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Consolidated Evidence on Research Expansion and Innovation Pathways in Fermented-Food and Gut-Health Studies (2010–2025)

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ABSTRACT
Fermented foods are increasingly studied as complex food–microbial systems with potential relevance to gut health through microorganisms, fermentation-derived metabolites, bioactive compounds, and interactions with the gut microbiome. However, research remains uneven across food matrices, microbial systems, geographical settings, and health-related mechanisms. This study mapped the research landscape of fermented foods and gut health from 2010 to 2025, characterized its intellectual, thematic, and geographic structure, identified potential research gaps and innovation white spaces, and developed the GAP-TO-GROWTH Technology Innovation Pathways Framework. A bibliometric analysis of 642 Scopus-indexed articles was conducted using established performance-analysis and science-mapping approaches. Publication activity increased markedly after 2020, with fermentation, fermented foods, probiotics, microorganisms, gut microbiota, and functional foods forming the principal knowledge core. Emerging research increasingly addressed microbiome-related concepts, metabolites, bioactive compounds, and health-oriented mechanisms. Six potential innovation white spaces were identified: diversification of food matrices and indigenous fermentation resources; novel microbial and fermentation systems; food–microbe–metabolite–gut integration; mechanistic gut-health validation; metabolite and postbiotic applications; and interdisciplinary collaboration. The GAP-TO-GROWTH framework extends conventional bibliometric mapping by translating these evidence patterns into a structured pathway from Research Landscape and Dominant Themes through Knowledge Gaps and Innovation White Spaces to Technology Opportunities and Innovation Pathways. It therefore provides an evidence-informed structure for research prioritization, technology-oriented development, and innovation planning while recognizing that identified opportunities require independent validation of feasibility, safety, health effects, regulatory requirements, and commercialization potential.
Keywords: fermented foods; gut health; bibliometric analysis; science mapping; innovation gaps; white spaces; technology innovation pathways

INTRODUCTION
Fermented foods are increasingly examined not only as traditional foods and preservation systems but also as complex food–microbial systems with potential relevance to gastrointestinal health. Fermentation can modify food composition, generate or enrich bioactive compounds, reduce undesirable components, and introduce microorganisms and microbial metabolites that interact with the gastrointestinal environment [1,2]. This interest occurs within a substantial global burden of digestive disorders. A Global Burden of Diseases analysis estimated approximately 2.86 billion prevalent digestive-disease cases, 8 million deaths, and 277 million disability-adjusted life years in 2019 [3]. The Rome Foundation Global Study reported functional gastrointestinal disorders in 20.7% of household-survey respondents and 40.3% of internet-survey respondents across participating countries [4].

Research increasingly focuses on interactions among fermented-food matrices, microorganisms, fermentation-derived metabolites, gut microbiota, and host responses. Human and translational studies have reported associations between fermented-food consumption and changes in gut microbial or metabolic profiles, although evidence remains heterogeneous and mechanisms are not uniformly established [2,5,6]. Recent work has expanded beyond live microorganisms to include microbial metabolites, bioactive compounds, and postbiotic components, while omics approaches provide increasingly detailed views of fermented-food microbiomes and metabolomes [7-9].

This diversity is relevant to the Philippine setting, where fermented foods include balao-balao, burong isda, burong mustasa, alamang, bagoong, patis, tuba, and vinegar-based products. Earlier work documented diverse bacterial communities in selected Philippine fermented foods, including lactic- and acetic-acid bacteria with established or potential functional relevance. National food-consumption data also include fermented fish and fish products, cultured and other milk products, fermented beans, nuts and seeds, and pickled or preserved vegetables. Much Philippine research, however, has focused on individual products or strains rather than the structure of the broader research field.

Narrative and systematic reviews synthesize biological evidence, but they do not necessarily reveal how a research field is organized across time, countries, institutions, intellectual communities, thematic clusters, and emerging topics. Bibliometric analysis provides this complementary perspective by examining publication performance and relationships among authors, countries, references, keywords, and concepts [10,11]. Such mapping can distinguish established research concentrations from comparatively weakly connected or emerging areas. Importantly, bibliometric white spaces represent potential areas for investigation rather than proof of novelty, feasibility, clinical value, or commercial opportunity.

Accordingly, this study mapped fermented-food and gut-health research from 2010 to 2025 to: (1) characterize research performance and participation; (2) examine intellectual, geographic, thematic, relational, and conceptual structures; and (3) synthesize the evidence into potential research gaps, innovation white spaces, and the GAP-TO-GROWTH Technology Innovation Pathways Framework. The framework's novelty lies in connecting bibliometric evidence to a translational sequence from research landscape and dominant themes through knowledge gaps and innovation white spaces to technology opportunities and innovation pathways.

METHODS
Research design and analytical logic
A bibliometric research design was used to map scientific literature on fermented foods and gut health published from 2010 to 2025. Bibliometric methods support quantitative examination of scientific production and intellectual, conceptual, and social relationships within a research field [10,11]. The study combined performance analysis and science mapping, followed by evidence synthesis for identifying potential

gaps and white spaces and developing the GAP-TO-GROWTH framework. This sequence was selected because publication counts alone cannot characterize the structure or development of a multidisciplinary field.

Data source and search strategy

Scopus was used as the sole bibliographic database because it provides structured metadata required for publication, citation, affiliation, country, keyword, and reference analyses. The initial search retrieved 14,388 records. The search string was:

("fermented food" OR "fermented foods" OR "fermented beverage" OR "fermented beverages") AND ("gut health" OR "gastrointestinal health" OR "intestinal health" OR "digestive health" OR "gut microbiota" OR "gut microbiome" OR microbiome OR microbiota OR probiotic OR probiotics OR prebiotic OR prebiotics OR synbiotic OR synbiotics) NOT (animal OR livestock OR poultry OR aquaculture OR cosmetic OR skincare)

Scopus filters were applied for publication year (2010–2025), subject area (Agricultural and Biological Sciences), document type (Article), language (English), publication stage (Final), and Open Access (All). These filters yielded 642 records for analysis.

Eligibility criteria

Eligibility criteria were established before data screening to ensure consistency in the selection of records for the bibliometric analysis. Records were included when they satisfied all predefined bibliographic, temporal, subject-area, language, publication-stage, and topical requirements. Records that did not meet any of these criteria were excluded from the analytical dataset. The criteria are summarized in Table 1.

Table 1. Eligibility criteria for the bibliometric analysis of fermented foods and gut health

Criterion	Inclusion	Exclusion
Database	Scopus-indexed	Non-Scopus records
Period	2010–2025	Outside study period
Document type	Article	Other types
Language	English	Other languages
Subject area	Agricultural and Biological Sciences	Outside selected area
Publication stage	Final	Non-final records
Topic	Fermented foods/beverages linked to gut health or related microbiome/biotic concepts	Primarily animal, livestock, poultry, aquaculture, cosmetic, skincare, or otherwise out of scope

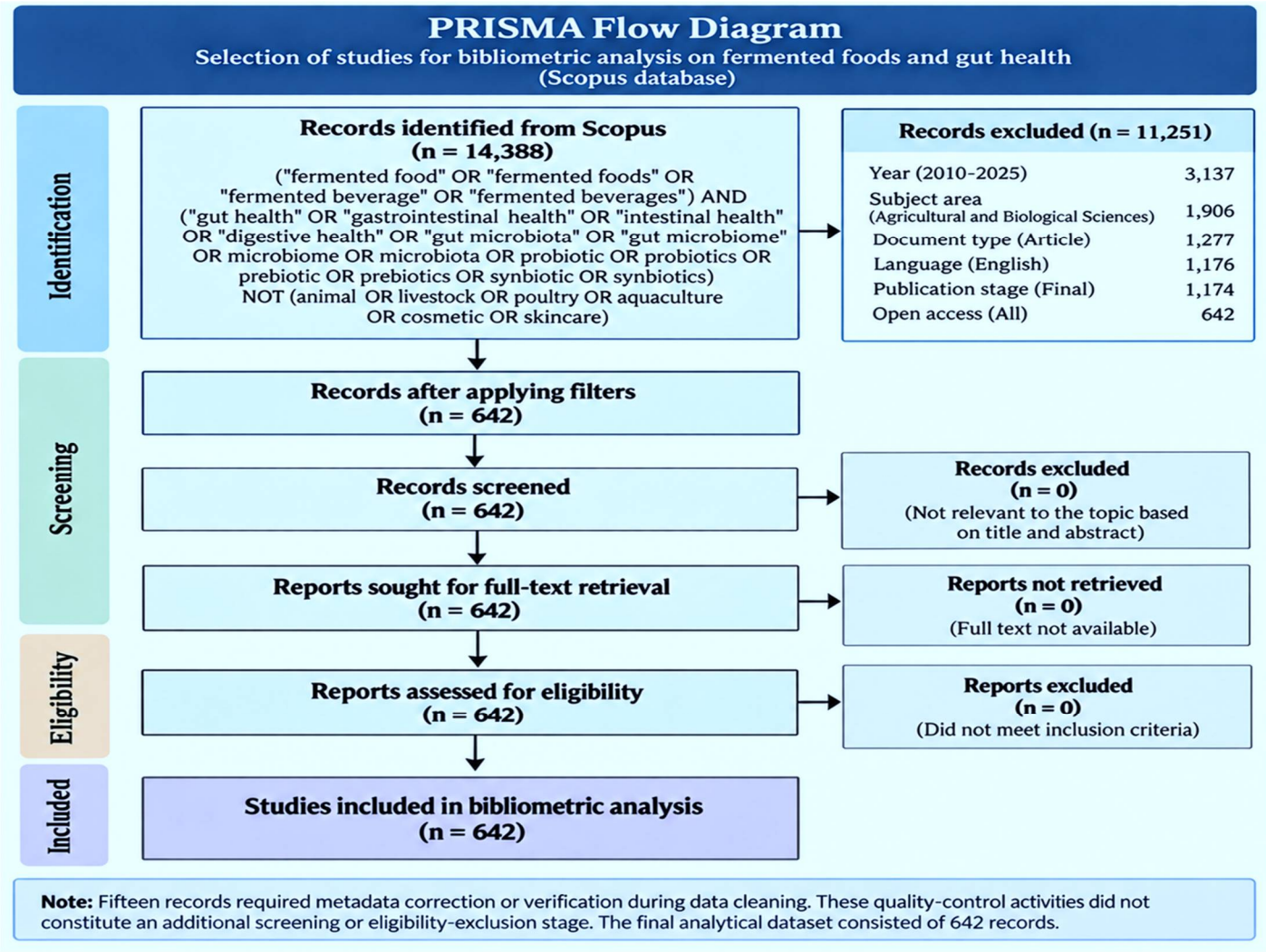

Figure 1. PRISMA Flow Diagram of the Study Selection Process for the Bibliometric Analysis of Fermented Foods and Gut Health.

The criteria were designed to maintain topical and bibliographic consistency while limiting the dataset to literature directly relevant to the study objectives. The topical criterion was particularly important because the search strategy included broader microbiome- and biotic-related terms that could retrieve heterogeneous records. Accordingly, records were excluded when their primary focus was outside the human food and gut-health context, including animal production, aquaculture, cosmetics, skincare, and other unrelated applications. Application of these predefined criteria provided a transparent basis for the subsequent filtering, quality control, and bibliometric analysis.

Data filtering and cleaning and quality control

Based on Figure 1, following the Scopus search and application of the predefined eligibility filters, 642 records were retained for bibliometric analysis. The records were exported for metadata quality control and subsequently prepared for analysis in RStudio using Bibliometrix and Biblioshiny. Quality control focused on duplicate detection, metadata completeness and consistency, and alignment with the predefined study scope. Fifteen records required metadata correction or verification during data preparation; these quality-control activities did not constitute a separate screening or eligibility-exclusion stage. After quality checking and structural preparation of the dataset, the final analytical dataset comprised 642 records. Detailed identifier-level duplicate checks and spreadsheet procedures were retained as supplementary quality-control documentation rather than reported as separate analytical steps.

Bibliometric analysis

Analyses were conducted in R using Bibliometrix and Biblioshiny. Performance analysis covered annual scientific production, authors' production over time, globally cited documents, corresponding-author countries, relevant affiliations, and relevant authors. Science mapping comprised co-citation analysis, country production over time, country collaboration, keyword co-occurrence/thematic mapping, three-field analysis, trend-topic analysis, and conceptual structure analysis. The outputs were selected to provide complementary evidence across productivity and visibility, geographic and social participation, intellectual relationships, and thematic/conceptual development, consistent with established bibliometric practice [10,11].

RESULTS

Performance analysis

Annual scientific production

The final dataset contained 642 Scopus-indexed articles published from 2010 to 2025. Publication activity increased substantially, with the strongest expansion after 2020 (Figure 2). The pattern indicates that fermented-food and gut-health research became increasingly active during the latter study period. Recent literature provides context for this expansion through growing attention to fermented-food microbiomes, probiotics and other biotics, fermentation-derived metabolites, and host–microbe interactions [2,12,13].

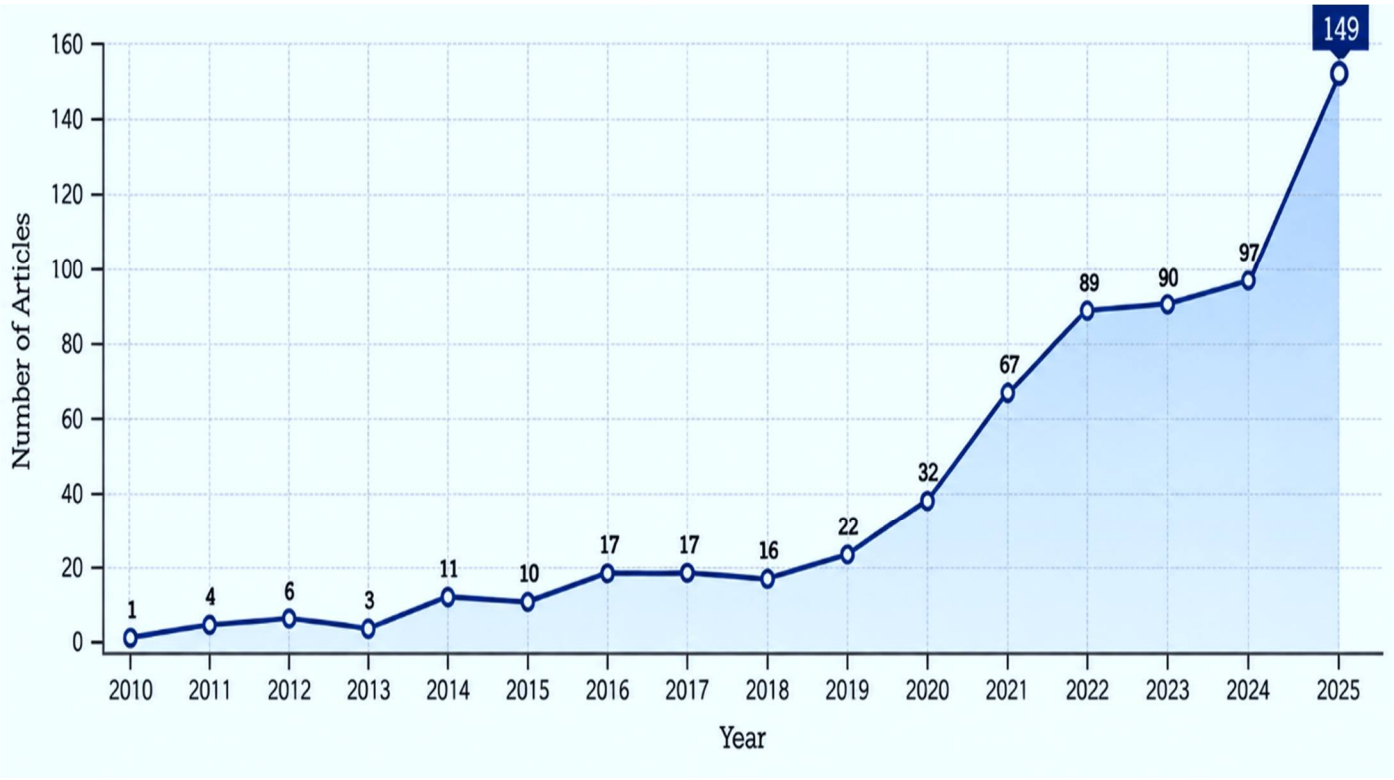

Figure 2. Annual scientific production on fermented foods and gut health, 2010–2025

Authors' production over time

Figure 3 indicates both continuity and expansion in the author community. Liu & Zhang show sustained activity, whereas Wang et al. become more visible in the later period [14]. This pattern is consistent with established research lines continuing alongside newer groups addressing microbiomes, metabolites, probiotics, and gut-health mechanisms. Publication frequency should be interpreted as participation rather than scientific quality or influence.

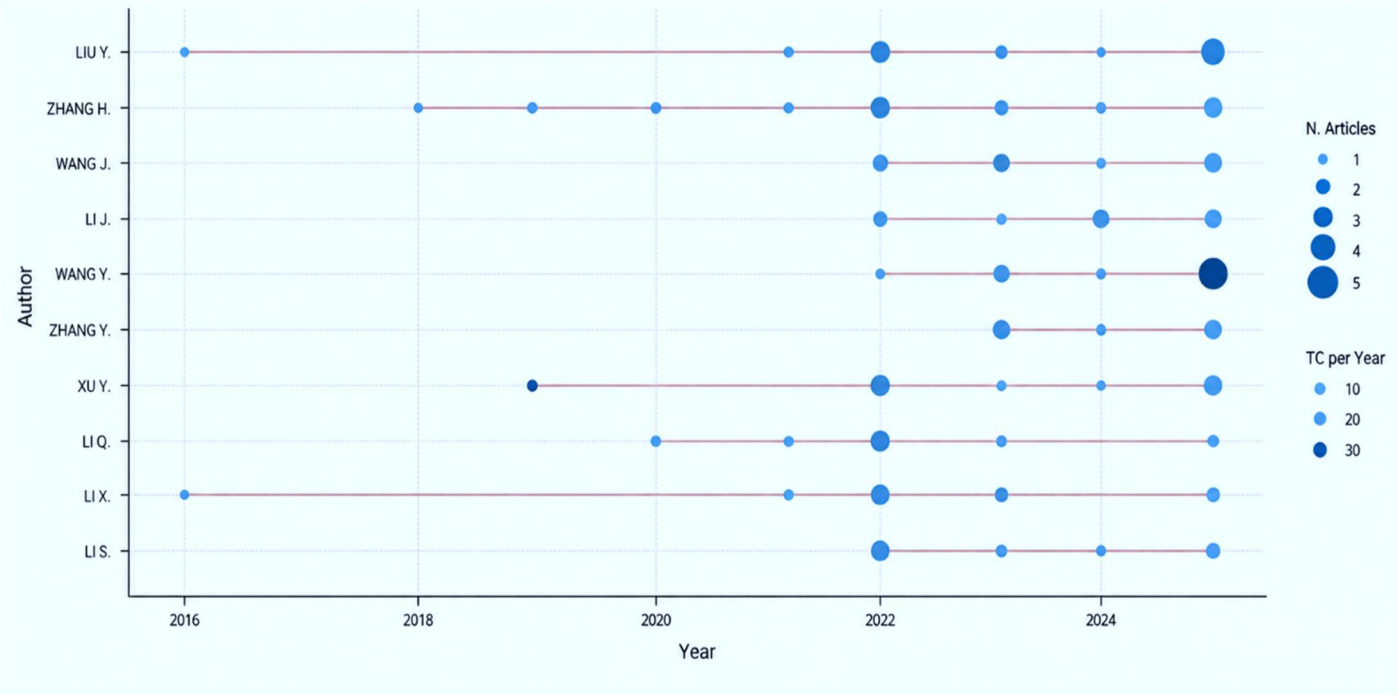

Figure 3. Authors' scientific production over time in fermented food and gut health research, 2010–2025

Most globally cited documents

Citation accumulation was uneven among the most globally cited documents (Figure 4). Jung had 482 citations in the dataset, whereas Chung had 166 among the cited documents highlighted. Citation counts indicate scholarly uptake, but they are affected by publication age, topic, journal visibility, accessibility, and citation practices. The highly cited literature nevertheless provides an intellectual base for research on fermented foods, probiotics, microbiome interactions, and health-related mechanisms [2,12,13].

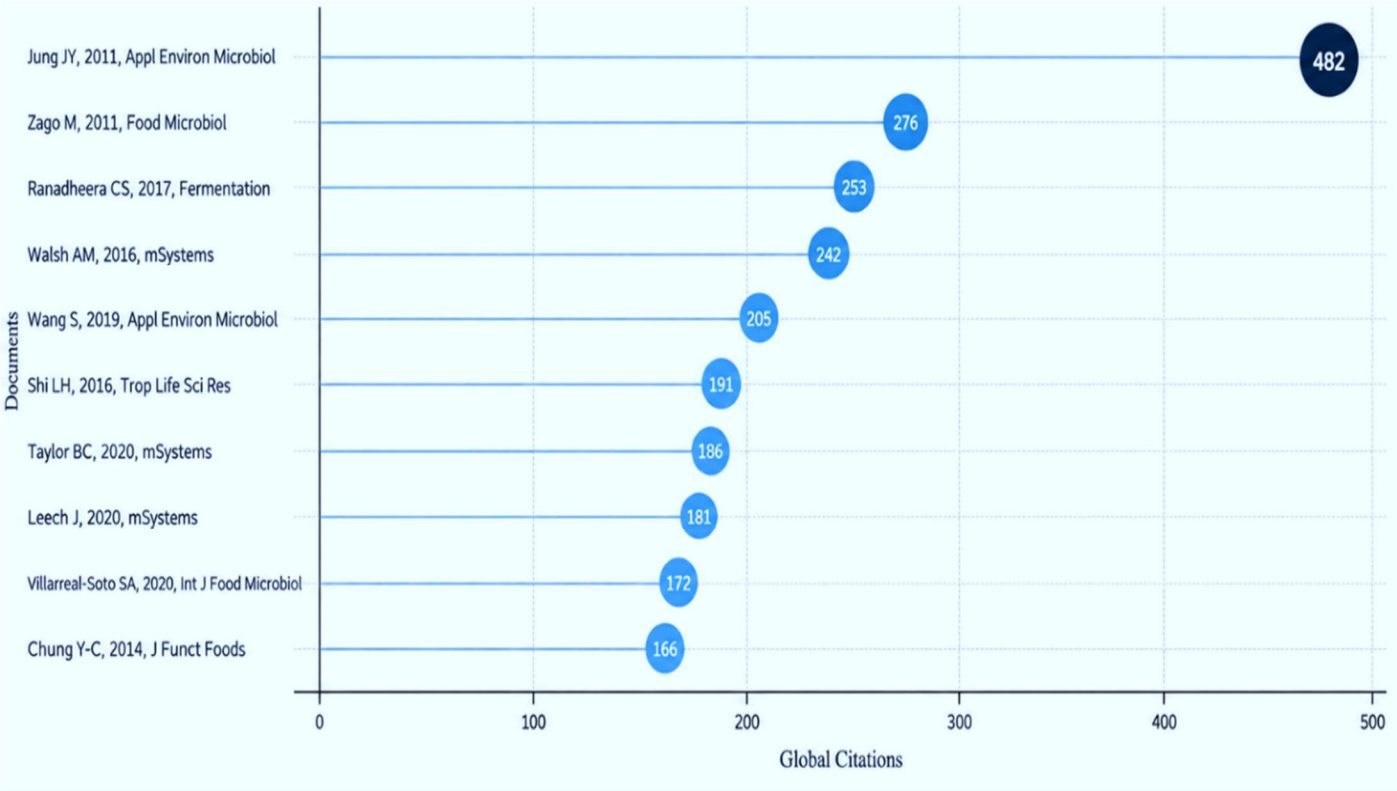

Figure 4. Most globally cited documents in fermented food and gut health research, 2010–2025

Corresponding author countries

The corresponding-author analysis shows strong geographic concentration, with China and India contributing substantially more publications than the other countries shown, followed by Korea, Italy, Brazil, Turkey, Spain, Thailand, and the USA (Figure 5). Single-country publications generally exceed multiple-country publications. The pattern may reflect differences in research capacity, funding, institutional expertise, local fermented-food resources, and database coverage; lower representation therefore cannot by itself be interpreted as a research deficit.

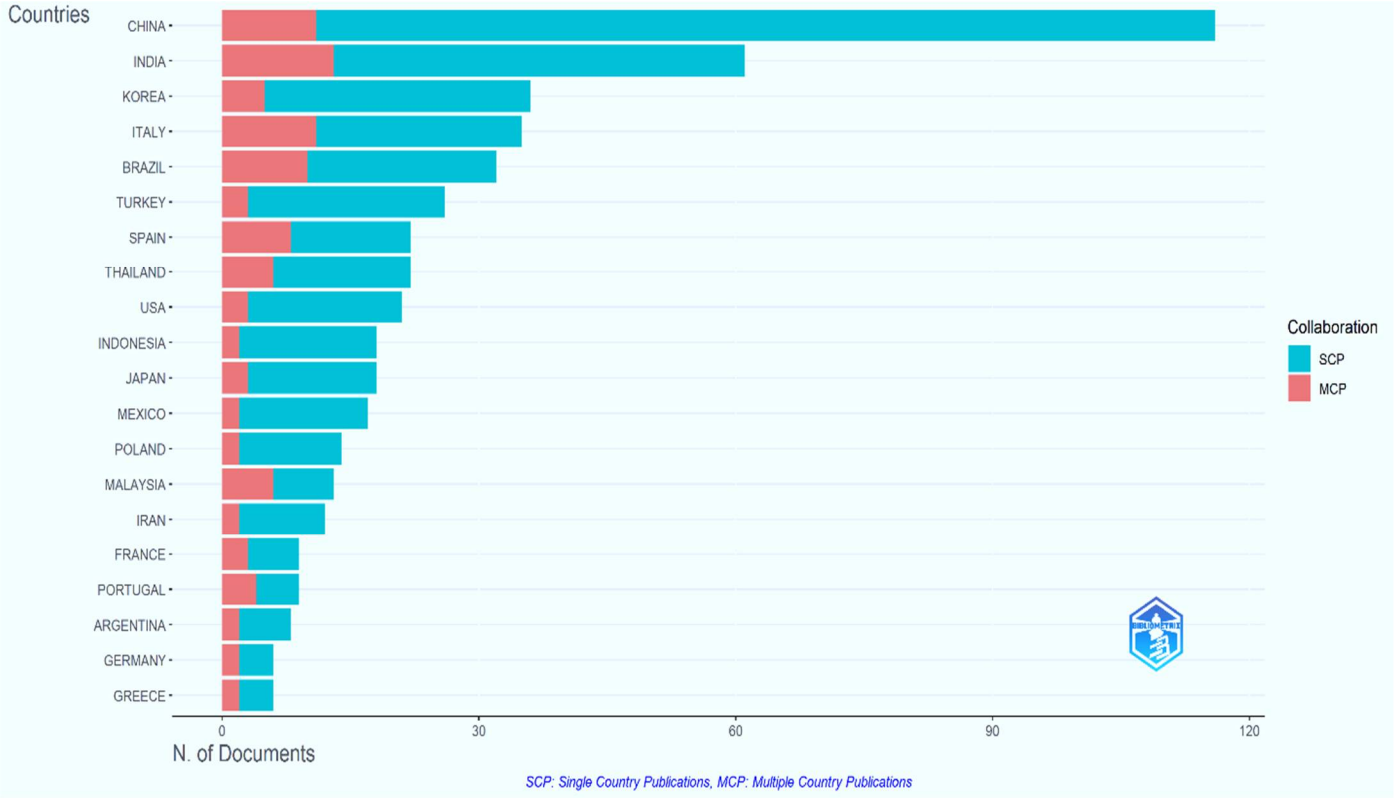

Figure 5. Corresponding author countries in fermented food and gut health research, 2010–2025

Most relevant affiliations

Institutional output is also concentrated (Figure 6). Jiangnan University has the strongest presence among the affiliations shown, followed by Sichuan Agricultural University, the World Institute of Kimchi, University College Cork, Ningbo University, the University of Parma, and Chiang Mai University. The pattern is consistent with the contribution of established food-science and fermentation centers and provides potential collaboration points for groups seeking specialized methods or facilities.

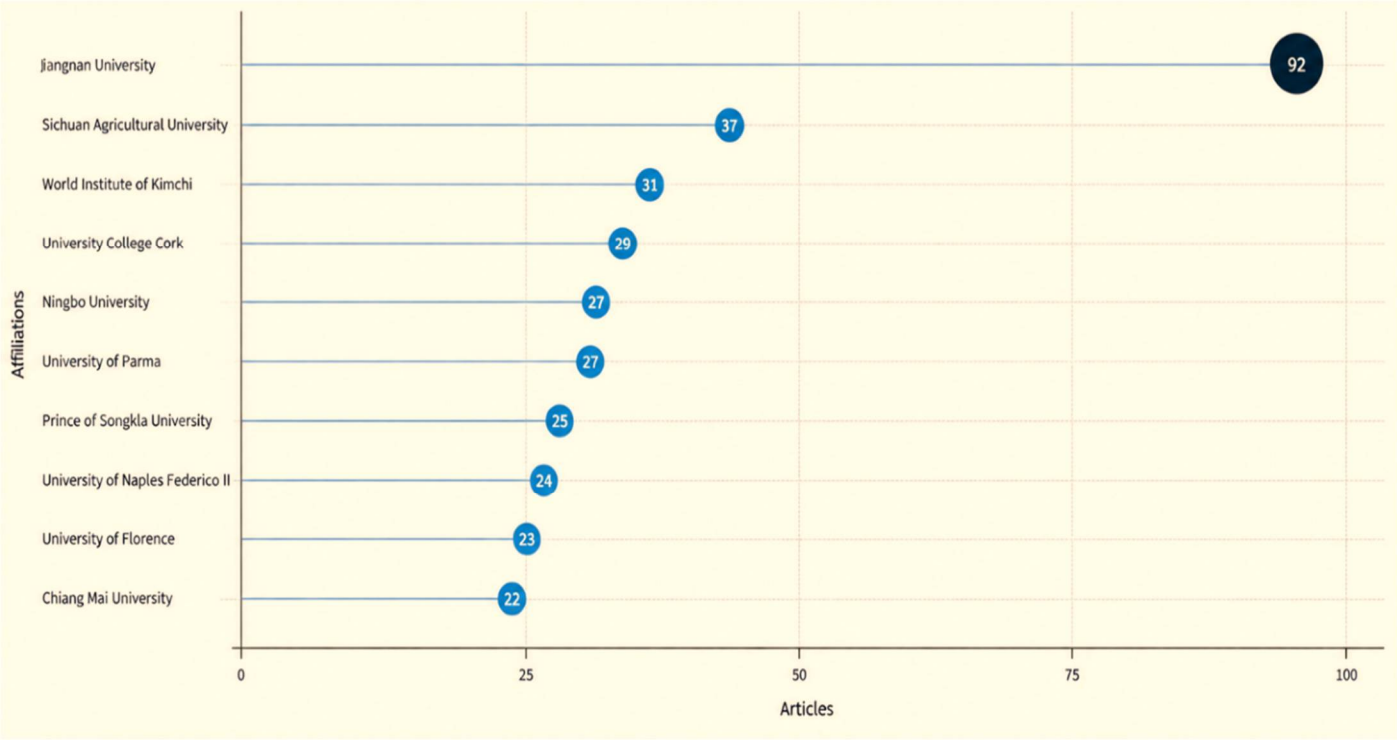

Figure 6. Most relevant affiliations in fermented food and gut health research, 2010–2025

Most relevant authors

The leading authors produced between 7 and 12 documents (Figure 7), showing a relatively distributed productivity profile rather than one overwhelmingly dominant contributor. This complements the multidisciplinary structure of the field. Author productivity, however, should be considered together with citation, collaboration, and thematic indicators.

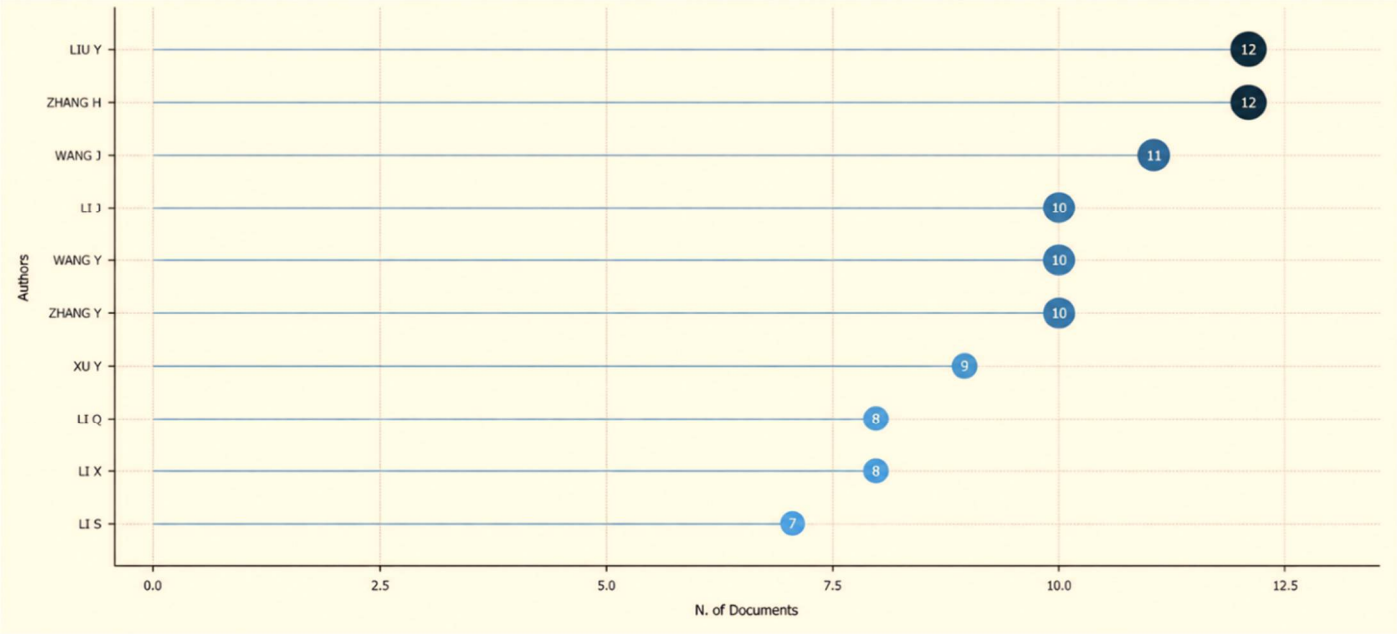

Figure 7. Most relevant authors in fermented food and gut health research, 2010–2025

Science mapping

Co-citation network

The co-citation network (Figure 8) forms several interconnected clusters rather than one isolated intellectual stream. Cross-cluster links connect literature on fermented foods, microorganisms, probiotics, microbial ecology, nutrition, and health. This structure supports an interdisciplinary interpretation, while peripheral nodes should not automatically be treated as gaps because network position is affected by topic size, publication age, terminology, and citation practices.

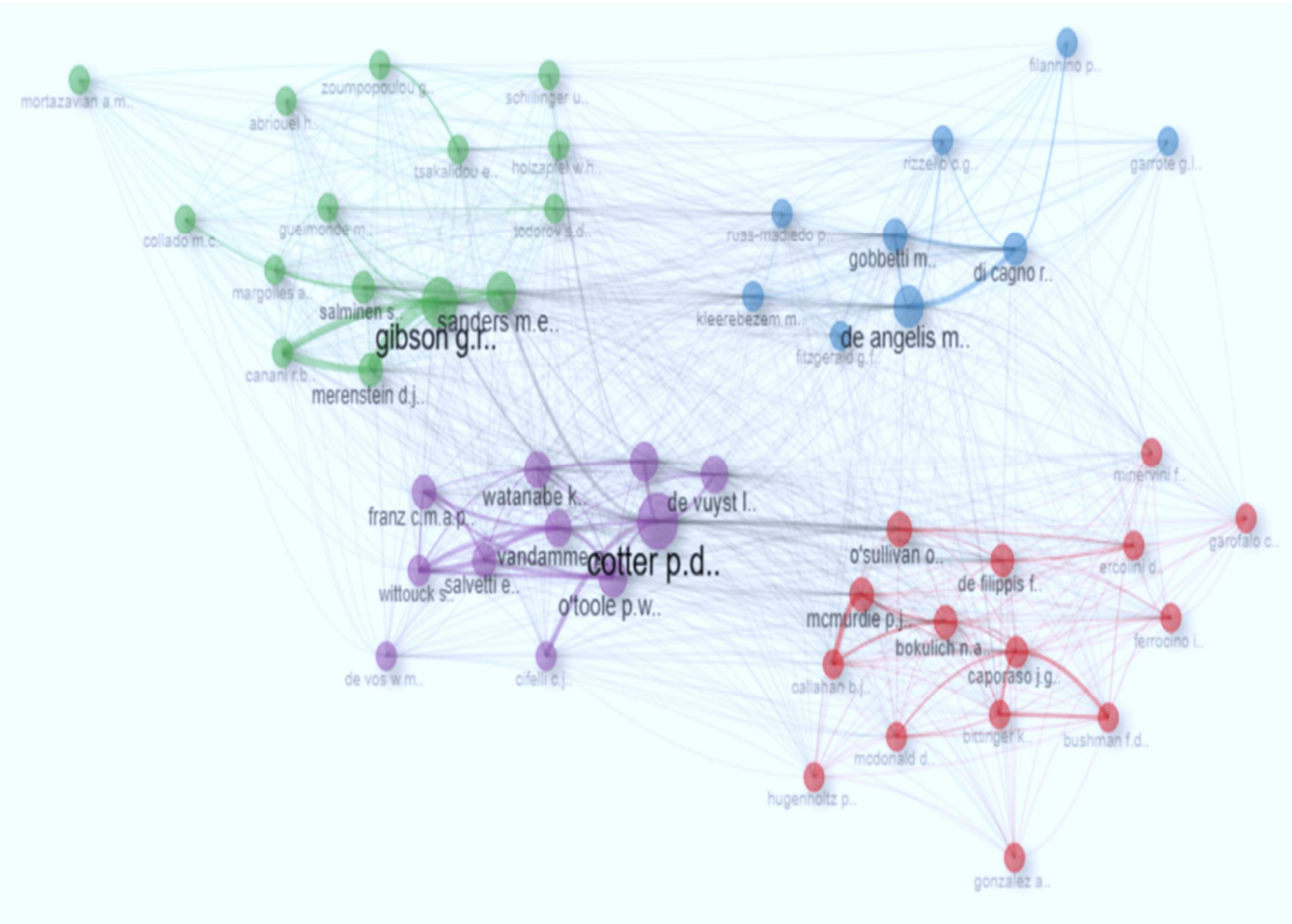

Figure 8. Co-citation network of research on fermented foods and gut health, 2010–2025

Country production over time

Country production over time (Figure 9) shows stronger growth after approximately 2018 and especially after 2020. China shows the strongest acceleration in the later period, while India, Korea, Italy, and Brazil also increase. The differentiated trajectories are compatible with variation in traditional food systems, institutional capacity, research investment, and access to sequencing and metabolomics technologies [15,16].

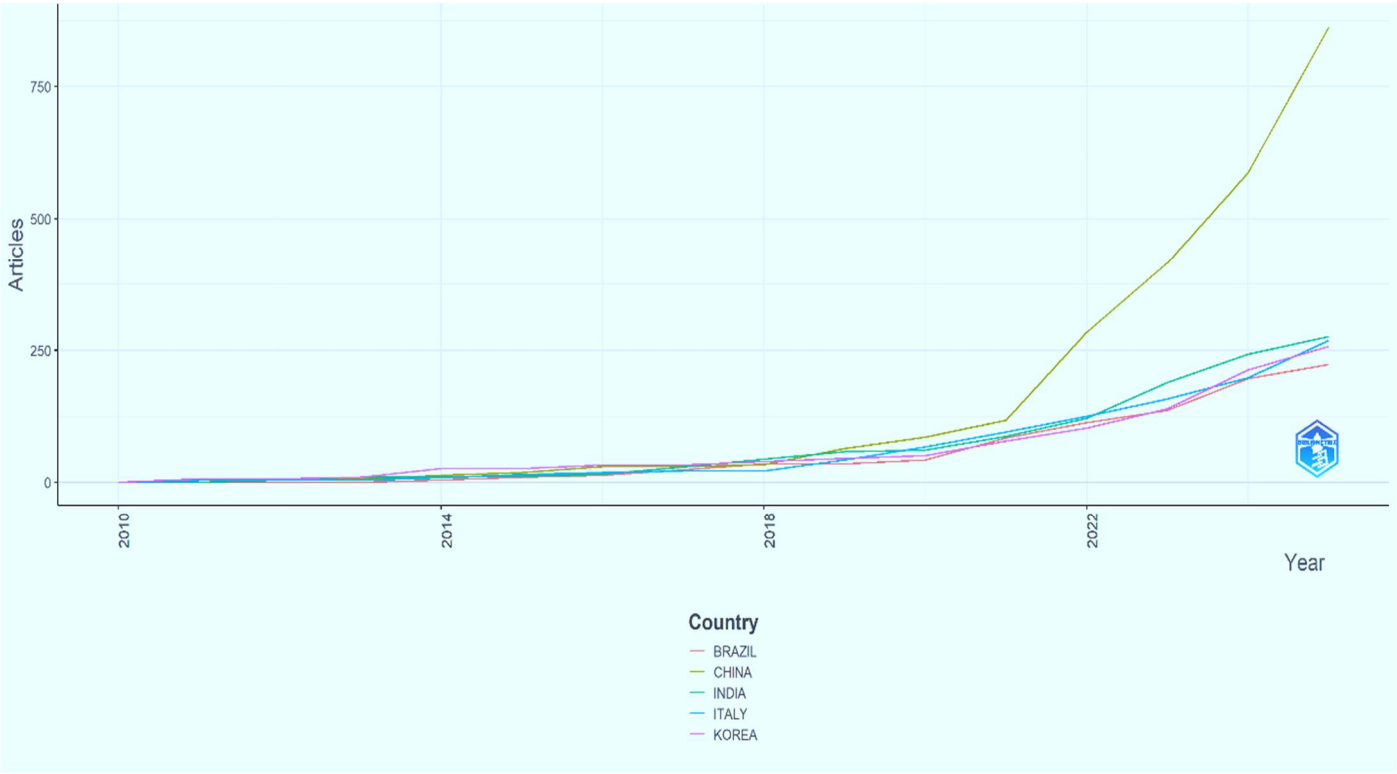

Figure 9. Country scientific production over time in fermented food and gut health research, 2010–2025

Country collaboration map

The country collaboration map (Figure 10) shows cross-regional connections spanning Asia, Europe, the Americas, and Oceania. Publication productivity and international connectedness therefore represent different dimensions of participation. Cross-border links are relevant because fermented foods differ in matrices, substrates, microbial resources, and processing practices, creating opportunities for comparative research [15,17].

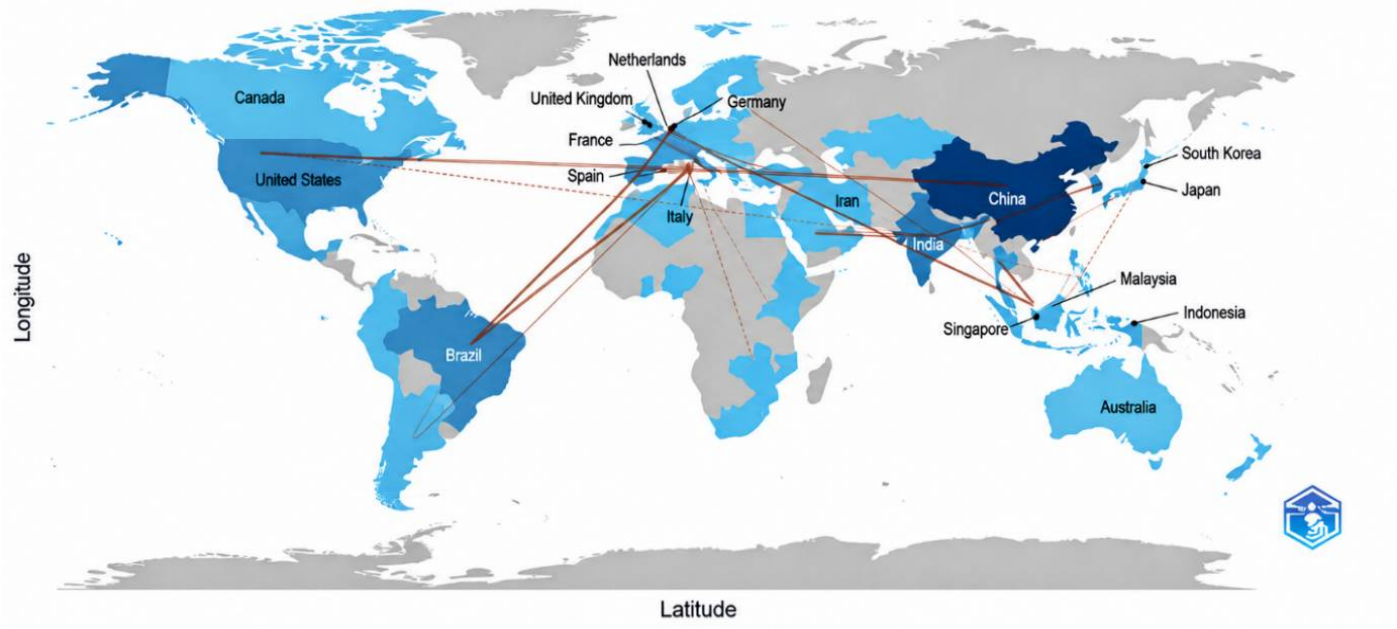

Figure 10. Country collaboration map of fermented food and gut health research, 2010–2025

Thematic map

The thematic map (Figure 11) places fermentation, fermented foods, and fermented product among the central, well-developed themes. Probiotics and lactic acid bacteria remain connected but occupy different thematic positions. The pattern indicates a strong fermentation core with expanding links to microbial, metabolic, and health-related questions [13,18].

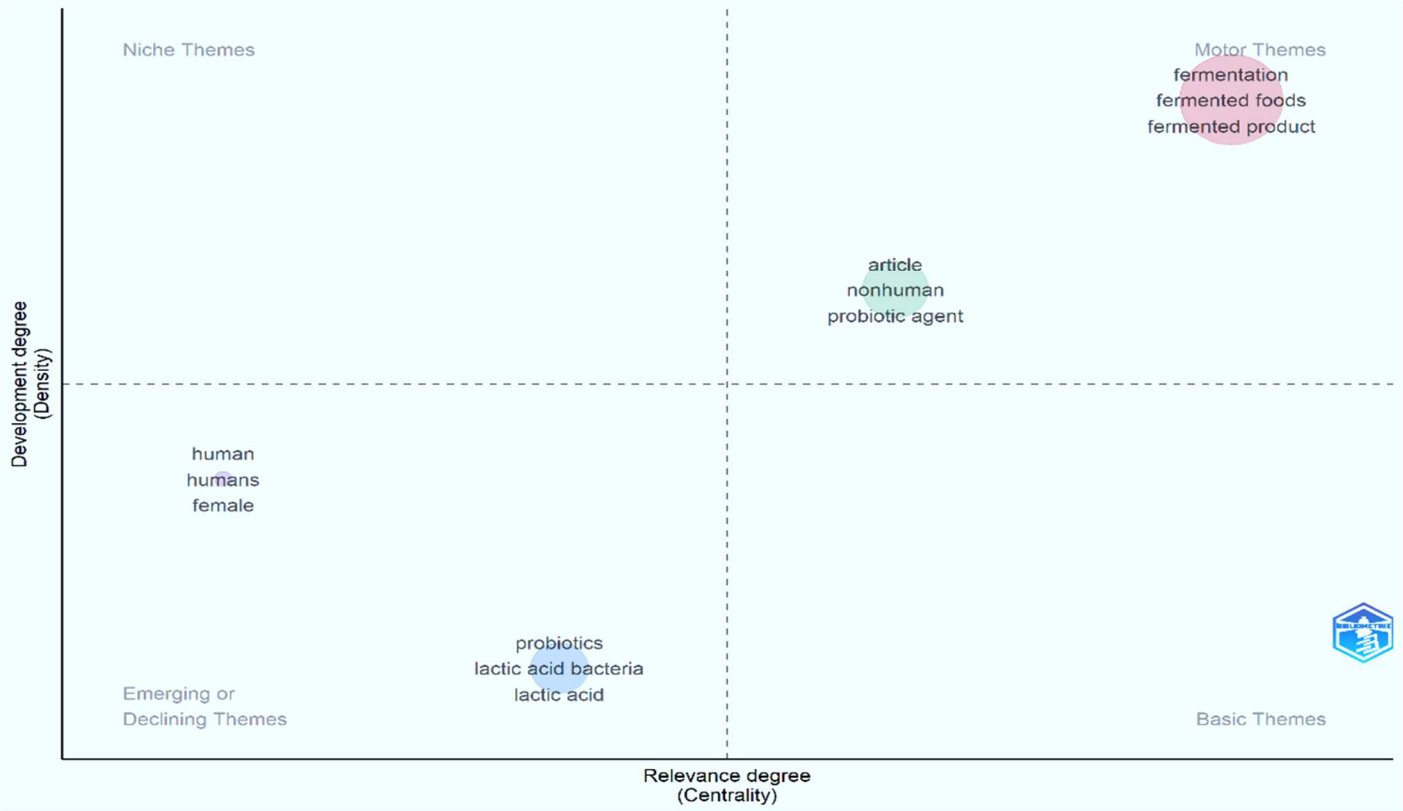

Figure 11. Thematic map of research on fermented foods and gut health, 2010–2025

Three-field plot

The three-field plot (Figure 12) shows dense relationships among cited references, authors, and merged keywords. Fermentation connects fermented foods, probiotics, lactic acid bacteria, microbiota, and microbial processes. The structure suggests continuity between established knowledge and newer topics, while also indicating opportunities to strengthen links involving underrepresented food matrices, indigenous microorganisms, metabolites, and defined gut-health outcomes. These are bibliometric relationships and do not establish biological causality.

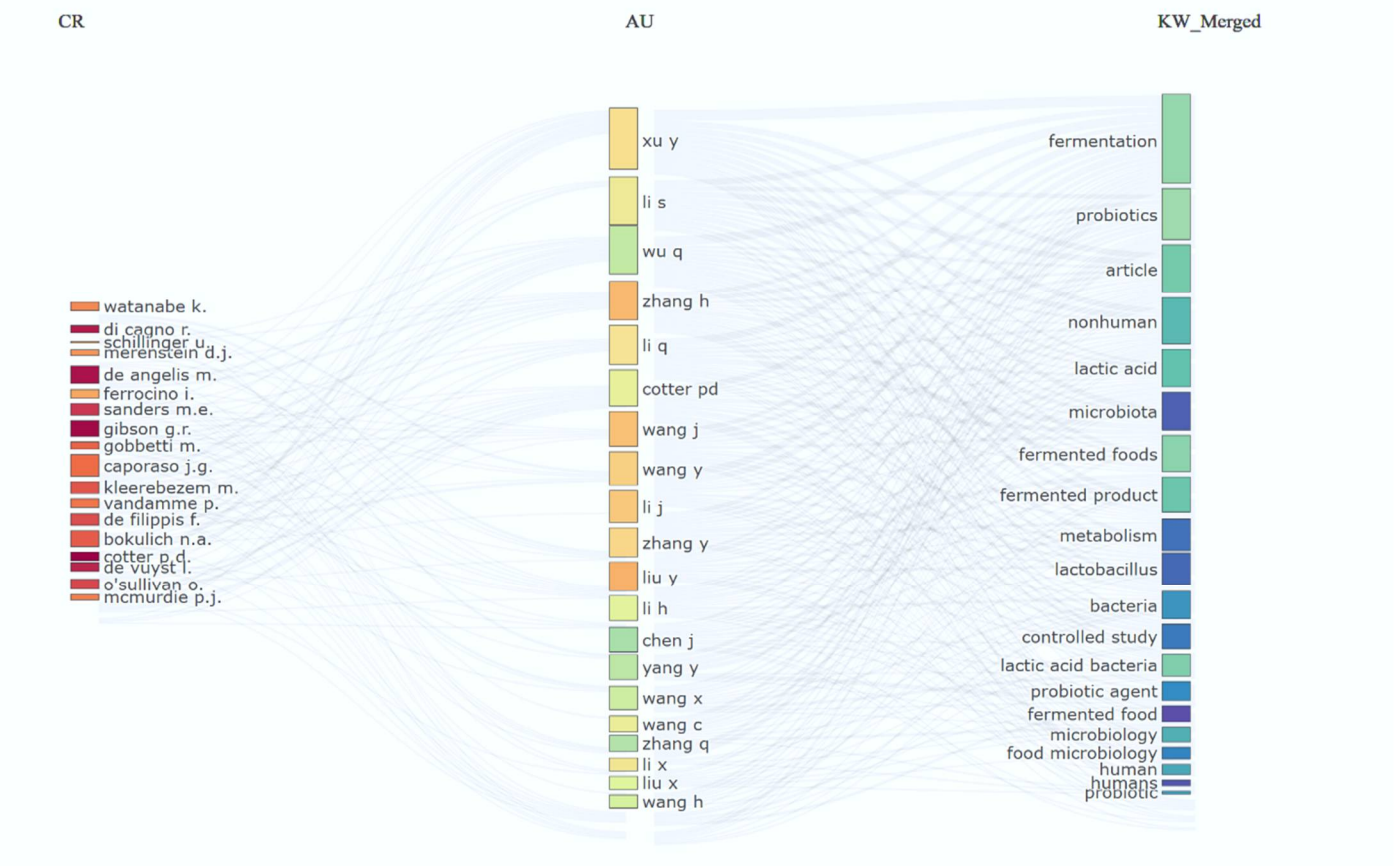

Figure 12. Three-field plot of authors, keywords, and sources in fermented food and gut health research, 2010–2025

Trend topics

Trend-topic analysis (Figure 13) indicates a temporal expansion from foundational microbial and genetic characterization toward fermentation, probiotics, fermented foods, metabolism, oxidative stress, flavor, and other functional dimensions. The increasing visibility of metabolite-related topics is consistent with the expanding use of metabolomics and other omics approaches [7,19].

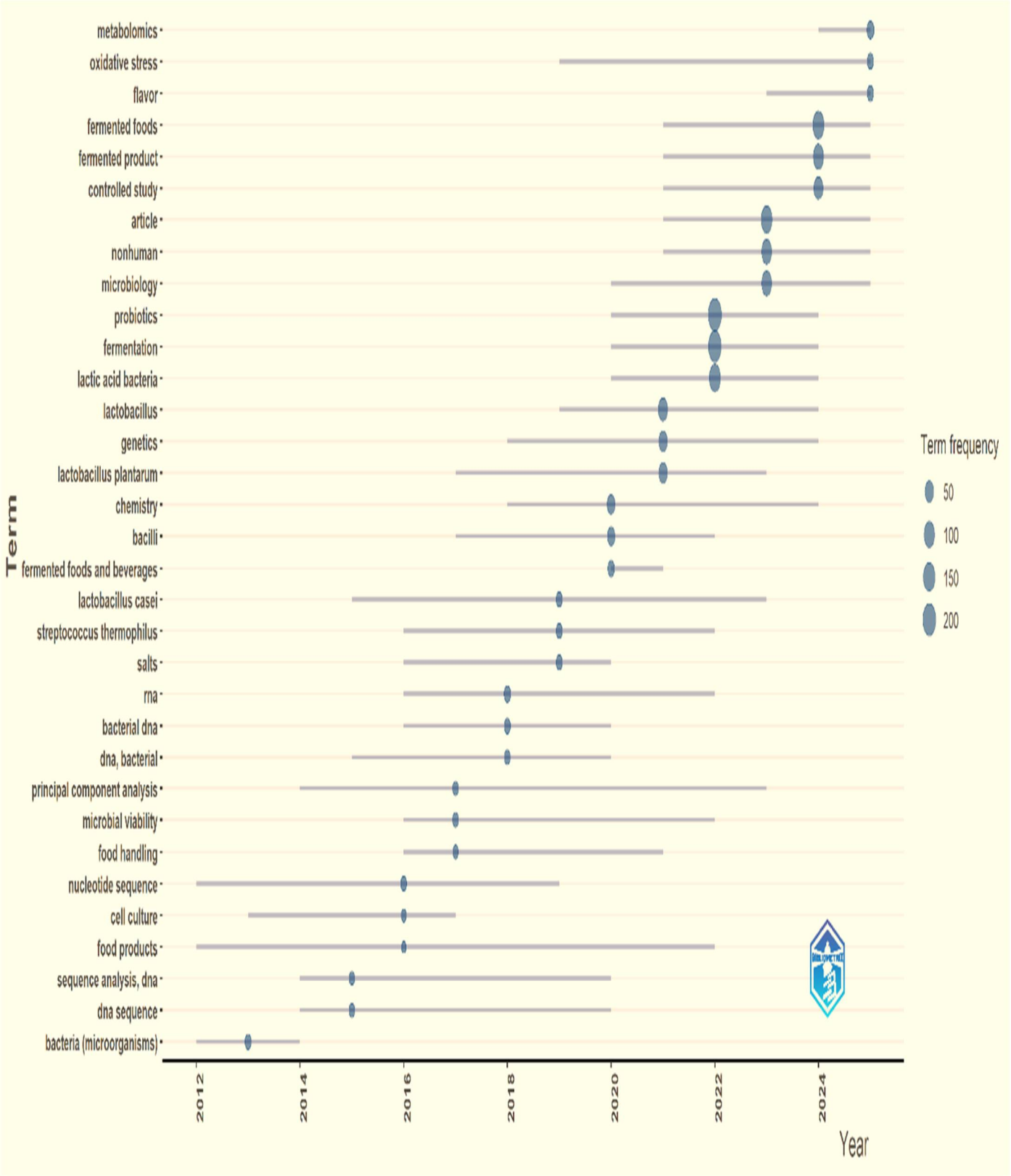

Figure 13. Trend topics in fermented food and gut health research, 2010–2025

Conceptual structure of fermented food and gut health research

The conceptual structure map (Figure 14) shows two principal dimensions, with the first explaining 66.75% and the second 20.64% of the variation. Food- and probiotic-oriented terms are connected with microbiological, metabolic, genetic, and human-related concepts. This broad conceptual space is consistent with increasing integration of food matrices, microbial communities, metabolites, and host-related outcomes, although the MCA represents keyword associations rather than biological relationships.

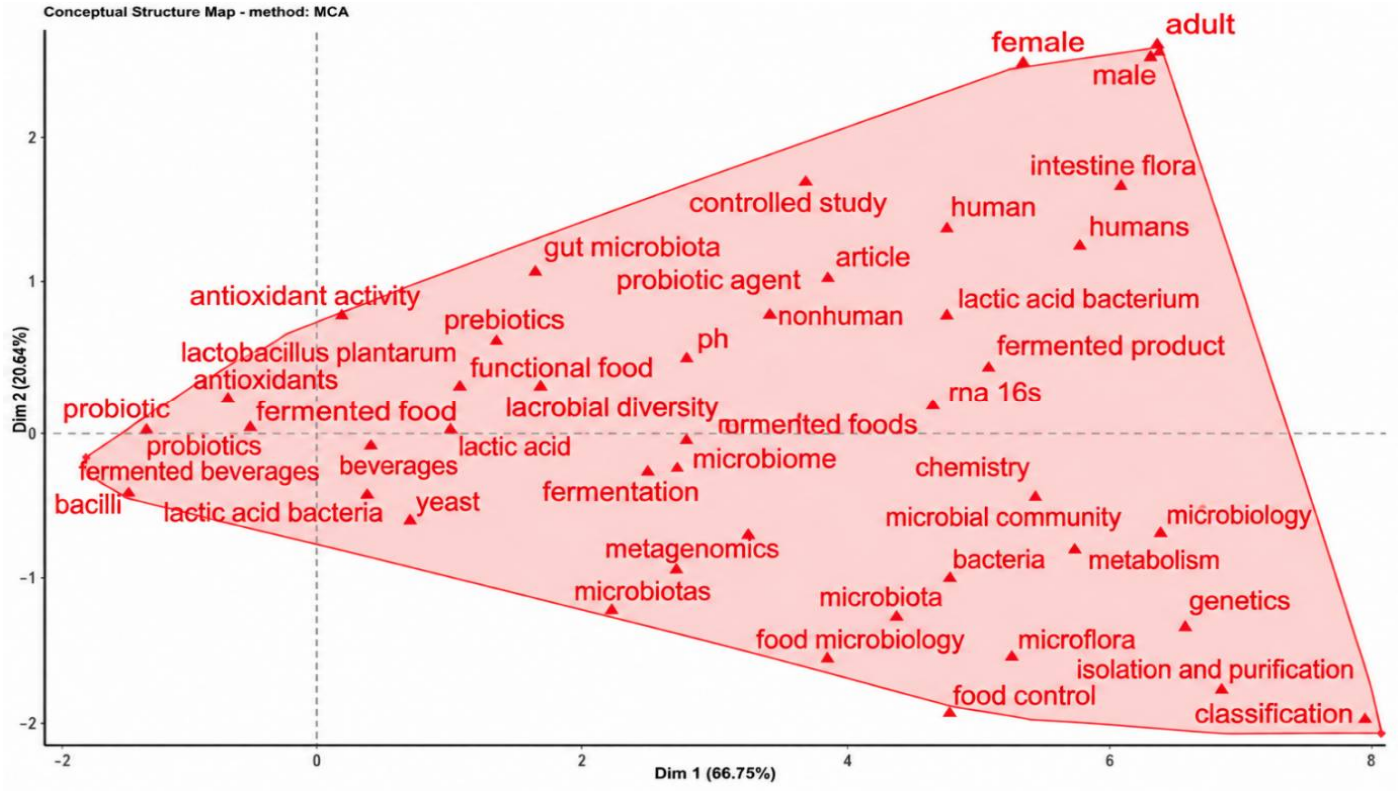

Figure 14. Conceptual Structure Map of Fermented Food and Gut Health Research, 2010–2025

Research gaps and innovation white-spaces

The integrated findings identify six potential areas for further development: (1) diversification of food matrices and geographic resources, including plant-based, indigenous, and region-specific fermented foods; (2) diversification of microbial and fermentation systems through novel strains, consortia, starter cultures, and process conditions; (3) stronger food–microbe–metabolite–gut integration; (4) deeper investigation of metabolites, bioactive compounds, and postbiotics; (5) mechanistic and human validation of gut-health effects; and (6) interdisciplinary and international collaboration linking food science, microbiology, nutrition, biotechnology, metabolomics, and gut-health research [2,9,20].

These white spaces are opportunity areas rather than proof that particular topics are absent or deficient. Underrepresentation can reflect terminology, indexing, funding, infrastructure, collaboration, or publication practices. The strongest opportunities therefore occur at intersections of established and emerging domains, such as fermentation and metabolomics, indigenous food matrices and microbial ecology, or fermented-food metabolites and defined gut-health outcomes. Experimental, mechanistic, human, safety, regulatory, intellectual-property, and market evidence remain necessary before an opportunity can be considered a validated technology.

DISCUSSION

From an expanding growth to an expanding knowledge architecture

The publication trajectory demonstrates expansion of fermented-food and gut-health research into a multidisciplinary field, particularly after 2020. The simultaneous growth of authors, countries, institutions, and thematic activity suggests broader participation as well as increased publication volume. Recent scholarship provides context through growing attention to fermented-food microbiomes, biotics, metabolites, and gastrointestinal mechanisms [2,12,15,18]. The bibliometric pattern itself does not establish why publication activity increased, but the convergence of these research directions is consistent with the observed broadening of the field.

Co-citation, three-field, thematic, and conceptual results collectively show a connected core centered on fermentation and fermented foods, with expanding links to probiotics, microorganisms, microbiota, metabolites, and health. Geographic and institutional concentration indicates that the indexed literature does not represent all fermented-food traditions equally. This is relevant because traditional fermented foods can contain distinctive microbial communities and metabolites shaped by local substrates and processes [14,21]. Less indexed representation should therefore be interpreted cautiously rather than equated with low scientific value.

Why the white spaces matter

A central opportunity is stronger integration among food matrices, microbial communities, fermentation-derived compounds, gut microbiota, and defined health outcomes. Multi-omics, metabolomics, microbial profiling, food chemistry, nutrition, and human studies can provide complementary evidence when coordinated within an appropriate design [8,19,22]. Such integration can help determine which food and fermentation characteristics are associated with specific microbial or metabolic responses and whether findings are reproducible across food systems and populations.

Indigenous and plant-based fermented foods also provide opportunities to broaden the evidence base. Traditional foods can provide microbial diversity and locally adapted substrates, while plant-based fermentation is increasingly investigated for product development and functional properties [23-25]. Diversification should, however, be accompanied by safety assessment, standardized characterization, process control, and appropriate human evidence. Likewise, interest in metabolites and postbiotics should not be equated with established health efficacy; these areas require mechanistic validation and well-designed interventions [9,26,27].

Operationalizing GAP-TO-GROWTH

GAP-TO-GROWTH converts bibliometric evidence into a structured sequence for research planning and innovation-oriented development. Performance analysis and science mapping establish the research landscape by identifying publication activity, intellectual relationships, geographic participation, thematic structures, and emerging research directions. These outputs inform the identification of dominant themes and established knowledge structures, followed by research gaps and underdeveloped connections characterized by emerging, fragmented, weakly connected, or geographically concentrated areas. These evidence-based gaps are then translated into potential innovation white spaces, which represent candidate areas where research themes, technologies, food matrices, microbial systems, metabolites, or health-related applications may intersect. Potential technology opportunities subsequently identify possible research or development responses, while the GAP-TO-GROWTH Innovation Pathways connect these opportunities to validation, collaboration, technology development, and downstream application.

The framework is intentionally iterative rather than linear. Candidate pathways require further experimental characterization, safety and quality assessment, mechanistic validation, human evaluation where appropriate, technology assessment, regulatory review, intellectual-property analysis, and market or sustainability assessment. New scientific findings, technological developments, regulatory changes, emerging research themes, and collaboration patterns can subsequently refine the identified gaps and innovation white spaces. Thus, GAP-TO-GROWTH does not represent a portfolio of validated technologies or establish technological, clinical, or commercial feasibility. Rather, it provides an evidence-informed bridge between bibliometric intelligence and subsequent research, validation, and innovation planning, with final technology or application decisions dependent on independent scientific and translational evidence.

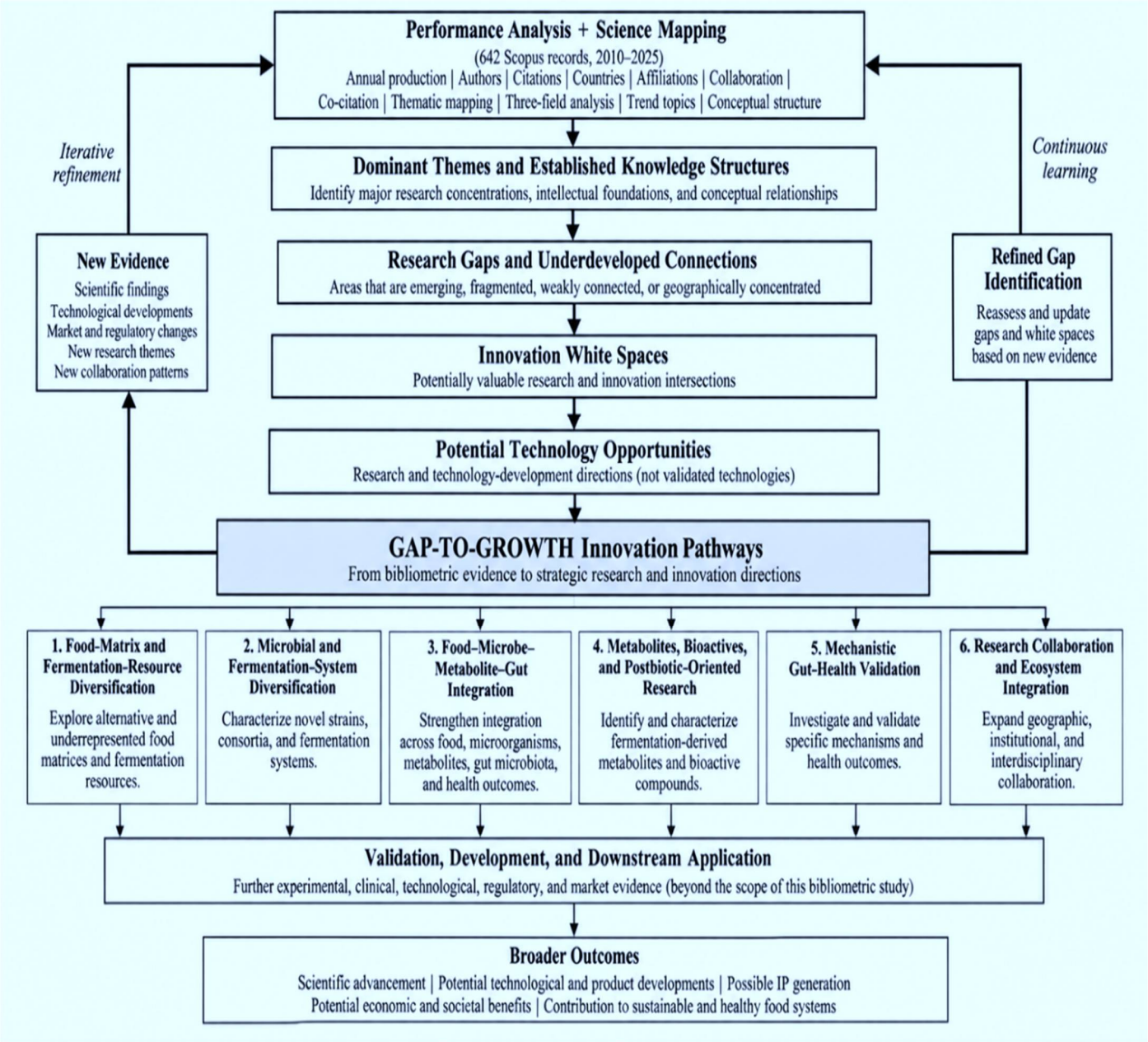

Figure 15. GAP-TO-GROWTH innovation pathways framework for fermented foods and gut health

Implications for research and policy

For researchers, the findings support study designs that integrate food characterization, microbial ecology, metabolomics, and health assessment. For institutions and funders, the geographic and institutional patterns can inform collaboration between established analytical centers and groups working with locally distinctive fermented foods and microbial resources. For innovation-support organizations and policymakers, the

framework can serve as a portfolio-planning tool for identifying candidate areas for feasibility studies, while independent requirements for safety, regulatory compliance, human evidence, intellectual-property assessment, and commercialization remain necessary.

Limitations

The study has several limitations. First, it used Scopus as the sole database; relevant records indexed in Web of Science, PubMed, regional databases, or other sources may therefore be absent. Second, the dataset was limited to English-language articles in Agricultural and Biological Sciences and to 2010–2025. Third, bibliometric findings are sensitive to search terms, indexing, keyword selection, author-name disambiguation, citation practices, and metadata completeness. Fourth, the search strategy may omit studies using different terminology while broad microbiome and biotic terms may introduce some heterogeneity requiring screening. Finally, bibliometric relationships describe patterns of scholarly production and association; they do not establish biological causality, health efficacy, technological performance, commercial viability, or societal impact.

CONCLUSION

Fermented-food and gut-health research expanded substantially from 2010 to 2025, developing into a multidisciplinary knowledge structure centered on fermentation and fermented foods, with increasing connections to probiotics, microorganisms, gut microbiota, metabolites, bioactive compounds, and health-related mechanisms. Bibliometric performance analysis and science mapping revealed potential innovation opportunities involving food-matrix and geographic diversification, indigenous fermentation resources, novel microbial and fermentation systems, food–microbe–metabolite–gut integration, metabolite and postbiotic research, mechanistic validation, and interdisciplinary collaboration. The GAP-TO-GROWTH Technology Innovation Pathways Framework translates these evidence patterns into a structured and iterative approach for identifying research gaps, innovation white spaces, potential technology opportunities, and subsequent validation pathways.

Future research should prioritize comparative characterization of underrepresented fermented foods; standardized microbial, metabolomic, and food-matrix profiling; integrated mechanistic studies; appropriately designed human interventions; and systematic safety, regulatory, sustainability, and technology assessments. Greater collaboration between established research centers and groups working with locally distinctive fermented foods may also broaden the geographic and biological representation of the evidence base. However, these priorities should be interpreted within the limitations of the Scopus-based dataset, English-language restriction, selected subject area, and search strategy. The identified gaps and opportunities therefore represent evidence-informed directions for further investigation rather than validated technologies, products, or established health interventions, and require independent experimental and translational evaluation before implementation or commercialization.

Ethical consideration, competing interest and source of funding

-This bibliometric analysis adheres to ethical research standards, ensuring responsible use of secondary data and full compliance with principles of integrity and transparency.
-There is no conflict of interest related to this publication.
-Source of funding is the authors.

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