives for applying microbial biotechnology in sustainable agriculture based on a better understanding of plant-microbiome interactions
137	[12]	Integrated systems for biopolymers and bioenergy production from organic waste and by-products: A review of microbial processes
131	[13]	Microbial symbionts: A resource for the management of insect-related problems
100	[14]	Microbial biotechnology and sustainable agriculture
98	[15]	Current knowledge on the Ralstonia solanacearum type III secretion system
75	[16]	Salinity stress: Toward sustainable plant strategies and using plant growth-promoting rhizobacteria encapsulation for reducing it
63	[17]	Recombinant entomopathogenic agents: a review of biotechnological approaches to pest insect control
60	[18]	Microbes and microbial technology: Agricultural and environmental applications

Source: Scopus Database

Keyword Co-Occurrence

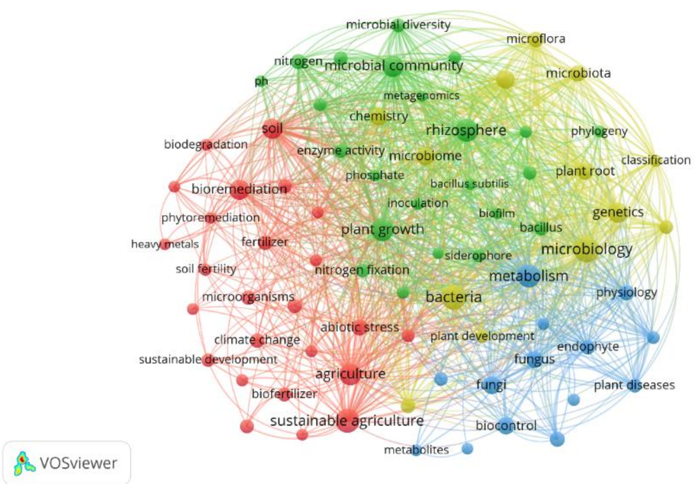

Figure 4. Network Visualization
Source: Data Analysis

Figure 4 is a keyword co-occurrence map of the literature in microbial biotechnology for sustainable agriculture over the past decade. The nodes are single keywords extracted from author-assigned terms, and the size of the node indicates how frequently it has appeared across the literature. The color-coded clusters are sets of related terms that frequently co-occur, and they indicate the main thematic research areas in this field. The network is very dense and interconnected, reflecting the cooperative and interdisciplinary nature of the microbial biotechnology research. The red cluster to the left focuses on the environmental sustainability issues, more specifically in relation to bioremediation, soil health, sustainable development, and the impacts of climate change. Identical key words such as soil, phytoremediation, microorganisms, biofertilizer, and heavy metals show a high interest in the use of microbial biotechnology for the remediation of soil pollution and enhancement of soil fertility under polluted or degraded conditions. These studies often explore microbial strategies for detoxifying the ecosystems and enhancing agricultural productivity under stress environments.

The central green cluster identifies the plant-microbe-soil interaction axis. Core keywords like rhizosphere, plant growth, bacteria, nitrogen fixation, and microbial community take up this space, indicating a core research stream of exploring and developing plant-microbe interactions for enhancing crop health and nutrition. This cluster is strongly related to terms such as enzyme activity, microbiome, phosphate, and inoculation that describe mechanistic research on microbial agent plant nutrition and soil dynamics improvement. At the right, the yellow cluster is made up of words relating to microbial taxonomy, physiology, and genetics. Microbiota, genetics, phylogeny, classification, plant root, and physiology are terms that suggest a deeper, molecular-level approach to the understanding of microbial traits and functional roles in agroecosystems. This cluster also overlaps with the green core, indicating that molecular techniques and genetic analysis are at the center of microbial community studies in the rhizosphere and soil habitats. The lower right blue cluster represents work on microbial agents for plant protection, such as biocontrol, fungus, plant disease, and endophyte. That these terms represent research seeking to employ beneficial microbes to suppress plant pathogens, make plants more tolerant, and reduce the application of chemical pesticides is evident from the terms. That terms like metabolites, siderophore, and biofilm are present indicates that researchers are looking into the biochemical mechanisms by which microbes exert protective or growth-promoting influences.

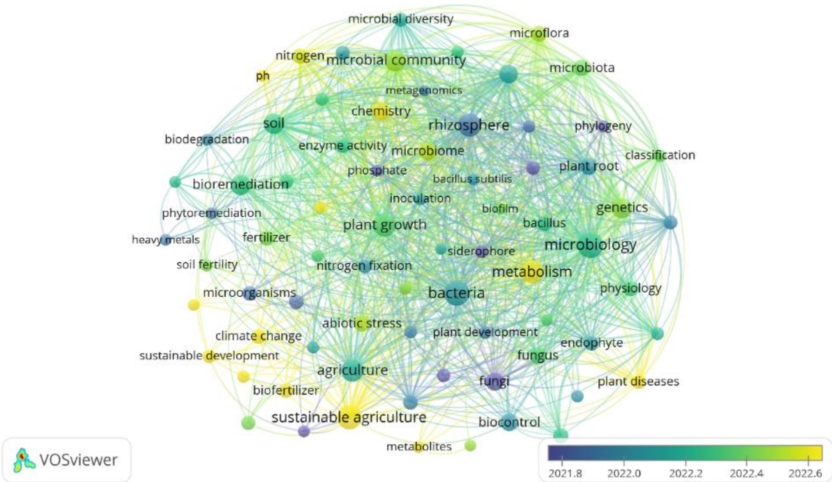

Figure 5. Overlay Visualization
Source: Data Analysis

Figure 5 presents a temporal analysis of keyword co-occurrence in microbial biotechnology research for sustainable agriculture, using color gradients to indicate the average publication year of each term. The color scale ranges from purple (earlier terms, ~2021.8) to yellow (more recent terms, ~2022.6), allowing us to trace the evolution of research themes over time. Central concepts such as plant growth, bacteria, rhizosphere, and metabolism appear in green, indicating their continued relevance across the time period. These keywords form the foundational core of microbial biotechnology, consistently studied for their roles in plant-microbe-soil interactions and nutrient cycling. Newer areas of interest can be observed through the yellow-colored keywords, which include climate change, microorganisms, microbiota, and sustainable development. Their positioning suggests a recent surge in publications that integrate microbial research with broader sustainability goals and climate-resilient agriculture. The emergence of climate change as a co-occurring term reflects the growing acknowledgment of global environmental challenges in microbial biotechnology studies. Similarly, microbiota and microflora indicate a rising focus on the comprehensive characterization of microbial communities using advanced genomic tools, particularly within the context of agricultural ecosystems. Conversely, purple and blue-toned keywords, such as fungus, biocontrol, endophyte, plant diseases, and metabolites, represent slightly older topics that may have reached a stage of maturity or stabilization in research attention. While still relevant, these themes appear to have been more prominent in earlier phases of the decade. This suggests a temporal shift from earlier studies focused on microbial disease control and biochemical mechanisms toward more integrated systems-based approaches emphasizing sustainability, climate adaptation, and microbiome-level understanding.

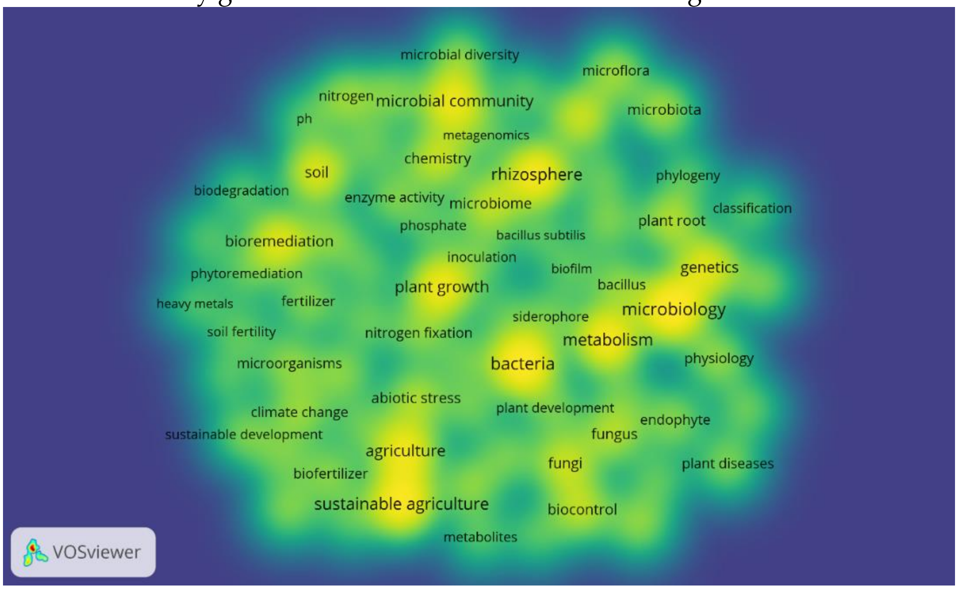

Figure 6. Density Visualization
Source: Data Analysis

Figure 6 illustrates the frequency and concentration of keyword usage in microbial biotechnology research related to sustainable agriculture. In this heatmap-like display, terms shown in bright yellow represent the most frequently occurring and intensively studied concepts, while green to blue shades indicate decreasing levels of prominence. Central and high-density terms such as bacteria, plant growth, microbiology, metabolism, rhizosphere, and sustainable agriculture are highlighted in bright yellow, signifying their dominant roles in the literature. These core themes reflect the foundational interest in plant-microbe interactions, soil health, and microbial mechanisms that enhance sustainable agricultural productivity. Surrounding these core areas, terms like bioremediation, biofertilizer, microbial community, nitrogen fixation, soil, and microbiota appear in green, suggesting consistent yet moderately lower research intensity. These keywords highlight the breadth of the field, encompassing environmental restoration, soil-microbe dynamics, and biotechnological interventions. The outermost areas, depicted in darker blue shades, include more specialized or emerging terms such as metabolites, biocontrol, plant diseases, and fungi, which may represent niche or supporting research themes.

Practical Implication

The findings of this scientometric study offer significant practical value for stakeholders in agriculture, biotechnology, and environmental management. By mapping the evolution of research themes and identifying key contributors and collaboration networks, this study provides actionable insights for policymakers, agricultural practitioners, and agritech companies. For example, the strong focus on keywords such as biofertilizer, bioremediation, plant growth, and soil health highlights areas where microbial interventions can be directly applied to reduce chemical dependency, improve crop resilience, and restore degraded land. Additionally, understanding international collaboration patterns helps governments and institutions foster global partnerships and capacity building. Extension services and sustainable farming initiatives can also benefit from the thematic trends identified, enabling better alignment between research outputs and field-level implementation.

Theoretical Contribution

This study contributes to the theoretical development of sustainable agriculture by framing microbial biotechnology not just as a technical solution, but as an evolving interdisciplinary paradigm. By integrating scientometric analysis into agricultural research discourse, the study illuminates how concepts such as the rhizosphere, microbiome, and metabolites have matured into central theoretical pillars of plant-soil-microbe interaction models. Moreover, the emergence of terms like climate change, microbial diversity, and sustainable development within co-occurrence networks reflects a theoretical shift toward systems thinking and ecological resilience. This work advances the academic understanding of microbial biotechnology by revealing how scientific focus has shifted from isolated microbial studies toward more integrated ecological frameworks—thus encouraging the development of new theoretical models that embrace complexity, adaptability, and environmental stewardship.

Limitation

Despite its valuable insights, this study has several limitations. First, the analysis is confined to data sourced from the Scopus database, which, while comprehensive, may exclude relevant publications indexed elsewhere (e.g., Web of Science, PubMed, or local journals). Second, the bibliometric tools employed—especially keyword co-occurrence and clustering algorithms—rely on author-supplied terms, which may introduce inconsistency or bias due to varying terminologies. Third, while the analysis captures trends from 2014 to 2024, it may overlook emerging themes that have not yet gained citation traction but are gaining momentum. Additionally, the study focuses on quantitative patterns rather than qualitative content, which means it cannot fully capture the depth of conceptual development or real-world application impact of the research. Future studies combining scientometric and content analysis methods could address these gaps.

4. CONCLUSION

This scientometric review provides a comprehensive overview of the evolution, structure, and emerging trends in microbial biotechnology research for sustainable agriculture over the past decade. Through the use of VOSviewer-based analysis, the study reveals a dynamic and interdisciplinary research landscape characterized by growing attention to key themes such as plant-microbe interactions, soil health, biofertilizers, and bioremediation. India, along with several Asian, African, and Western countries, has emerged as a leading contributor, demonstrating strong international collaboration networks. Thematic clusters and keyword density maps highlight a gradual shift from foundational topics toward more integrated approaches that address climate change, ecological sustainability, and systems-based agricultural solutions. Despite limitations related to data scope and keyword variability, the findings offer valuable insights for researchers, policymakers, and practitioners seeking to harness the full potential of microbial biotechnology in transforming agriculture toward a more sustainable and resilient future.

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