A BIBLIOMETRIC ANALYSIS OF MICROBIAL INOCULANT RESEARCH IN ORGANIC AGRICULTURE

Naveen Kumar Krishnan[1], Kavitha Chinnasamy [2*], Balachandar Dananjeyan[3], Sivakumar Venkatachalam[4], Boominathan Parasuraman[5] and Manoranjitham S. Karuppannan[6]

[1]Department of Fruit Science, Horticultural College and Research Institute, Tamil Nadu Agricultural University, Coimbatore-641003., Tamil Nadu, India.
[2]Turmeric Research Centre, Tamil Nadu Agricultural University, Bhavanisagar-638451, Tamil Nadu, India.
[3] Department of Agricultural Microbiology, Tamil Nadu Agricultural University, Coimbatore-641003., Tamil Nadu, India.
[4] Controllerate of Examinations, Tamil Nadu Agricultural University, Coimbatore-641003., Tamil Nadu, India.
[5] Department of Crop Physiology, Tamil Nadu Agricultural University, Coimbatore-641003., Tamil Nadu, India.
[6] Centre for Plant Protection Studies, Tamil Nadu Agricultural University, Coimbatore-641003., Tamil Nadu, India.
* Corresponding Author: ck77@tnau.ac.in

ABSTRACT
Organic agriculture, arbuscular mycorrhizal fungi and plant growth-promoting rhizobacteria constitute three interconnected pillars of sustainable soil management and ecologically sound crop production. Despite the increasing volume of scientific publications at this nexus, no comprehensive bibliometric synthesis exists to map the global research landscape, identify intellectual hubs, or trace thematic evolution over time. This study presents a systematic bibliometric analysis of 1,533 Scopus-indexed documents published between January 2010 and May 2026 to address this gap. Literature was retrieved from the Scopus database and bibliometric analyses were performed using the bibliometrix R package, and VOSviewer. Key analyses included annual production trends, source analysis, keyword co-occurrence networks and open-access distribution. Annual output grew nine-fold from 27 documents (2010) to 243 (2025), with a sharp post-2019 acceleration coinciding with expanded global sustainability policy mandates. A total of 551 unique journals published the corpus, led by Science of the Total Environment, followed by Agronomy and Scientia Horticulturae. Keyword analysis identified dominant clusters; Arbuscular mycorrhizal fungi and sustainable agriculture were the highest-frequency keywords, with PGPR, soil health, rhizosphere, and fruit quality forming a strongly interconnected conceptual core. The keyword co-occurrence network revealed emerging themes including climate change resilience, bio stimulants and life cycle assessment as post-2020 frontiers. This bibliometric analysis provides a data-driven portrait of a rapidly expanding field and identifies critical knowledge gaps, particularly in integrated AMF-PGPR consortia studies for tropical fruit crops that represent priority directions for future research.

KEYWORDS: Bibliometrics; organic agriculture; arbuscular mycorrhizal fungi; plant growth-promoting rhizobacteria; sustainable agriculture.

1. INTRODUCTION

The global food system faces a profound and interconnected set of crises: a growing human population projected to exceed 9.7 billion by 2050, escalating climate volatility that threatens crop yields across all continents, accelerating soil degradation from decades of chemical-intensive agriculture, and increasing consumer demand for food produced through environmentally responsible methods [1,2]. These converging pressures have elevated organic agriculture, soil biological health, and microbially mediated nutrient cycling to the forefront of both scientific inquiry and agricultural policy [3,4].

Arbuscular mycorrhizal fungi (AMF), obligate biotrophs that form mutualistic symbioses with approximately 80% of terrestrial plant species and plant growth-promoting rhizobacteria (PGPR) are both central to the biological intensification paradigm [5,6]. AMF enhance nutrient uptake (particularly phosphorus), improve soil structure, confer drought and salinity tolerance, and bolster plant immunity [7,8]. PGPR, including genera such as Azospirillum, Bacillus, Pseudomonas, Rhizobium, and Gluconacetobacter, promote plant growth through multiple mechanisms including nitrogen fixation, phosphate solubilisation, production of phytohormones, and induction of systemic resistance [9,10]. When deployed as components of organic farming systems in conjunction with amendments such as vermicompost, biochar, and green manures, these microorganisms offer a scientifically validated pathway to simultaneously maintain productivity, restore soil fertility, and reduce environmental externalities [11,12].

The scientific literature addressing this nexus has expanded enormously over the past two decades, yet the field remains characterised by disciplinary fragmentation: mechanistic AMF biology, field-level agronomy, rhizosphere microbiology, horticultural science, and environmental sustainability science have each developed distinct publication traditions, methodological vocabularies, and citation communities. This fragmentation makes it difficult for researchers, policymakers, and practitioners to obtain a panoramic, evidence-based view of where knowledge is concentrated, which topics remain under-studied, and which collaborative networks are most productive.

Bibliometric analysis is the application of statistical and mathematical methods to bodies of published literature that provides precisely such a panoramic view [13,14]. Drawing on foundational laws of information science (Bradford's Law of journal scattering and Zipf's Law of word frequency), and extended by modern network science through keyword co-occurrence and co-citation mapping, bibliometrics has become an indispensable tool for mapping intellectual landscapes in medicine, engineering, economics, and increasingly in agricultural and environmental sciences [15,16]. Recent bibliometric analyses have mapped research trends in mycorrhizal biology [17], PGPR [18], agroecology [19] and soil organic carbon [20], but no study has synthesised the intersection of organic agriculture, AMF, and PGPR within a single bibliometric framework covering the period 2010-2026.

The present study addresses this gap by conducting a comprehensive bibliometric analysis of 1,533 Scopus-indexed documents published between January 2010 and May 2026, with the following objectives: (i) to characterise annual trends in scientific production and identify growth phases; (ii) to identify the productive journals (iii) to map the conceptual structure of the field through author keyword frequency and co-occurrence network analysis; (iv) to identify emerging and declining research themes via temporal overlay analysis; and (v) to delineate knowledge gaps and propose priority directions for future research.

2. MATERIALS AND METHODS

2.1 Data Source and Search Strategy

All bibliometric data were retrieved from the Scopus database (Elsevier B.V., Amsterdam, the Netherlands) in May 2026. Scopus was selected as the data source because it is the largest abstract and citation database of peer-reviewed literature, indexing more than 27,000 active journals across all disciplines and providing structured, machine-readable metadata compatible with bibliometric software [21].

The search strategy employed a combination of title-abstract-keyword (TIAB) search strings including terms such as; 1. (Microbial inoculants OR PGPR OR Plant Growth Promoting Rhizobacteria OR Arbuscular Mycorrhizal Fungi OR AMF) 2. (Organic Farming OR Organic Agriculture AND Fruit crops OR Horticulture) 3. (Soil health OR Sustainable). The search was restricted to documents indexed between January 2010 and May 2026. English-language restrictions were applied during retrieval; subsequent filtering retained only original research articles and review articles, excluding conference papers, book chapters, editorials, and errata. The final cleaned dataset comprised 1,533 documents.

2.2 Data Processing and Cleaning

Raw data were exported from Scopus in CSV format, retaining fields for authors, author full names, title, year, source title, volume, issue, page numbers, DOI, abstract, author keywords, index keywords, document type, open access status, and EID. Data cleaning and processing were performed in Python (v3.11) using the pandas library [22]. Duplicate records were identified and removed based on EID. Author keywords were standardised using a custom thesaurus that merged terminological variants (e.g., "AMF" → "arbuscular mycorrhizal fungi"; "PGPR" → "plant growth-promoting rhizobacteria"; British and American spelling variants harmonised). Missing keyword entries (n = 75, 4.9%) were excluded from keyword-specific analyses but retained in all other analyses.

2.3 Bibliometric Analyses

Analyses were conducted using three complementary platforms. (1) Python (v3.11) with the matplotlib (v3.8), seaborn (v0.13), pandas (v2.1), and networkx (v3.2) libraries was used for all descriptive statistics, graphical outputs (Figs. 1-8), and keyword co-occurrence network construction [22,23]. (2) The bibliometrix R package (v4.3) was used for Bradford's Law zone classification, keyword growth mapping, thematic mapping using the strategic diagram approach, and conceptual structure mapping via correspondence analysis [24]. (3) VOSviewer (v1.6.20) was used for interactive visualisation of keyword co-occurrence and co-authorship networks, with a minimum keyword occurrence threshold of five and a minimum co-occurrence count of three [25].

The keyword co-occurrence network was constructed from the most frequent author keywords. Node size reflects keyword frequency; edge weight reflects co-occurrence count. Community detection was performed using the modularity-based Louvain algorithm as implemented in VOSviewer. Temporal overlay analysis was conducted by colouring nodes according to mean publication year to identify keyword emergence trajectories.

2.4 Analytical Frameworks Applied

Three classical bibliometric laws were applied to characterise the corpus. Bradford's Law [26] was used to identify the core, scatter, and periphery journal zones contributing to the field. Zipf's Law [27] underpinned the keyword frequency analysis, predicting that keyword occurrence frequency is inversely proportional to its rank. In addition, Price's Square Root Law [28] was used to contextualise elite authorship concentration within the corpus.

3. RESULTS AND DISCUSSION

3.1 Annual Scientific Production

The annual distribution of publications reveals an unmistakably robust and accelerating growth trajectory across the 2010-2026 study period (Fig. 1). Output rose from 27 documents in 2010 to 243 in 2025, representing a nine-fold increase and a compound annual growth rate (CAGR) of approximately 16.8%. The cumulative corpus reached 1,416 documents by end-2025, with an additional 117 documents indexed in the first four months of 2026 (excluded from trend fitting as a partial year).

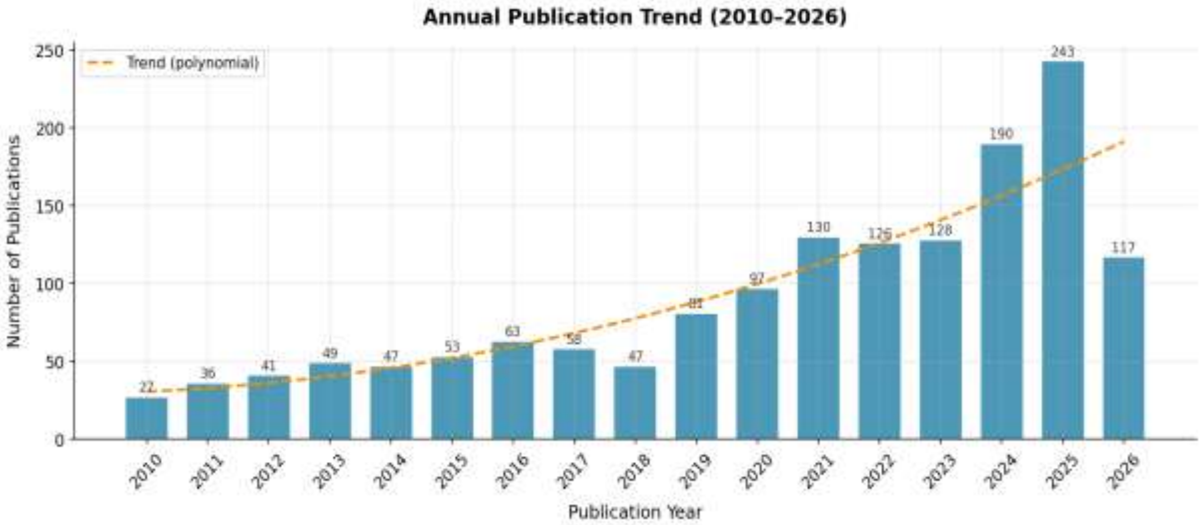

Fig. 1. Annual scientific production of Scopus indexed publications on organic agriculture, AMF, PGPR, and sustainable soil management (2010-2026). Bars denote annual publication counts; the dashed curve represents a second order polynomial trend line fitted to 2010-2025 data.

Three distinct growth phases are identifiable from Fig. 1. Phase I (Gradual Expansion, 2010-2018) saw output grow incrementally from 27 to 63 publications, with moderate year-on-year variability and a transient dip in 2017-2018. This phase corresponds to a period when organic farming research was primarily niche, concentrated in European and North American academic groups, and predominantly focused on mechanistic studies of AMF phosphorus uptake and PGPR nitrogen fixation [29,30]. Phase II (Rapid Acceleration, 2019-2021) is characterised by a dramatic 72.3% single year surge in 2019 (from 47 to 81 publications), likely reflecting the catalytic influence of the United Nations Sustainable Development Goals (SDGs), particularly SDG 2, SDG 12, and SDG 15 on research funding allocation globally, as well as the European Union's Farm-to-Fork Strategy launched in 2020 [31,32]. Phase III (Consolidation and Surge, 2022-2025) saw publication rates stabilise at 126-130 in 2022-2023, followed by a sharp 48.4% jump to 190 in 2024 and a further 27.9% rise to 243 in 2025, driven by expanded publication in open-access journals and increasing research output from China, India, and Morocco [33].

This exponential growth is consistent with Price's Law [28], which describes the doubling time of scientific literature in emerging fields, and mirrors bibliometric analyses of related domains including soil carbon sequestration [20], biofertilizer commercialisation [34], and climate smart agriculture [35]. The growth trajectory signals that the field is transitioning from an early growth to a mature growth phase, a stage at which systematic reviews and meta-analyses become increasingly essential for synthesising the rapidly accumulating evidence base [36].

3.2 Document Type Distribution and the Rise of Review Synthesis

Of the 1,533 retrieved documents, 1,298 (84.7%) are original research articles and 235 (15.3%) are review articles (Fig. 2). The 15.3% review proportion is characteristic of a field that has achieved critical publication mass sufficient to support meta-analytical synthesis [37].

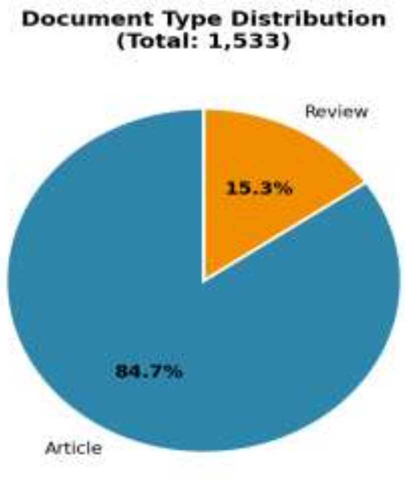

Fig. 2. Proportional distribution of document types within the bibliometric corpus (n = 1,533). Research articles constitute 84.7% and review articles 15.3% of total output.

The temporal distribution of document types (Fig. 3) reveals that review publication began accelerating markedly from 2019 onward, with the review article count approximately tripling between 2019 and 2024.

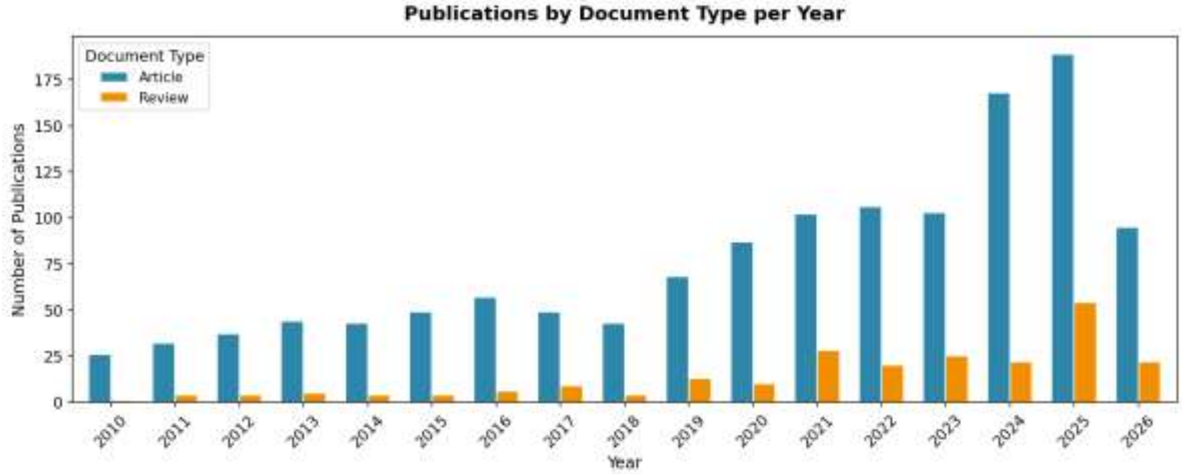

Fig. 3. Annual publication output disaggregated by document type (Articles vs. Reviews), 2010-2026. The accelerating review proportion from 2019 onward signals maturation of the field and growing demand for evidence synthesis.

The proliferation of reviews post-2019 is noteworthy because it coincides with the period of greatest primary research output, suggesting not a slowdown in empirical work but rather the emergence of a parallel synthesis enterprise. This pattern is consistent with observations in environmental science bibliometrics and reflects increased demand from policymakers and agricultural extension systems for evidence-based guidance on the deployment of AMF and PGPR inoculants in commercial organic production [38]. The dominance of research articles (84.7%) nevertheless confirms that the empirical frontier remains highly active, with substantial primary research still needed, particularly on tropical fruit crops, where the literature base is comparatively thin relative to temperate cereals and vegetables [39].

3.3 Most Productive Journals: Bradford's Core and Disciplinary Breadth

The 1,533 publications were distributed across 551 unique source titles, with an average of 2.8 documents per journal, reflecting broad disciplinary dissemination (Fig. 4). Bradford's Law analysis partitioned the corpus into three zones: Zone 1 (core), comprising 11 journals accounting for approximately 33% of total publications; Zone 2 (scatter), comprising approximately 65 journals accounting for a further 33%; and Zone 3 (periphery), comprising the remaining 475 journals contributing the final third. This zone structure confirms that the field is epistemically dispersed across multiple disciplines, consistent with the inherently cross-cutting nature of sustainable soil biology research.

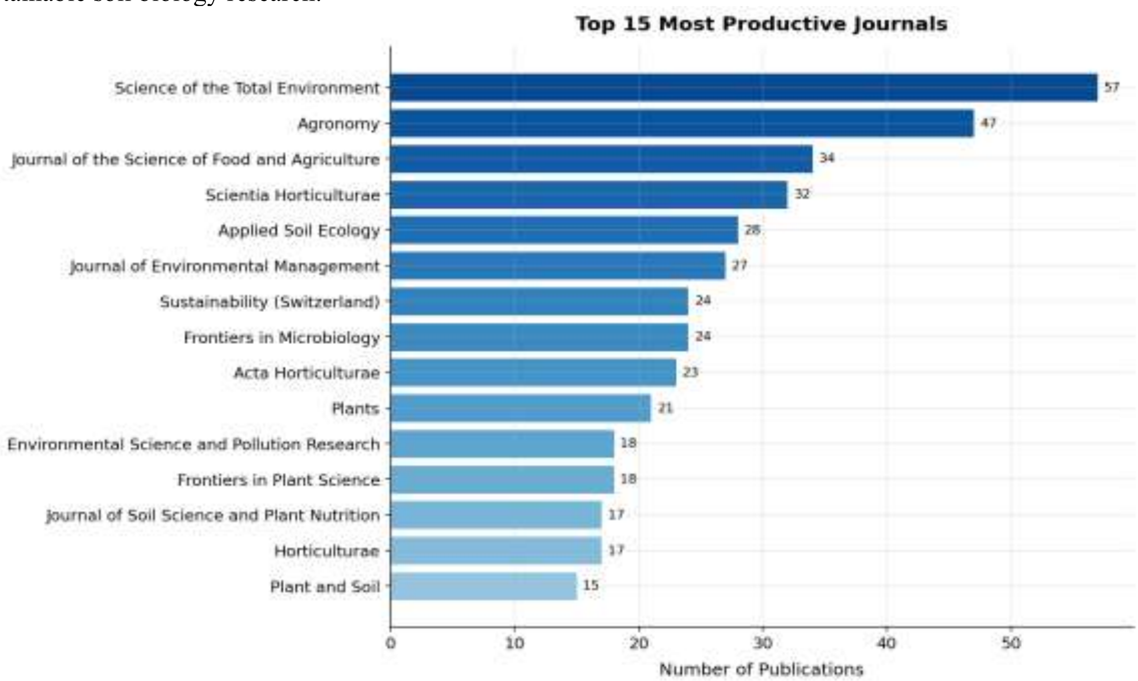

Fig. 4. Top 15 most productive journals for publications on organic agriculture, AMF, PGPR, and sustainable soil management in Scopus (2010-2026). Horizontal bar shows publication counts.

Science of the Total Environment ranked first with 57 publications (3.72%), affirming its position as the leading interdisciplinary venue for research at the environment-agriculture interface. Agronomy (MDPI; n = 47, 3.07%) ranked second, reflecting the rapid growth of open-access publishing in agricultural sciences. The Journal of the Science of Food and Agriculture (n = 34), Scientia Horticulturae (n = 32), Applied Soil Ecology (n = 28), and Journal of Environmental Management (n = 27) together constitute a recognisable disciplinary core spanning horticultural science, soil ecology, and environmental management.

The dual presence of Frontiers in Microbiology (n = 24) and Frontiers in Plant Science (n = 18) in the top 15 underscores the mechanistic microbiological and plant biology dimensions of AMF and PGPR research, while the inclusion of Sustainability (n = 24) and Horticulturae (n = 17) reflects the growing applied and policy-relevant publication streams. Notably, Plants (n = 21), Horticulturae (n = 17), and Agronomy are all MDPI open-access titles, collectively contributing 85 documents (5.5% of total), consistent with broader evidence that MDPI journals have grown substantially in agricultural science output since 2018. The high Bradford scattering across 551 journals implies that comprehensive literature searches in this field must span multiple disciplinary databases and cannot be confined to a narrow journal shortlist.

3.4 Open Access Publishing Landscape

Open access (OA) analysis reveals that 828 documents (54.0%) are freely accessible in at least one form, while 705 (46.0%) remain behind subscription paywalls (Fig. 5). Among OA documents, the most common dissemination routes were Gold OA (published in fully open-access journals), Hybrid Gold OA (open access within subscription journals), Green OA (author self-archiving in institutional or subject repositories), and Bronze OA (freely readable without an explicit open licence).

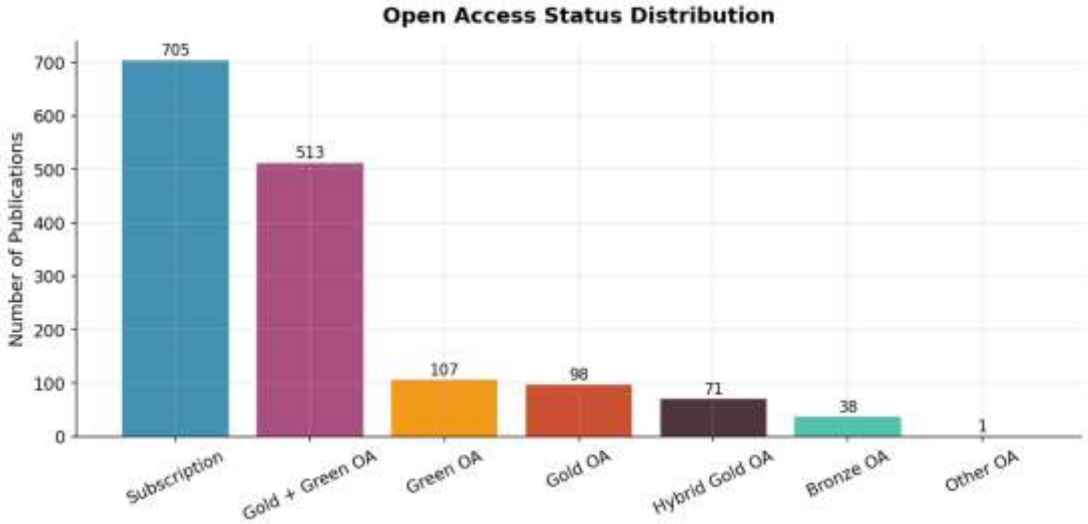

Fig. 5. Open access status distribution of the bibliometric corpus (n = 1,533). Over 54% of documents are accessible through one or more open access channels, reflecting expanding funder mandates and author preferences for broad dissemination.

The 54% OA rate exceeds the estimated global average OA proportion of approximately 46% for scientific publications [40], suggesting that the organic agriculture and soil biology research community has embraced open-access mandates more rapidly than science as a whole. This is consistent with the high representation of MDPI and Frontiers journals in the corpus, which publish exclusively on a Gold OA model. Increased OA availability is consequential for knowledge translation: inoculant-based farming technologies developed in academic settings are more likely to reach practitioners, extension workers, and policymakers in low- and middle-income countries when the underlying evidence is freely accessible [41]. However, the 46% subscription-locked proportion remains substantial, and targeted efforts to deposit pre-prints or author-accepted manuscripts in open repositories such as PubMed Central or Zenodo are warranted to maximise the reach of findings.

3.5 Author Keyword Frequency: Mapping the Conceptual Core

Author keyword analysis is among the most direct and reliable windows into the conceptual architecture of a research field [42]. Analysis of 1,458 documents with author keywords yielded a universe of 3,247 unique terms after standardisation. The top 25 keywords by frequency are presented in Fig. 6.

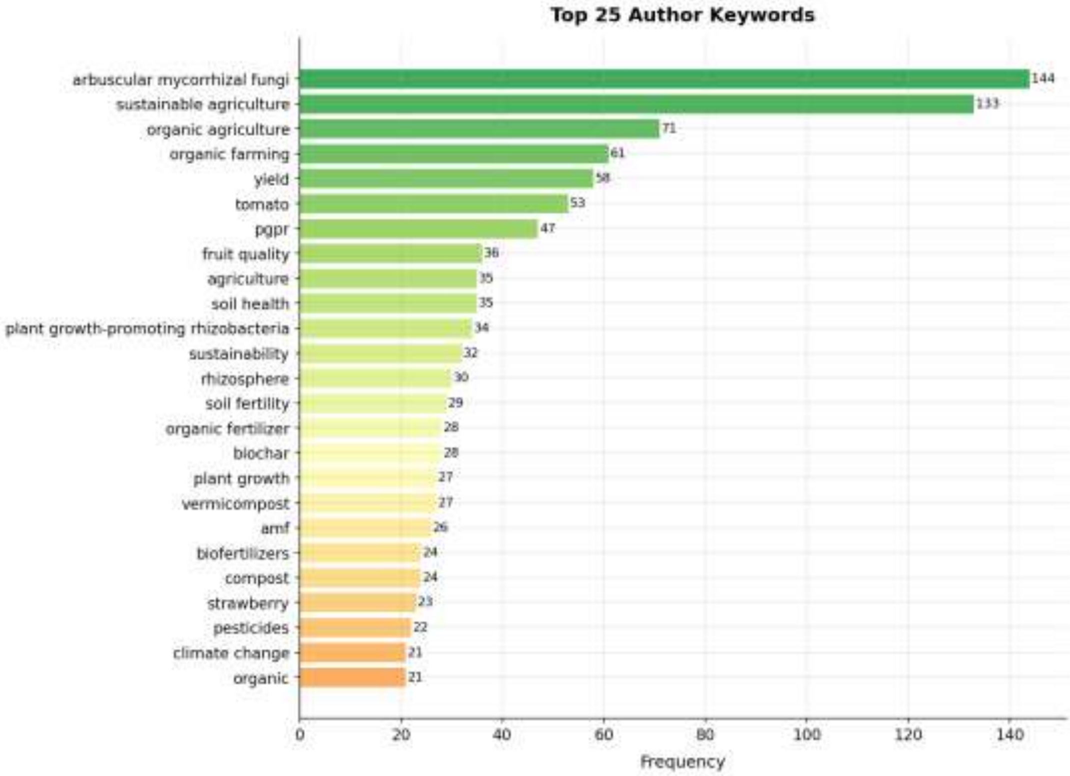

Fig. 6. Top 25 most frequent author keywords in the bibliometric corpus (2010-2026), ordered by frequency.

Arbuscular mycorrhizal fungi (AMF; n = 144) is the single most frequent keyword, confirming AMF research as the dominant mechanistic axis of the corpus. This primacy is consistent with the foundational importance of mycorrhizal symbiosis in soil phosphorus nutrition and the global recognition of AMF inoculants as commercially viable bio stimulants [43]. Sustainable agriculture (n = 133) ranks second, reflecting the overarching sustainability framing within which most applied research is contextualised. The third through fifth keywords organic agriculture (n = 71), organic farming (n = 61), and yield (n = 58), reveal a strong production systems orientation, consistent with the applied goals of the research community.

The presence of PGPR (n = 47), plant growth-promoting rhizobacteria (n = 34), rhizosphere (n = 30), and soil fertility (n = 29) confirms the second major thematic axis of the corpus. Biochar (n = 28) and vermicompost (n = 27) indicate that AMF/PGPR research is frequently embedded within broader organic amendment frameworks, reflecting the synergistic effects of combining biological and organic inputs documented across multiple crops [11,44].

Three keyword clusters emerge from the frequency data: (i) a Microbial Inoculant Mechanisms cluster anchored by AMF, PGPR, rhizosphere, nitrogen fixation, phosphate solubilisation, and microbial community; (ii) a Sustainable Production Systems cluster encompassing sustainable agriculture, organic farming, organic fertiliser, vermicompost, biochar, compost, soil health, and soil fertility; and (iii) a Crop Ecophysiology and Quality cluster represented by tomato, strawberry, yield, fruit quality, plant growth, and antioxidant capacity. These clusters align with the three disciplinary traditions contributing to the corpus: basic soil microbiology, applied agronomy, and horticultural science.

3.6 Keyword Co-occurrence Network: Structural Architecture and Thematic Clusters

The keyword co-occurrence network (Fig. 7) provides a visual representation of the relational structure of the field's conceptual vocabulary, with node size corresponding to keyword frequency and edge thickness reflecting the strength of co-occurrence between terms [25,45]. Large, centrally positioned nodes, such as sustainable agriculture, arbuscular mycorrhizal fungi, and organic agriculture function as primary conceptual bridges, connecting broader agronomic themes with specific microbial applications and illustrating their role as the most integrative topics in the current literature.

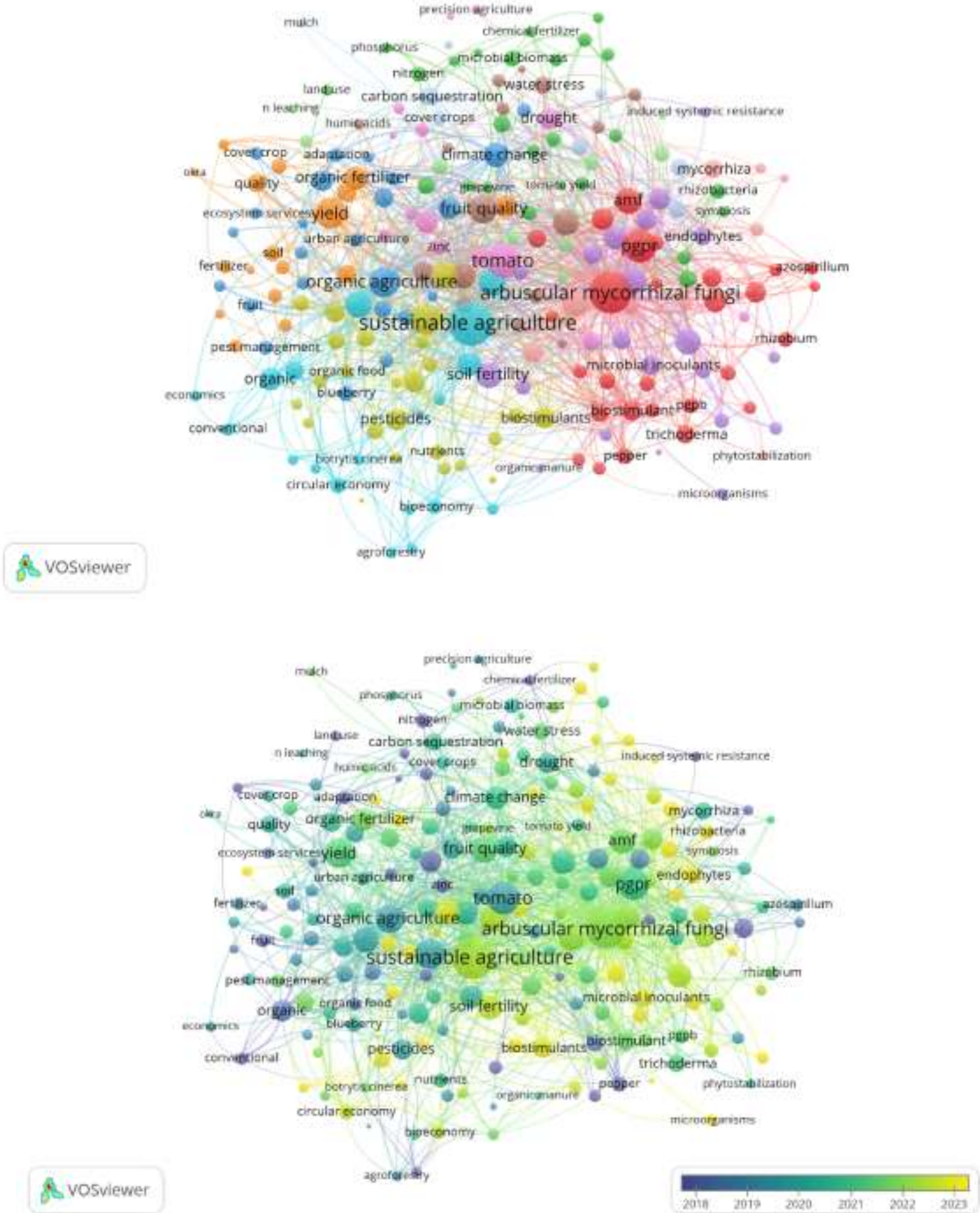

Fig. 7. Author keyword co-occurrence network (top panel: cluster network view; bottom panel: temporal overlay view). Node size is proportional to keyword frequency; edge thickness reflects co-occurrence strength.

The central positioning of arbuscular mycorrhizal fungi, sustainable agriculture, and organic agriculture as bridge nodes connecting all clusters is conceptually significant: it indicates that these concepts function as interdisciplinary connectors linking mechanistic microbiological research with applied production systems science and horticultural quality assessment. This network architecture suggests that integrative research designs, for instance, studies that simultaneously characterise rhizosphere microbial community changes, soil health parameters, and fruit quality outcomes in response to combined AMF-PGPR inoculation in organic farming contexts are well-positioned to generate the most cross-disciplinary impact [46].

The temporal overlay analysis (Fig. 7) reveals a clear chronological shift in research focus. Traditional mechanistic themes, including rhizobacteria, rhizosphere, and phosphorus are predominantly associated with earlier publications (dark blue/purple, 2018-2019), whereas the frontier of the field has shifted toward contemporary challenges. Keywords such as climate change, drought, bioeconomy, and circular economy are concentrated in more recent publications (yellow/bright green, post-2022). Furthermore, keywords including bio stimulants, microbiome, life cycle assessment, and induced systemic resistance are concentrated among publications from

2021-2026, signalling the emerging thematic frontiers of the field. Conversely, phosphorus uptake, nitrogen fixation, and auxin production are predominantly associated with pre-2015 publications, representing the established mechanistic foundation upon which more applied contemporary research is built [47,48]. The relative distance of the climate change node from the AMF and PGPR core suggests that integration of mycorrhizal and rhizobacterial biology with climate adaptation frameworks, while growing remains underdeveloped relative to its potential importance [49].

The network also highlights strong integration between fruit quality, yield, and organic fertiliser, forming a distinct cluster focused on production outcomes. By contrast, the relative isolation of pesticide- and biocontrol-related nodes from the central AMF/PGPR core suggests a continuing conceptual gap between biocontrol and biofertilizer research streams, representing a significant opportunity for future interdisciplinary synthesis.

3.7 Synthesis: Knowledge Gaps and Future Directions

The bibliometric architecture revealed in this analysis points to several well-defined knowledge gaps and research opportunities. First, the dominant crop focus on tomato and strawberry temperate vegetables and small fruits contrasts sharply with the relative paucity of AMF and PGPR studies on tropical fruit crops including mango, banana, papaya, guava, and sapota. Given that tropical fruits represent major export commodities and food security crops across South and Southeast Asia, sub-Saharan Africa, and Latin America, the absence of a robust evidence base for bioinoculant application in these systems is a critical gap [50].

Second, the keyword network reveals limited connectivity between the AMF-PGPR mechanistic cluster and the climate change/resilience cluster, suggesting that the role of mycorrhizal and rhizobacterial inoculants in building crop resilience to abiotic stresses drought, salinity, heat, and flooding under projected climate scenarios is understudied relative to its agronomic importance [49,51]. Third, despite the strong representation of sustainability keywords, life cycle assessment (LCA) studies that quantify the carbon footprint, energy balance, and ecosystem service trade-offs of bioinoculant-based organic systems remain rare [52]. Fourth, the intellectual geography of the field dominated by Chinese, European, Indian, and Moroccan research centre leaves substantial representation gaps for sub-Saharan Africa, Southeast Asia, and small island developing states, where sustainable intensification pressures are most acute [53].

These gaps collectively define a high-priority research agenda: integrated AMF-PGPR-biochar systems studies in tropical fruit crops, climate resilience trials incorporating inoculant treatments under controlled stress conditions, LCA-based sustainability assessment of bioinoculant supply chains, and equitable North-South research partnerships to extend the evidence base to underrepresented geographies and crop systems.

4. CONCLUSION

This bibliometric analysis of 1,533 Scopus indexed documents (2010-2026) provides the first comprehensive quantitative portrait of the research landscape at the nexus of organic agriculture, arbuscular mycorrhizal fungi, plant growth promoting rhizobacteria, and sustainable soil management. The analysis confirms a nine-fold surge in annual publication output over fifteen years, a broadening disciplinary base spanning 551 journals, and a dominant intellectual core centred on AMF biology, sustainable production systems, and horticultural ecophysiology.

Keyword co-occurrence network analysis identified integrated thematic clusters microbial inoculant mechanisms, sustainable production systems, and crop ecophysiology linked by conceptual bridges including AMF, sustainable agriculture, and soil health. Emerging post-2020 keywords (climate change, bio stimulants, microbiome, life cycle assessment) signal the field's expanding scope toward climate resilience and full-system sustainability evaluation. Critical knowledge gaps identified include the relative neglect of tropical fruit crops, the limited integration of climate adaptation frameworks with AMF-PGPR research, the scarcity of LCA-based sustainability assessments, and under-representation of research from tropical and sub-Saharan agricultural systems. Addressing these gaps through targeted, interdisciplinary, and geographically inclusive research programmes will be essential for translating the field's growing scientific momentum into tangible improvements in sustainable food production globally.

The bibliometric framework, figures, VOSviewer data files, and R scripts used in this analysis are provided as supplementary materials to facilitate replication, extension, and integration of these findings into future systematic reviews and meta-analyses.

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Conflict of Interest

The authors declare that this research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Author Contributions

NKK: Writing - original draft, Conceptualization, Methodology, Formal Analysis & Visualization; KC: Writing - review & editing, Data curation, Project administration; BD: Writing- review & editing, Conceptualization, Methodology, Resources; VS, BP and MSK: Writing- review & editing.

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