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Review

Bibliometric Review on the Role of Microbial Fertilizers in Soil Health Enhancement

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Abstract

Soil degradation caused by intensive land use (e.g., compaction, acidification, salinization, and continuous cropping obstacles) is a major constraint on the biological function and sustainable productivity of terrestrial agroecosystems. Microbial fertilizers (biofertilizers), which deploy beneficial functional microorganisms, are increasingly considered a promising biotic intervention to improve degraded soils by restoring microbial-driven ecosystem services. We quantitatively analyzed the intellectual evolution and spatiotemporal trajectories of 1,937 publications regarding biofertilizer-mediated soil improvement retrieved from the Web of Science Core Collection (2000-2025). The annual number of publications evolved through three phases: exploration period (2000-2006), stable development period (2007-2019), and rapid development period (2020-2025). The research is inherently interdisciplinary, centered on a “microorganism-soil-plant” framework, with India, China, and Pakistan emerging as the most productive countries. Co-citation network analysis reveals an intellectual evolution from classical soil analytics to modern applications in sustainable agronomy. Five interconnected thematic clusters emerged, representing the mechanistic chain from microbial function to ecosystem-level soil health. Research hotspots have shifted from basic methodology and functional mechanisms to sustainable agriculture integration. Future endeavors should integrate multi-omics insights with precision field applications to support the transition from empirical fertilization to microbial-based soil health management.

Keywords: microbial fertilizers, biofertilizer, beneficial microbes, soil degradation, knowledge graph

Introduction

Although the intensification of modern agriculture has increased crop yields, prolonged yield-oriented cropping regimes have induced systemic degradation of soil ecosystem functions [1]. Conventional agricultural practices, characterized by continuous monoculture systems of high-value crops and intensive application of chemical fertilizers and pesticides, have led to the accumulation of acidic anions such as SO_4^{2-} and NO_3^-, leading to soil acidification [2]. These combined stressors have caused persistent soil deterioration, manifested as compaction, acidification, salinization, and continuous cropping obstacles [3]. Soil degradation has emerged as a constraint on sustainable agricultural development [4, 5]. Therefore, developing effective

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soil amendment strategies to mitigate these constraints and achieve sustainable restoration of soil ecological functions constitutes a research priority in agricultural science.

Multiple amelioration approaches have been explored for degraded soils. Physical amendments (e.g., deep tillage, soil replacement) [6, 7] and chemical interventions (e.g., lime application for acid neutralization) [8] can provide short-term relief for specific soil issues. However, these methods are often costly and short-lived in effectiveness, with potential risks of soil structural degradation or secondary salinization. Agricultural management practices, including crop rotation [9], green manure cultivation [10], and organic fertilizer application (e.g., crop residues, livestock manure), have been reported to enhance soil organic matter content and structural properties [11], yet their widespread adoption in modern large-scale agriculture remains constrained by long amendment periods and high labor demands.

Biologically-driven soil health restoration, specifically via microbial fertilizers, has promoted the development of regenerative agriculture [12]. Studies suggest that these bio-inoculants regulate the composition and structure of the soil microbiome, and may lead to a series of changes in physicochemical properties and functional stability [13]. Specifically, plant growth-promoting rhizobacteria (PGPR) and arbuscular mycorrhizal fungi (AMF) have been reported to enhance wheat nutrient use efficiencies by 20-40% through biological nitrogen fixation and mobilization of phosphorus and potassium [14], while antagonistic strains may competitively suppress soil-borne pathogens, reducing disease incidence [15]. Additionally, microbially-secreted exopolysaccharides (EPS) and organic acids are thought to promote soil aggregate formation [16], thereby potentially improving soil porosity and water-holding capacity.

Despite the potential benefits of microbial fertilizers and the growing body of related research, literature shows fragmented research themes, inconsistent terminology, and unclear evolutionary trajectories. Against this backdrop, several scientific questions remain unaddressed: (1) What is the overall publication landscape in terms of volume, journals, authors, and institutions? (2) What are the core research themes and how have they evolved over time? (3) What are the dynamic evolutionary trends of research hotspots? To map the progress in this field, this study employs bibliometric methods to conduct a comprehensive review and visualization analysis of literature on soil amelioration using microbial fertilizers. The aim is to clarify the historical evolution of research development and track the dynamic trends of research hotspots, thereby providing a scientific reference framework for future research.

Materials and Methods

Data Acquiring

The literature data for this bibliometric analysis were retrieved from the Web of Science (WOS) Core Collection, a widely recognized database for scholarly publications. WOS provides comprehensive coverage of high-quality research outputs, along with tools for citation tracking and analysis, making it suitable for bibliometric investigations. Science Citation Index Expanded (SCI-EXPANDED) within WOS was selected as the primary data source to ensure the inclusion of influential and rigorously peer-reviewed journal articles.

Bacterial fertilizers are referred to in the literature under various terms, including “biofertilizer”, “microbial fertilizer”, and “microbial inoculant”. Similarly, concepts related to soil enhancement are expressed through phrases such as “soil improvement”, “soil amendment”, and “soil health”. To cover the combined topics of micro-fertilization and soil health, a refined Boolean query was optimized in the Web of Science (WOS) database. The search was conducted using the topic (TS) field with the following query:

TS = ((biofertiliz* OR “microbial fertilizer*” OR “microbial inoculant*” OR PGPR) AND (“soil improvement” OR “soil amendment” OR “soil remed*” OR “soil health” OR “soil quality” OR “soil fertilit*”))

The timespan was restricted to publications between January 1, 2000, and December 31, 2025. No language restrictions were applied during the retrieval process. The document types included in the retrieval were Article, Review, Book Chapter, Early Access, Proceedings Paper, Editorial Material, as well as compound types combining the above (e.g., Article; Book Chapter, Review; Early Access, etc.). The literature search and raw data export were completed on January 9, 2026. This search yielded a total of 1,937 documents. All retrieved records were exported as plain text files with full records and cited references to support subsequent bibliometric analysis.

Bibliometric Analysis

Bibliometrics enables the structured processing and analysis of extensive literature, thereby revealing research progress in a given field, identifying key authors and representative works, tracing the development of the discipline, and anticipating future research directions [17, 18]. In this study, bibliometric analysis was performed using the *bibliometrix* package in R (version 4.5.2) [17], an open source and script-based tool that supports reproducible, flexible, and efficient data processing and visualization. In the bibliometric analysis, no manual merging or standardization was performed on author keywords or Web of Science subject terms. This approach retained the original diversity of terminological expressions and reflected the actual terminology usage habits in this research field. Based on the literature related to microbial fertilizers and soil improvement, the analysis was structured along three dimensions: the overall research landscape, knowledge foundations, and research themes. The overall analytical framework is presented in Fig. 1.

The general landscape of the research includes annual publication output, disciplinary distribution, source journals, productive authors, and major countries and institutions. Based on the yearly number of publications, the temporal trend from 2000 to 2025 was visualized. By identifying obvious turning points in the trend curve, the study first adopted visual inspection to divide the entire period into three stages (2000-2006, 2007-2019, and 2020-2025). Subsequently, segmented regression was applied to each stage separately, using linear, quadratic polynomial, and exponential models to characterize the evolutionary pattern of each phase.

Disciplinary categories were derived by the Web of Science (WOS) database. The 1,937 publications were classified to identify the main research disciplines involved. The *bibliometrix* package was also used to determine the journals publishing in this field, which may guide future submissions. Furthermore, statistical analysis of authors, countries, and institutions helped identify contributors and research hubs, providing information on the research forces in the domain.

The knowledge foundation mainly involves the analysis of highly cited literature and co-cited literature, which is intended to reveal the achievements and academic nodes in the development process of this field. Co-citation analysis included the top 50 most frequently cited papers as nodes. Isolated nodes were removed, and a minimum of 2 co-citation edges was required for inclusion. Community detection was performed using the Louvain algorithm. An in-depth analysis of the core content and academic contributions of such studies can improve the understanding of the current research status of the field, clarify the inheritance and evolution paths of academic ideas, and thus sort out the overall development context of the field.

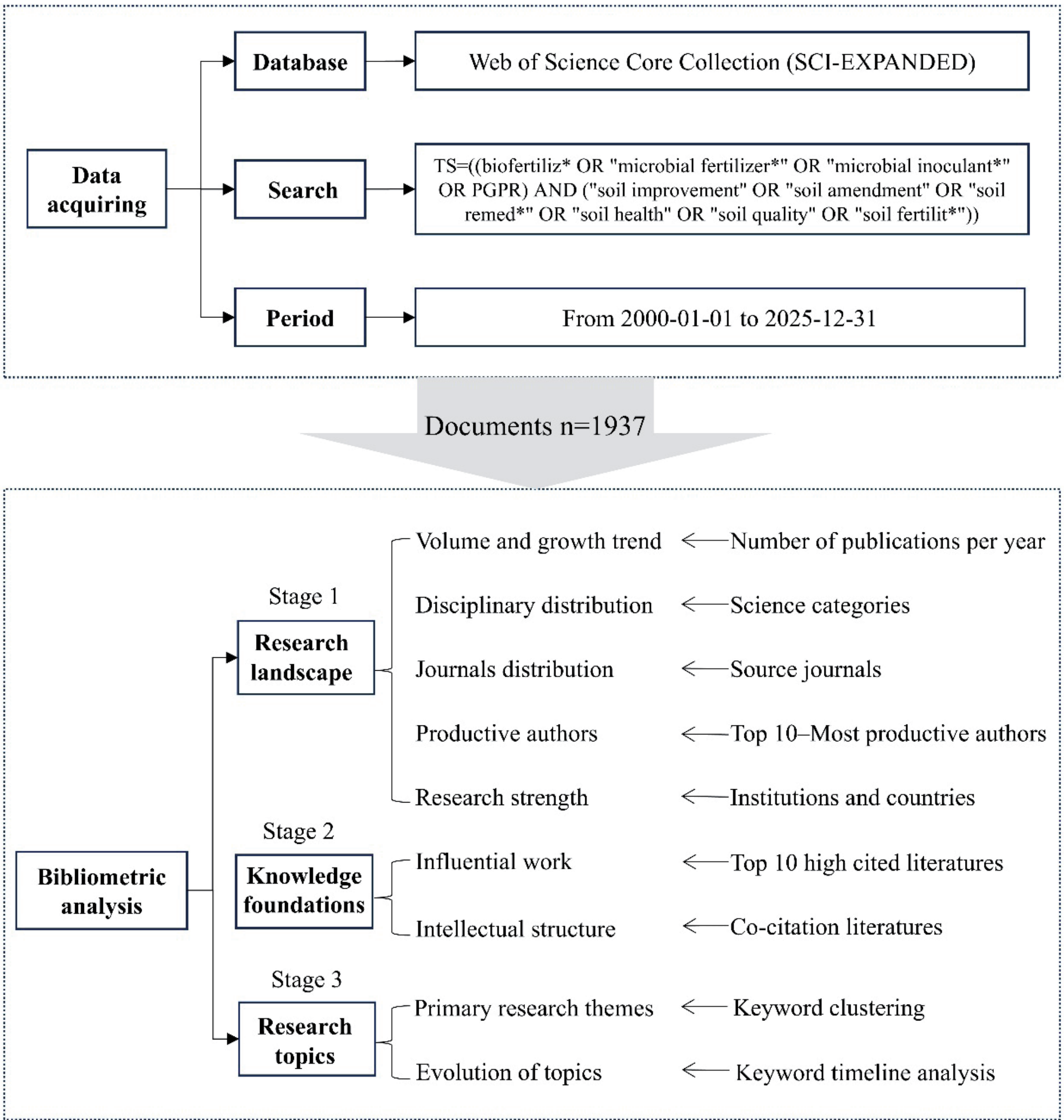

Fig. 1. The framework of data acquisition and bibliometric analysis.

Research topics analysis is centered on keywords, which serve as core indicators reflecting the primary content of publications. Keywords were grouped into distinct thematic clusters based on their co-occurrence relationships. Keyword analysis was performed using Keywords Plus (field = “ID” in *bibliometrix*) from Web of Science. Only keywords with a minimum occurrence of 10 were retained to ensure statistical stability and representativeness. A timeline visualization was further used to dynamically track the evolution of these hotspots, frontiers, and trends over time, providing empirical evidence for anticipating future research directions.

Results and Discussion

Research Landscape

Publication Output and Time Distribution

From 2000 to 2025, a total of 1,937 publications focusing on microbial fertilizer-mediated soil improvement were retrieved. The temporal evolution of this research field can be divided into three distinct phases (Fig. 2). Phase I (2000-2006) corresponds to an exploratory phase, during which the annual number of publications remained below five. Phase II (2007-2019) was a stage of steady development, where the annual publication output exhibited a continuous upward trend, increasing from 10 in 2007 to 77 in 2019. Phase III (2020-2025) showed exponential growth, reaching 473 articles in 2025 and fitting an exponential model ($y = 78.904e^{0.291(x\text{-}2019)}$, $R^2 = 0.9720$). The temporal evolution of publication output in microbial fertilizer-mediated soil improvement (2000-2025) reveals a trajectory from exploratory germination to exponential growth. The polynomial growth in Phase II coincided with advances in microbial isolation and identification technologies [19], while the exponential growth in Phase III is likely attributed to the confluence of climate change-induced soil degradation [20] and policy support for sustainable agriculture [21].

Disciplinary Distribution

Research on microbial fertilizer-mediated soil improvement spans multiple disciplines (Fig. 3). Core fields include plant science, environmental science, agronomy, soil science, and microbiology, each with approximately 250-470 publications. To date, studies in this area show a “microorganism–soil–plant” framework, and branch into environmental, biological, horticultural, and chemical disciplines, reflecting an interdisciplinary character.

Journals Distribution

The top 10 journals in terms of publication output in this field each published more than 30 papers (Table 1), accumulating a total of 417 publications, accounting for approximately 21.47% of the overall literature. Agronomy-Basel ranked first with 61 publications, focusing primarily on agriculture and plant science. Frontiers in Microbiology, the second-ranked journal, exhibited the highest average citation frequency (52.93), reflecting notable academic influence. Although Applied Soil Ecology ranked eighth in terms of

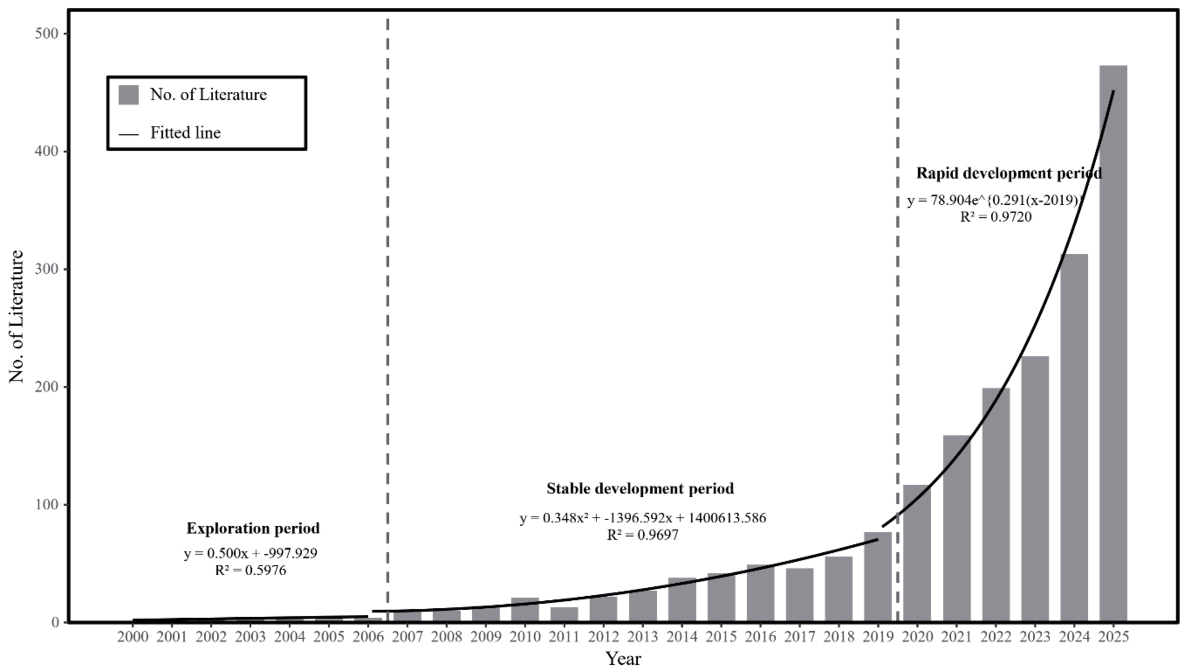

Fig. 2. Number of publications on soil improvement by microbial fertilizer (2000-2025).

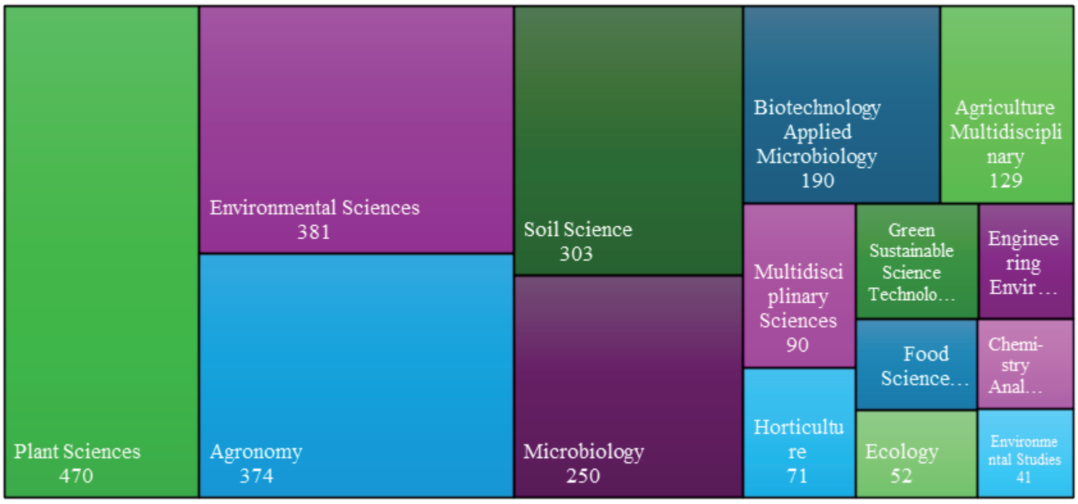

Fig. 3. Treemap of the top 15 Web of Science subject categories based on co-occurrence frequency. The area of each rectangle is proportional to the number of publications in the corresponding category, and the specific publication count is shown below the category name. Different colours are used to distinguish disciplinary groups.

publication volume, it achieved the highest impact factor (IF = 5.0, Q1). Overall, these core journals cover four disciplines – plant science, agronomy, microbiology, and soil science – with most journals ranked in JCR Q1 or Q2, reflecting the interdisciplinary diffusion of research topics and the quality of the published outputs.

Productive Authors

A total of 8,365 authors have contributed to this field. The top 10 most productive authors each have published no fewer than 16 papers (Table 2). Indian scholar Kumar A. ranked first with 47 articles and 1,804 total citations (38 per paper). His research focuses on the synergistic effects of plant-growth-promoting rhizobacteria (PGPR) and nano-fertilizers, with an emphasis on salt stress alleviation and the ecotoxicology of nanomaterials. South African researcher Babalola O.O., a Clarivate Highly Cited Researcher, ranks first in both total citations (2,343) and average citations per paper (146). Her research centers on sustainable agriculture in Africa, particularly rhizosphere microbe diversity and its application in biofertilizers and biocontrol. Indian scholar Prasanna R., the earliest contributor among the top ten authors (with her first publication in 2007), has 18 publications with 1,004 total citations (3^{rd}) and 56 citations per paper (2^{nd}). Her expertise lies in cyanobacterial biofertilizers and metabolomics, suggesting the role of cyanobacteria-microbe interactions in soil health and crop stress resilience.

Table 1. Sources and impact factor (IF) of the top 10 literature journals published.

Journal	Volume	Average Citation	Subject Category	IF	Quartile
Agronomy-Basel	61	18.93	Agronomy; Plant sciences	3.4	Q1
Frontiers in Microbiology	54	52.93	Microbiology	4.5	Q1
Journal of Soil science and Plant Nutrition	45	10.82	Environmental sciences; Plant sciences; Soil science	3.1	Q2
Plants-Basel	42	33.07	Plant sciences	4.1	Q1
Frontiers in Plant Science	40	18.52	Plant sciences	4.8	Q1
Journal of Plant Nutrition	39	11.31	Plant sciences	1.7	Q2
Communications in Soil Science and Plant Analysis	38	10.53	Agronomy; Chemistry; Plant sciences; Soil science	1.4	Q3
Applied Soil Ecology	34	40.03	Soil science	5.0	Q1
Microorganisms	32	27.03	Microbiology	4.2	Q2
Sustainability	32	25.38	Environmental sciences; Environmental studies	3.3	Q2

Table 2. Top 10 most productive authors in microbial fertilizer-mediated soil improvement.

Author	No. of articles	Start year	Total citations	Citations per paper	Research field
Kumar A.	47	2009	1,804	38	PGPR, Nano-fertilizers, Salt stress
Kumar S.	33	2014	687	21	Organic amendments, Biofertilizers, Soil health
Sharma A.	23	2014	670	29	Nano-agriculture, PGPR, Controlled-release nutrient
Kumar R.	23	2013	638	28	Microbial fertilizers, Organic amendments, Sustainable agriculture
Sharma P.	19	2013	318	17	PGPR, Stress physiology, Saline soils
Prasanna R.	18	2007	1,004	56	Cyanobacteria, Bio-fertilizers, Metabolomics
Kumar D.	18	2010	300	17	Resource recycling, Agricultural waste valorization, Soil carbon
Singh A.	17	2016	257	15	Vermicomposting, Waste resource recovery, Microbial inoculants
Babalola O.O.	16	2010	2,343	146	PGPR diversity, Bio-fertilizers, Biocontrol
Meddich A.	16	2019	647	40	AMF, PGPR, Drought & salt stress

Research Strength

Country-level research output ranks India first with 556 publications (Fig. 4), constituting 28.91% of the total. The most productive authors in this field, including Kumar A., Kumar S., Sharma A., and Prasanna R., are affiliated with India, primarily through the Indian Council of Agricultural Research (ICAR). China follows with 382 publications (19.9%), largely contributed by institutions such as the Chinese Academy of Sciences and the Chinese Academy of Agricultural Sciences, with notable authors including Zhang Y. and Li Y. Pakistan accounts for 101 publications (5.3%), while all other countries each contributed fewer than 100

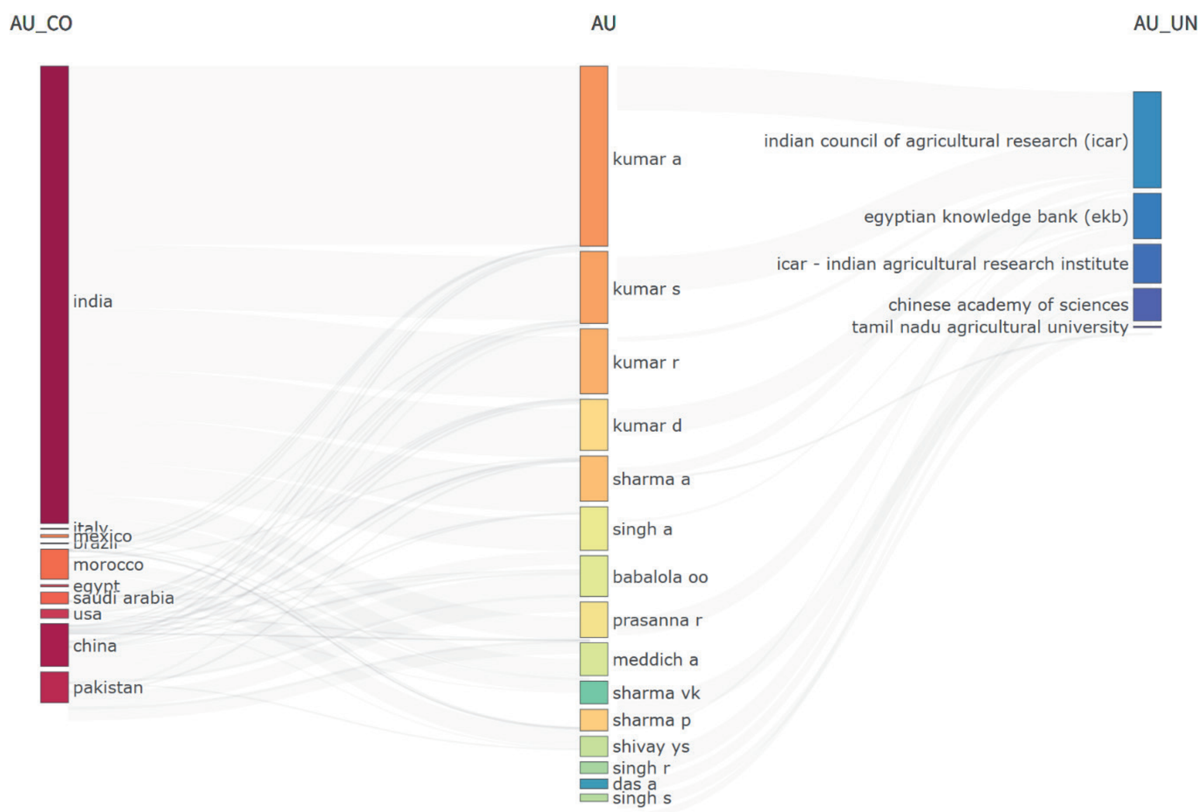

Fig. 4. Research associations and contribution distribution among countries (AU_CO), authors (AU), and institutions (AU_UN) in the field of microbial fertilizer application for soil improvement. Bar height reflects publication count, colours distinguish entities, and line thickness indicates collaborative frequency. Only major contributors are shown based on publication thresholds.

Table 3. Details of the top 10 most-cited literature.

Rank	Title	Year	Journal	Total Cited	Type	First author
1	Soil beneficial bacteria and their role in plant growth promotion: A review. (DOI: 10.1007/s13213-010-0117-1)	2010	Annals of Microbiology	1,298	Review	Hayat R
2	Microbial phosphorus solubilization and its potential for use in sustainable agriculture. (DOI: 10.3389/fmicb.2017.00971)	2017	Frontiers in Microbiology	1,048	Review	Alori ET
3	Revitalization of plant growth-promoting rhizobacteria for sustainable development in agriculture. (DOI: 10.1016/j.micres.2017.08.016)	2018	Microbiological Research	658	Review	Gouda S
4	The role of mycorrhizae and plant growth-promoting rhizobacteria (PGPR) in improving crop productivity under stressful environments. (DOI: 10.1016/j.biotechadv.2013.12.005)	2014	Biotechnology Advances	643	Review	Nadeem SM
5	Biofertilizers function as a key player in sustainable agriculture by improving soil fertility, plant tolerance, and crop productivity. (DOI: 10.1186/1475-2859-13-66)	2014	Microbial Cell Factories	621	Review	Bhardwaj D
6	Plant-microbe interactions in enhanced fertilizer-use efficiency. (DOI: 10.1007/s00253-009-2196-0)	2009	Applied Microbiology and Biotechnology	538	Review	Adesemoye AO
7	Plant growth-promoting rhizobacteria allow reduced application rates of chemical fertilizers. (DOI: 10.1007/s00248-009-9531-y)	2009	Microbial Ecology	525	Article	Adesemoye AO
8	Soil protists: A fertile frontier in soil biology research. (DOI: 10.1093/femsre/fuy006)	2018	FEMS Microbiology Reviews	480	Review	Geisen S
9	Effects of biofertilizer containing N-fixer, P and K solubilizers and AM fungi on maize growth: A greenhouse trial. (DOI: 10.1016/j.geoderma.2004.07.003)	2005	Geoderma	478	Article	Wu SC
10	Beneficial bacteria of agricultural importance. (DOI: 10.1007/s10529-010-0347-0)	2010	Biotechnology Letters	451	Review	Babalola OO

papers, representing less than 4% individually. These findings indicate that Asia, particularly India, China, and Pakistan, produces the highest volume of research in microbial fertilizer-mediated soil improvement. India's top position in publication count reflects its research activity in this field. The productivity of Asian countries may be associated with specific agronomic pressures (e.g., intensive cropping, soil salinity) and national investments in agricultural biotechnology [22, 23]. To enhance the global relevance and transferability of findings, future research should encourage greater geographic diversity and cross-continental collaboration.

Knowledge Foundation

Influential Work

Of the ten most cited papers in this field, eight are review articles and two are research articles (Table 3). Together, these works systematically outline the core advances and key issues from complementary perspectives. The most cited paper is a review by Hayat R. et al. (1,298 citations) focusing on plant growth-promoting rhizobacteria (PGPR) [24], which elaborates the concept and relevant mechanisms. Another review by Alori E.T. with over 1000 citations addresses phosphate solubilizing microorganisms and their presumed relevance to soil fertility and sustainable agricultural development [25]. Gouda S. (658 citations) proposes strategies for enhancing microbial fertilizer efficacy through modern technologies [26]. Nadeem S.M. reviews synergistic mechanisms between PGPR and mycorrhizal fungi under stress conditions [27]. Bhardwaj D. describes gene activation pathways through which biofertilizers regulate crop traits at the molecular level [28]. Babalola O.O. provides a systematic overview of agriculturally beneficial bacterial resources and major PGPR genera [29]. Adesemoye A.O. reported findings from tomato trials suggesting that PGPR inoculation may reduce chemical fertilizer input by approximately 25% while sustaining crop performance [30], suggesting the potential of microbial agents in nutrient management [31]. Likewise, trials reported by Wu S.C. in maize indicated that compound microbial fertilizers could promote plant growth, improve nutrient utilization efficiency, and optimize soil properties [32].

The knowledge foundation of microbial fertilizer-mediated soil improvement is built upon a core set of highly cited works that collectively define the theoretical and methodological underpinnings of the field. The dominance of review articles among the top-cited literature indicates that the discipline has developed through systematic synthesis, reflecting efforts to synthesize mechanisms, such as phosphorus solubilization [25], PGPR-plant interactions [33], and stress resilience [34].

Intellectual Structure

Co-citation analysis reveals three distinct yet thematically continuous clusters that map the intellectual evolution of the field (Fig. 5). The red cluster (1954-1984) centers on the early works of Walkley and Black and Olsen. The analytical frameworks they established – the Walkley-Black method for soil organic carbon [35] and the Olsen method for available phosphorus [36] – represent classical methods of soil science, providing a methodological and theoretical basis for subsequent research. The green cluster (1948-2008) comprises methodological advances in PGPR functional analysis. Pikovskaya introduced an early quantitative screen for phosphate-solubilizing microorganisms [37]. Schwyn and Neilands developed the universal Chrome Azurol S. (CAS) assay for siderophores [38], resolving a technical gap in quantifying microbial iron chelation. Though less densely cited, this cluster provided a key technical foundation that enabled the field's transition from methodological development to applied research. The blue cluster (2003-2022) contains influential contemporary literature representing a highly active research front. Vessey systematically summarized the agronomic implications and plant-growth-promoting mechanisms of PGPR as biofertilizers [33]. Bhattacharyya et al. comprehensively reviewed the multifunctional mechanisms and prospective agricultural applications of PGPR [39]. Glick further described PGPR modes of action and outlined their applications in agriculture, horticulture, and environmental remediation [40]. In summary, the co-citation network visually traces the intellectual lineage of the discipline – from classical soil analytics, through functional methodology development for PGPR, to modern application and expansion. These clusters suggest an integration of classical soil science with modern translational agronomy, indicating the field's shift toward sustainable agricultural practices.

Research Topics

Primary Research Themes

Keyword co-occurrence clustering delineates five thematically distinct research topics in microbial fertilizer–mediated soil improvement (Fig. 6, main keywords of each color cluster are listed in Supplementary Table S1). The purple cluster centers on the carbon cycle in agroecosystems, emphasizing how cropping systems, fertilization regimes (especially combined organic–mineral fertilization), and conservation practices influence soil organic carbon retention and physicochemical properties. This cluster focuses on the role of organic matter return

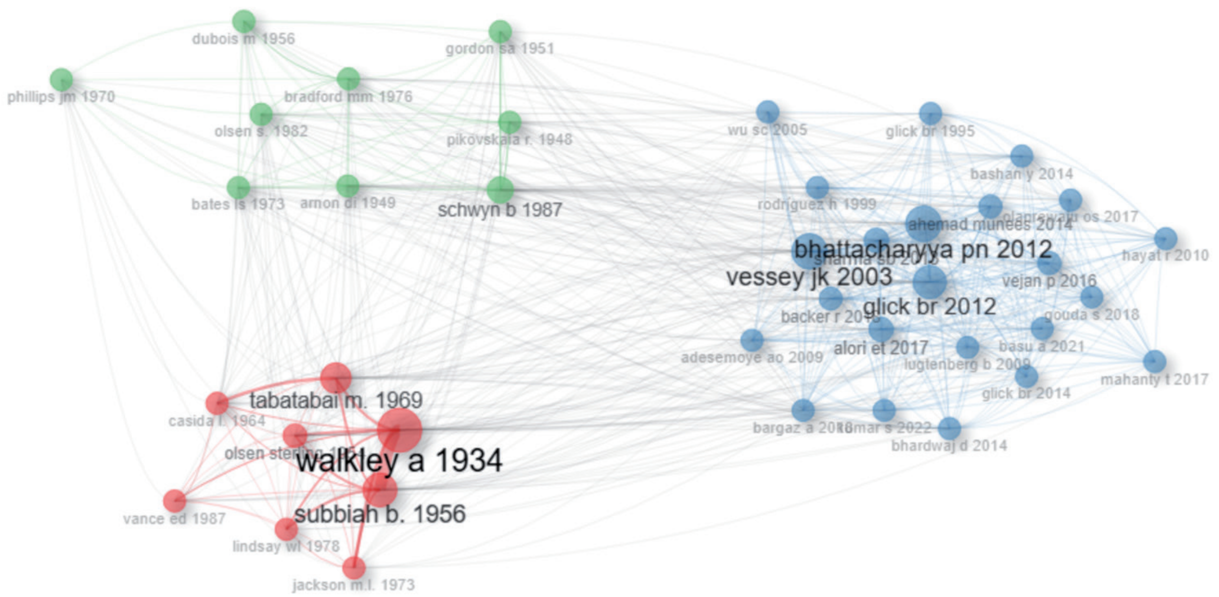

Fig. 5. Co-citation network of publications on microbial fertilizer-mediated soil improvement. Each node represents an individual publication, labeled with the author and year (e.g., Walkley A 1934). The size and darkness of the text label beside each node reflect the publication's impact: larger and darker text indicates higher citation influence. Node color denotes cluster affiliation; node size is proportional to the total citation count of the publication; line thickness represents co-citation strength between publications.

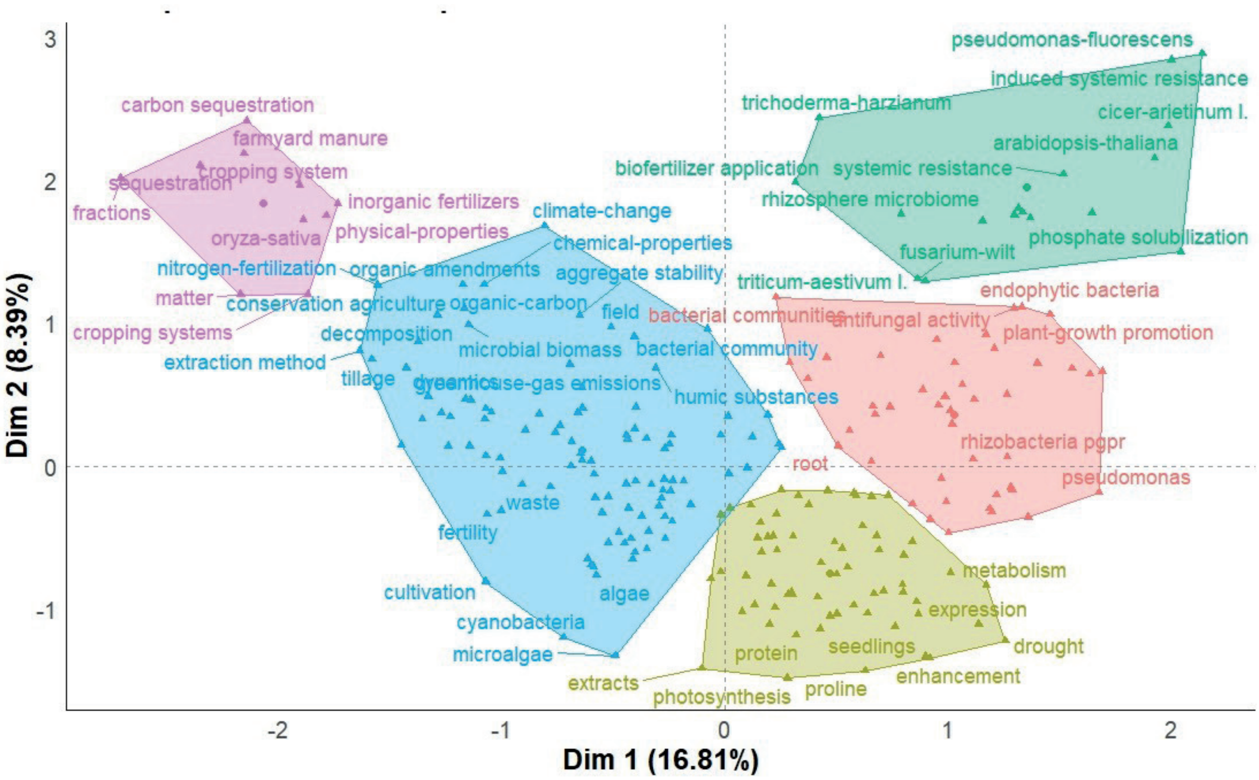

Fig. 6. Conceptual diagram of keyword clustering analysis. Each triangle represents a keyword, with the keyword text labeled beside each point; the distance between keywords reflects their co-occurrence similarity in the literature. Keywords are grouped into five distinct thematic clusters, which are visually distinguished by different colors.

in improving soil fertility and carbon sequestration. The blue cluster involves a systematic assessment spanning soil physicochemical and biological indicators. It focuses on the effects of various organic amendments (e.g., algal biomass, organic wastes) on soil health, structural stability, and greenhouse gas emissions under global change, reflecting interdisciplinary integration of environmental science and agricultural management. The green cluster is oriented toward the biocontrol functions of beneficial microorganisms and rhizosphere microecological regulation. It examines mechanisms by which *Pseudomonas fluorescens*, *Trichoderma harzianum*, and similar agents suppress soil-borne diseases (e.g., wilt) and maintain rhizosphere health through induced systemic resistance, phosphorus solubilization, and microbial community modulation. The red cluster concentrates on plant growth-promoting rhizobacteria (PGPR), particularly their colonization and functional expression in plants. Research in this cluster discusses potential growth-promoting effects and plant health regulation, often mediated through antifungal activity and other adaptive traits. The yellow cluster focuses on the physiological regulation of plants by microbial fertilizers. It reveals how microbial amendments could modulate photosynthesis, osmolyte accumulation (e.g., proline), and protein expression to enhance crop drought tolerance, with possible benefits for seedling growth and metabolic performance.

Evolution of Topics

Time-evolution analysis based on keywords delineates the dynamic shifts in research hotspots in this field, showing a phased progression from basic exploration to systematic integration (Fig. 7). (i) Methodology and Foundational Microbial Research (2007-2014). Early research primarily centered on basic technologies and the exploration of specific microbial species [41, 42]. High-frequency keywords during this phase included “gradient gel electrophoresis”, “EM”, “*Vigna unguiculata*”, “tomato plants”, etc., indicating that research focused on the interactions between specific crops and microorganisms, as well as the application of molecular biology detection techniques. (ii) Functional Mechanism and Ecological Impact (2015-2018). This stage represented a shift toward mechanistic and ecological studies [43]. Core keywords included “P-solubilization”, “suppression”, “*Rhizobium leguminosarum*”, “effective microorganisms”, “soil microbial biomass”, etc., reflecting investigations into functional mechanisms such as phosphorus solubilization, disease suppression, and microbial biomass dynamics. (iii) Sustainable Agricultural Integration and Meta-Analysis (2019-2024). Since 2019, research topics have shifted toward more systematic and holistic directions. Keywords such as “yield”, “growth”, “soil”, and “biofertilizer” indicate the focus on the agronomic performance of biofertilizers.

Concurrently, emerging terms like "sustainable agriculture", "soil health", "circular economy", and "meta-analysis" signal a broader transition from single-function studies to assessments of agricultural ecosystem sustainability. This evolution suggests that future research may advance in areas such as sustainable agriculture, circular technology industrialization, and soil health maintenance, characterized by growing interdisciplinary integration and methodological development.

Future Research Prospects

Based on our findings, several directions for future research can be identified:

1. Mechanistic depth through omics integration. Leveraging metagenomics, transcriptomics, and metabolomics to explore the complex interactions between microbial communities, soil metabolites, and plant signaling pathways, particularly under abiotic (drought, salinity) and biotic (pathogen) stress conditions.

2. Field-scale validation and long-term monitoring. Conducting multi-year, multi-location field trials to assess the field performance of microbial fertilizers, considering factors such as soil type, climate variability, and cropping system interactions. Long-term studies are also needed to evaluate potential ecological risks associated with microbial fertilizer application.

3. Interdisciplinary innovation. Integrating microbial fertilizer research with precision agriculture technologies (e.g., AI-aided microbial consortia design, sensor-based nutrient management) and circular economy practices (e.g., agricultural waste valorization for microbial inoculant production) to enhance its practical applicability.

4. Policy and industry support. Translating experimental findings into policy recommendations and industrial applications to bridge the gap between research and practice.

Limitations

Despite offering a systematic overview of the intellectual landscape and research trends in the field, this study has several limitations that should be acknowledged. First, the literature retrieval was based solely on the Web of Science Core Collection, and publications from other databases (e.g., Scopus, PubMed) were not included, which may restrict the coverage of relevant studies. Second, the findings depend on the selected search terms and inclusion criteria. Different keyword combinations or search strategies might have yielded a different set of publications, potentially affecting the observed trends and intellectual structure. Third, the bibliometric analysis is susceptible to citation-time bias, as newly published papers lack sufficient citation accumulation while early classic works possess longer citation accumulation periods. Additionally, we did not perform manual normalization or merging of synonymous keywords in the bibliometric analysis, which may lead to scattered distribution of some semantically similar term nodes and limit the fine division of local clustering results.

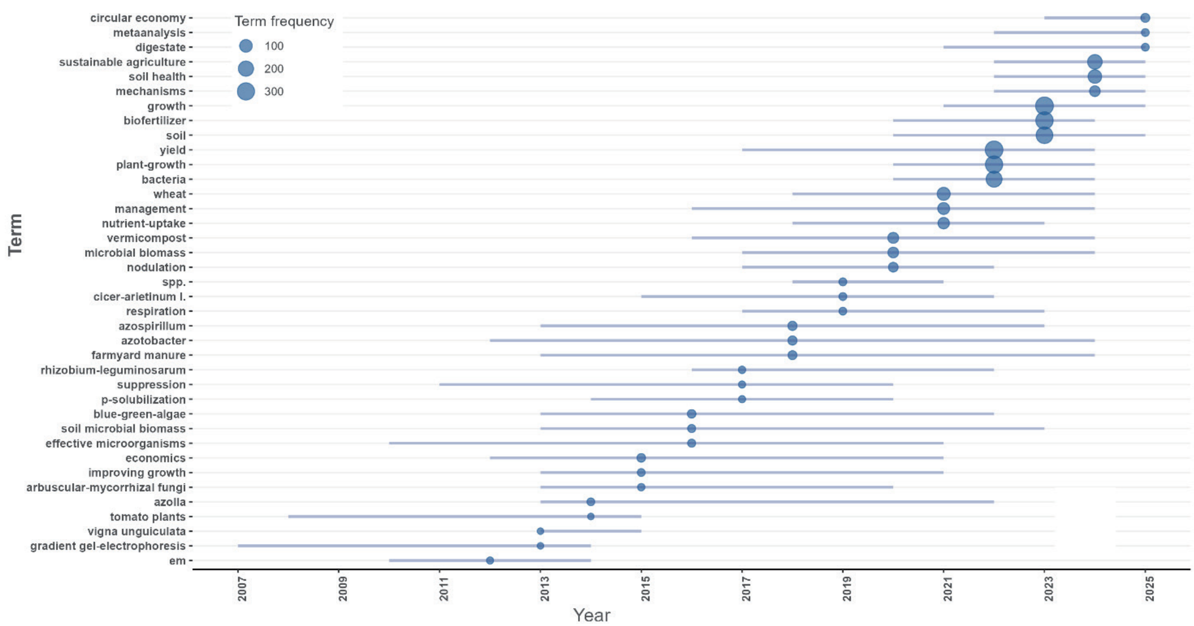

Fig. 7. Time evolution and frequency analysis of keywords in the field of microbial fertilizer-mediated soil improvement. The horizontal axis represents the publication year, and the vertical axis lists the keywords. Each circle represents the term frequency of a keyword, with circle size proportional to its frequency. The horizontal line extending from each keyword shows the time span from the first to the last occurrence of the keyword in the dataset.

Conclusions

This bibliometric analysis of 1,937 publications on microbial fertilizer-mediated soil improvement (200-0–2025) reveals three developmental stages, a core research hub in Asia dominated by India and China, and an interdisciplinary framework of microorganism-soil-plant. Five key research themes are identified, and the research hotspots have evolved from basic methodology and microbial functional exploration to sustainable agricultural integration, reflecting the field's shift from single-point to systematic research. As a potential approach to mitigating soil degradation, microbial fertilizers in their future development could prioritize decoding the "black box" of microbe-soil interactions by coupling spatially explicit microbial micro-niche dynamics with macroscale soil health trajectories. Furthermore, integrating these technologies into soil health management would benefit from technological innovation and targeted policy support, with the aim of providing scalable, sustainable biological solutions to advance global sustainable agriculture and support food security.

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Conflict of Interest

The authors declare no conflict of interest.

AI Usage Disclosure Statement

During the preparation of this work, the authors used Deepseek-V3 solely for language polishing, including grammar checking, error correction, and sentence fluency improvement. After using this tool, the authors reviewed and edited every sentence carefully and take full responsibility for the final content of the published article. The AI tool was not used for data analysis, figure generation, or the production of scientific conclusions.

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Supplementary Materials

Table S1. Main keywords within each of the five thematic clusters identified from keyword clustering analysis.

Cluster ID	Cluster color in Fig. 6	Representative keywords
1	purple	Carbon sequestration, farmyard manure, cropping system, Oryza-sativa, inorganic fertilizers, physical properties
2	blue	Climate change, nitrogen fertilization, organic amendments, chemical properties, aggregate stability, greenhouse gas emissions, bacterial community, conservation agriculture, organic carbon, decomposition, microbial biomass, extraction method, tillage, humic substances, waste, algae, cyanobacteria, microalgae
3	green	*Pseudomonas fluorescens*, *Trichoderma harzianum*, induced systemic resistance, phosphate solubilization, *Fusarium wilt*, *Cicer arietihum*, *Arabidopsis thallana*, biofertilizer application, systemic resistance, rhizosphere microbiome
4	red	Plant-growth promotion, endophytic bacteria, rhizobacteria PGPR, antifungal activity, *Pseudomonas*
5	yellow	Protein, photosynthesis, proline, drought, metabolism, seedlings, expression, enhancement, extracts