

# Global Research Landscape and Evidence Gaps in Diet-Gut Microbiota Science: A Bibliometric and Integrated Data Analysis

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**Abstract: Background:** Dietary pattern-gut microbiota research has expanded rapidly over the past decade, driven by growing recognition of the gut microbiota as a key biological mediator linking diet to health. While substantial evidence has accumulated, the overall structure, balance, and global distribution of this evidence particularly its alignment with nutritional needs and progression toward mechanistic understanding remain insufficiently examined. **Methods:** We conducted a multi-level bibliometric and data-integrated analysis of dietary pattern-gut microbiota research published between 2010 and 2025 using the Web of Science Core Collection. Bibliometric indicators were combined with external measures of nutritional burden and data infrastructure to assess research output, collaboration patterns, thematic evolution, evidence depth, and cross-country evidence inequality. A composite Evidence Inequality Index and a joint growth citation framework were used to identify structural imbalances and emerging research gaps. **Results:** Annual publication output increased markedly over time, with a transition from exploratory growth to rapid expansion after 2018. Research activity and collaboration networks were highly centralized, with output concentrated in a small number of high-income countries and institutions. Globally, research output showed weak alignment with nutritional burden, with countries facing high undernutrition frequently under-represented in the literature. Evidence depth varied substantially even among countries with similar publication volume, reflecting uneven progression toward mechanistic and data-intensive research. Thematic analyses revealed stable core research areas alongside rapidly expanding topics characterized by limited citation consolidation, indicating transitional stages of evidence development rather than mature research cores. **Conclusions:** Dietary pattern-gut microbiota research is structurally imbalanced in relation to nutritional need, evidence depth, and thematic maturity. The proposed framework provides a basis for prioritizing more equitable and impactful research directions.

## 1. Introduction

The gut microbiota has emerged as a central biological system linking environmental exposures to host metabolic and immune regulation. Among these exposures, diet is one of the most potent and modifiable drivers of microbial composition and function. While early microbiome research focused largely on individual nutrients, growing evidence indicates that overall dietary patterns more accurately capture the cumulative dietary signals shaping microbial ecosystems in real world settings. From a microbiome perspective, dietary patterns represent integrated exposure profiles that influence microbial community structure, metabolic capacity, and host-microbe interactions. Dietary intervention studies incorporating metagenomics, metabolomics, and immune phenotyping have demonstrated that fibre-rich or fermented-food-based dietary patterns can induce coordinated changes in microbial function and downstream host responses<sup>[1-4]</sup>. Enabled by advances in high-throughput sequencing and systems-level analyses, diet-microbiota research has expanded rapidly over the past decade. However, alongside this growth, increasing heterogeneity in study designs, exposure definitions, analytical strategies, and

population contexts has raised important questions about how microbiome evidence in this domain is generated, structured, and consolidated.

Despite the rapid expansion of diet-gut microbiota research, relatively little attention has been paid to how the existing body of evidence is structured and distributed as a whole. Most studies focus on the effects of specific dietary patterns or interventions on gut microbiota profiles and related health outcomes, and both original research and reviews are typically framed around mechanistic findings, methodological advances, or intervention efficacy<sup>[5,6]</sup>. Much less is known about whether research contributions are evenly distributed across countries, institutions, and research themes, or whether available microbiome evidence is disproportionately derived from particular populations or research settings<sup>[7]</sup>. Although bibliometric approaches have been applied to map research hotspots and trends in gut microbiota research, existing analyses have largely focused on microbiota-disease relationships, such as obesity or insulin resistance, and have commonly summarised the literature using publication counts, citation metrics, or keyword clustering<sup>[8]</sup>. In contrast, dietary patterns as a key exposure in microbiome research have

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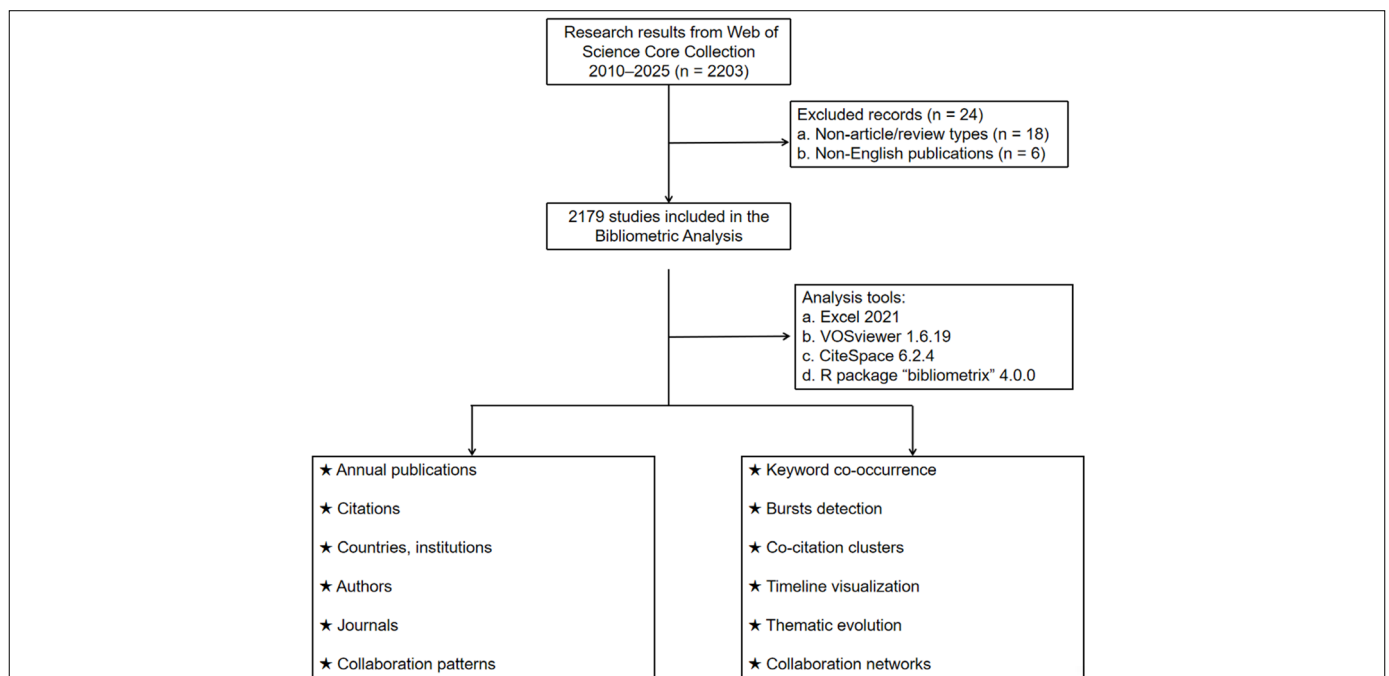
rarely been examined using a comprehensive bibliometric framework, particularly with respect to cross-national distribution, evidence depth, and alignment with global nutritional needs. From a microbiome perspective, this gap has important implications. The gut microbiota acts as a biological interface between dietary exposures and host health, and its composition and function are strongly shaped by long-term dietary habits, early-life nutrition, environmental conditions, and socio-economic context<sup>[9,10]</sup>. As a result, evidence linking dietary patterns to microbiome outcomes is highly context dependent<sup>[11-13]</sup>. If microbiome research on dietary patterns is drawn mainly from a small number of well-resourced settings with relatively homogeneous diets, the resulting mechanistic models and intervention frameworks may fail to capture the diversity of dietary exposures and microbial configurations that exist globally, particularly in populations affected by undernutrition or multiple nutritional burdens<sup>[14,15]</sup>. Without a systematic assessment of how evidence is distributed across regions, populations, and research themes, the generalisability of current diet-microbiota findings may therefore be overstated<sup>[16]</sup>. Evaluating the structural organisation of evidence in dietary pattern-gut microbiota research, and its alignment with global nutritional needs, is thus essential for guiding future research priorities. Current diet-gut microbiota research has generated a rapidly growing body of literature, yet how microbiome evidence in this field is structured and

represented across populations remains insufficiently understood. From a microbiome perspective, a central unresolved issue is whether accumulating research output has translated into broadly applicable mechanistic insight, or whether evidence generation remains concentrated in specific regions, dietary environments, and research settings. To address this gap, we conduct a multi-level assessment of the global evidence landscape of dietary pattern-gut microbiota research by integrating bibliometric analyses with indicators of nutritional burden and data infrastructure. This framework is used to characterise structural imbalances across countries and research themes and to identify areas where microbiome evidence remains context-limited or insufficiently consolidated.

## 2. Methods

### 2.1. Data Sources and Search Strategy

A comprehensive literature search was conducted on 15 December 2025 using the Web of Science Core Collection (WoSCC), specifically the Science Citation Index Expanded (SCI-E). To minimize potential bias introduced by database updates, all records were retrieved on the same day. The search strategy was designed to capture studies examining the relationships between



**Figure 1.** Flowchart of study design and bibliometric analysis workflow. The flowchart illustrates the literature retrieval, screening, and analytical framework of this study. Publications related to dietary pattern-gut microbiota research were retrieved from the Web of Science Core Collection (2010-2025). After exclusion of non-article/review document types and non-English records, a total of 2,179 studies were included for bibliometric analysis. Multiple analytical tools, including Excel, VOSviewer, CiteSpace, and the R package bibliometrix, were applied to examine publication trends, geographic and institutional contributions, author collaboration networks, journal and subject category distributions, keyword co-occurrence and burst patterns, reference co-citation structures, thematic evolution, and multi-center collaboration characteristics.

**Table 1. Detailed search strategy for literature retrieval from the Web of Science Core Collection (SCI-EXPANDED).**

Item	Description
Database	Web of Science Core Collection
Indexes searched	Science Citation Index Expanded (SCI-EXPANDED)
Search interface	Web of Science online platform
Search date	15-Dec-25
Time span	1 January 2010 - 15 December 2025
Document types	Article; Review
Language	English
Search fields	Topic (TS), including Title, Abstract, Author Keywords, and Keywords Plus
Search query	TS = (("dietary pattern" OR "diet patterns" OR "eating pattern" OR "diet quality" OR "diet quality score" OR "dietary score" OR "dietary index" OR "dietary diversity" OR "Mediterranean diet" OR "Western diet" OR "DASH diet" OR "plant-based diet" OR "ketogenic diet" OR "prudent diet") AND ("gut microbiome" OR "gut microbiota" OR "intestinal microbiome" OR "intestinal microbiota" OR "fecal microbiome" OR "fecal microbiota" OR microbiome OR microbiota OR "16S rRNA" OR "16S sequencing" OR metagenomic* OR "shotgun sequencing"))
Records retrieved	2,203

dietary patterns, the gut microbiome, and human health outcomes. A topic-based search (covering titles, abstracts, author keywords, and Keywords Plus) was applied using the following query: (“dietary pattern” OR “diet patterns” OR “eating pattern” OR “diet quality” OR “diet quality score” OR “dietary score” OR “dietary index” OR “dietary diversity” OR “Mediterranean diet” OR “Western diet” OR “DASH diet” OR “plant-based diet” OR “ketogenic diet” OR “prudent diet”) AND (“gut microbiome” OR “gut microbiota” OR “intestinal microbiome” OR “intestinal microbiota” OR “fecal microbiome” OR “fecal microbiota” OR microbiome OR microbiota OR “16S rRNA” OR “16S sequencing” OR metagenomic\* OR “shotgun sequencing”).

The publication time window was defined from 1 January 2010 to 15 December 2025. Only original research articles and review articles written in English were included. Conference abstracts, editorials, letters, and non-peer-reviewed records were excluded. The initial search yielded 2,203 records. After restricting to eligible document types and removing duplicate records, 2,179 publications were retained for subsequent bibliometric analyses. The detailed study selection process is illustrated in the PRISMA flow diagram (Figure 1). To ensure transparency and reproducibility, the complete Web of Science search strategy, including field specifications and query syntax, is provided in Table 1.

## 2.2. Inclusion and Exclusion Criteria

All records retrieved from the Web of Science Core Collection were screened independently by two reviewers based on titles and abstracts. Any discrepancies were resolved through discussion until consensus was reached. Studies were included if they met all of the following criteria:

(1) The study examined dietary patterns, diet quality indices, or predefined dietary models (e.g., Mediterranean, Western, DASH, or plant-based diets) as the primary exposure of interest;

(2) The study evaluated associations between dietary exposures and the gut microbiome, including microbial composition, diversity, or functional characteristics;

(3) The study reported outcomes related to human health or physiological status;

(4) The publication was an original research article or a review article written in English and indexed in the Science Citation Index Expanded (SCI-EXPANDED).

Studies were excluded if they met any of the following criteria:

(1) Dietary patterns or the gut microbiome were mentioned only tangentially without substantive analytical focus;

(2) The study was based exclusively on animal or *in vitro* models without direct relevance to human dietary patterns or human microbiome research;

(3) The publication type was an editorial, commentary, letter, conference abstract, book chapter, correction, or other non-peer-reviewed material;

(4) Duplicate records identified during the data cleaning process were removed prior to analysis.

## 2.3. Data Extraction and Processing

Bibliographic records were exported from the Web of Science Core Collection in plain-text and tab-delimited formats, including information on article titles, authors, author affiliations, publication years, journals, citation counts, keywords, and cited references. Data processing and cleaning were conducted prior to bibliometric analysis to ensure consistency and accuracy. Duplicate records within the Web of Science dataset were identified and removed based on DOI matching and exact title comparison. Author names and institutional affiliations were standardized to reduce inconsistencies caused by spelling variations and abbreviation differences. Keyword harmonization was performed by merging synonymous and semantically equivalent terms (e.g., “gut microbiota” and “intestinal microbiota”) and unifying plural or variant expressions. Document types were verified to ensure inclusion criteria were met, and records not classified as original articles or review articles were excluded. After data cleaning and standardization, a final dataset comprising 2,179 publications was obtained and used for all subsequent bibliometric, network, and visualization analyses.

## 2.4. Bibliometric Analysis and Visualization Tools

Bibliometric analyses were conducted using CiteSpace (version 6.3.R4), VOSviewer (version 1.6.20), and R software with the Bibliometrix package (version 4.2.1). CiteSpace was primarily used for reference co-citation analysis, cluster identification and labeling, citation burst detection, timeline visualization, and temporal network analysis. The time slicing was set from 2010 to 2025 with a one-year per slice interval. Network pruning was

performed using the Pathfinder algorithm and pruning of sliced networks to highlight the most salient structural relationships. VOSviewer was employed to construct co-authorship networks, as well as country-level and institutional collaboration maps, and keyword co-occurrence networks. Full counting was applied for collaboration and keyword analyses, and association strength normalization was used to calculate link weights. The Bibliometrix package in R was used to compute descriptive scientometric indicators, analyze annual publication trends, examine thematic evolution over time, and generate conceptual structure maps based on keyword co-occurrence patterns. All visualizations were exported in high-resolution TIFF or PDF formats to ensure publication-quality graphical output.

## 2.5. Quantification of Evidence Inequality

To quantify cross-country disparities in the availability and depth of evidence linking dietary patterns to the gut microbiome, we constructed a composite Evidence Inequality Index (EII). The index integrates four complementary dimensions capturing research volume, contextual relevance, and evidentiary depth: (i) research output, (ii) alignment with nutritional need, (iii) mechanistic evidence, and (iv) data infrastructure. Research output was defined as the total number of publications attributed to each country, normalized by national population size and expressed as publications per million population. Country attribution was based on author affiliation information, and population data were obtained from publicly available international demographic databases. Nutritional need was represented by nationally reported indicators of undernutrition. For analyses presented in Figure 5, adult undernourishment prevalence and child stunting prevalence were used as complementary indicators to capture population-level nutritional vulnerability. Alignment with nutritional need was operationalized by comparing observed research output with the expected output predicted from the overall empirical relationship between research output (log-transformed publications per million population) and national undernutrition prevalence. Expected values were estimated using a global regression model, and the residual (observed minus predicted output) was used to quantify the degree of misalignment for each country, with larger positive residuals indicating greater divergence between research activity and nutritional need. Mechanistic evidence was quantified as the proportion of publications from each country that explicitly investigated biological mechanisms linking dietary exposures to microbiome-mediated host processes, including microbial functional pathways, metabolites, or experimentally supported causal relationships. Operationally, a publication was classified as mechanistic if its title, abstract, or author keywords contained explicit reference to at least one of the following: microbial metabolic pathways (e.g., short-chain fatty acid production, bile acid metabolism, tryptophan catabolism), host–microbe signalling mechanisms (e.g., gut barrier function, immune modulation, gut–brain axis), or experimentally validated causal relationships between dietary exposures and microbiome-mediated host responses (e.g., dietary intervention with functional outcome measurement). Publications reporting only compositional or diversity associations between diet and microbiota, without addressing underlying biological mechanisms, were not classified as mechanistic. To ensure robustness, this metric was calculated only for countries contributing at least 50 publications to the dataset.

Data infrastructure was approximated by the proportion of studies from each country employing longitudinal designs, interventional frameworks, or multi-dimensional datasets (e.g., multi-omics or repeated-measure microbiome data), reflecting the capacity to generate temporally and mechanistically informative evidence. All component measures were standardized to a common scale prior to aggregation. The four dimensions were equally weighted and summed to generate the composite Evidence Inequality Index, with higher index values indicating greater disparity between research evidence availability and underlying nutritional need. Equal weighting was adopted in the absence of an established theoretical basis for prioritising any single dimension over others, and is consistent with standard practice in composite index construction where component dimensions are considered conceptually equivalent contributors to the underlying construct.

## 2.6. Identification of Emerging Research Gaps

To identify emerging gaps in diet-microbiota research, thematic topics were first derived from keyword co-occurrence networks generated from the cleaned bibliographic dataset. Topics corresponded to clusters of semantically related keywords identified through co-occurrence-based community detection, with each topic representing a coherent research theme. For each topic, publication growth was quantified as the absolute change in the number of publications between an early reference period (2010–2014) and a recent period (2020–

2025). Citation depth was defined as the mean number of citations per article accumulated during the recent period (2020-2025), reflecting the degree of scholarly attention and impact associated with each topic.

Topics were mapped into a two-dimensional growth-depth space, with publication growth on the x-axis and citation depth on the y-axis. Median values of growth and citation depth across all topics were used as cutoffs to divide the space into four quadrants. Topics located in the high-growth but low-depth quadrant were classified as emerging research gaps, indicating rapidly expanding research activity that has not yet translated into proportional citation impact or conceptual consolidation. To enhance interpretability, topic labels were generated using a curated set of biologically relevant keywords with the highest within-topic frequencies. Generic methodological terms, dataset identifiers, and analytical descriptors (e.g., sequencing platforms or statistical methods) were excluded from topic labeling to ensure conceptual clarity. For contextual comparison, three representative topics located in the high-growth and high-depth quadrant were annotated as established research hotspots. In the visualization, bubble size was scaled to reflect the total number of publications for each topic during the recent period (2020-2025).

## 2.7. Data Availability and Limitations

All bibliographic data analyzed in this study were retrieved from the Web of Science Core Collection (Science Citation Index Expanded). Due to database licensing restrictions, the raw bibliographic records exported from Web of Science cannot be publicly shared. However, the search strategy, data processing procedures, and analytical framework are described in sufficient detail to allow replication by readers with authorized access to the database. Several limitations should be acknowledged. First, this study was restricted to publications indexed in the Web of Science Core Collection and written in English. Consequently, relevant studies published in regional journals, non-English outlets, or emerging dissemination formats such as preprints were not included, which may have introduced selection bias and led to an underrepresentation of research output from certain regions. Second, as a bibliometric and evidence-mapping study, the analyses were based on published literature rather than primary experimental or clinical data. Measures such as mechanistic evidence and data infrastructure were operationalized using information available within bibliographic records and study designs, which may not fully capture the depth or quality of underlying experimental work. These limitations should be considered when interpreting cross-country comparisons and evidence inequality patterns.

## 2.8. Ethical Considerations

This study was based exclusively on publicly available bibliographic information and did not involve human participants, individual-level data, or animal experimentation. Therefore, ethical approval and informed consent were not required.

## 2.9. Clinical trial number

not applicable.

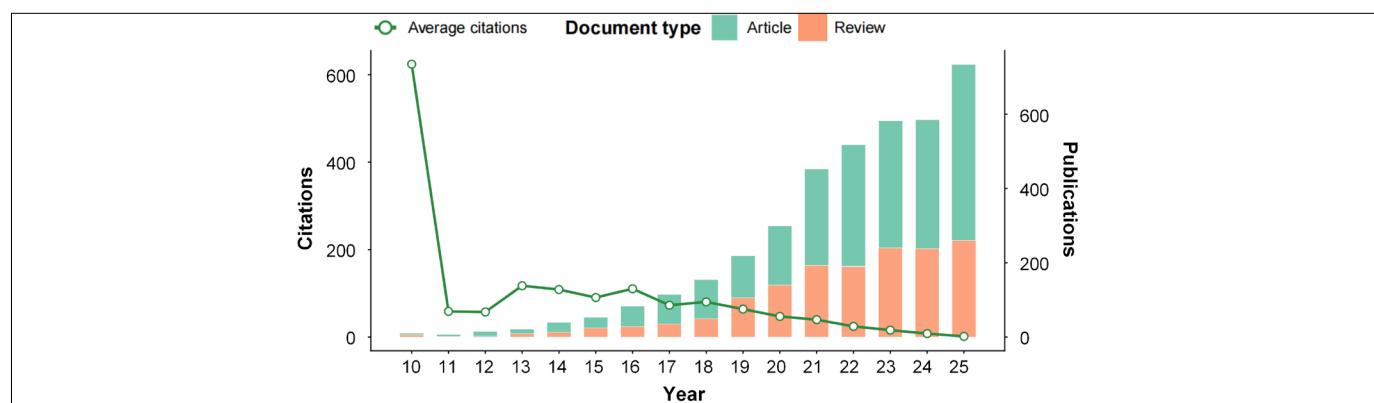
## 3. Results

### 3.1. Research ecosystem and publication dynamics

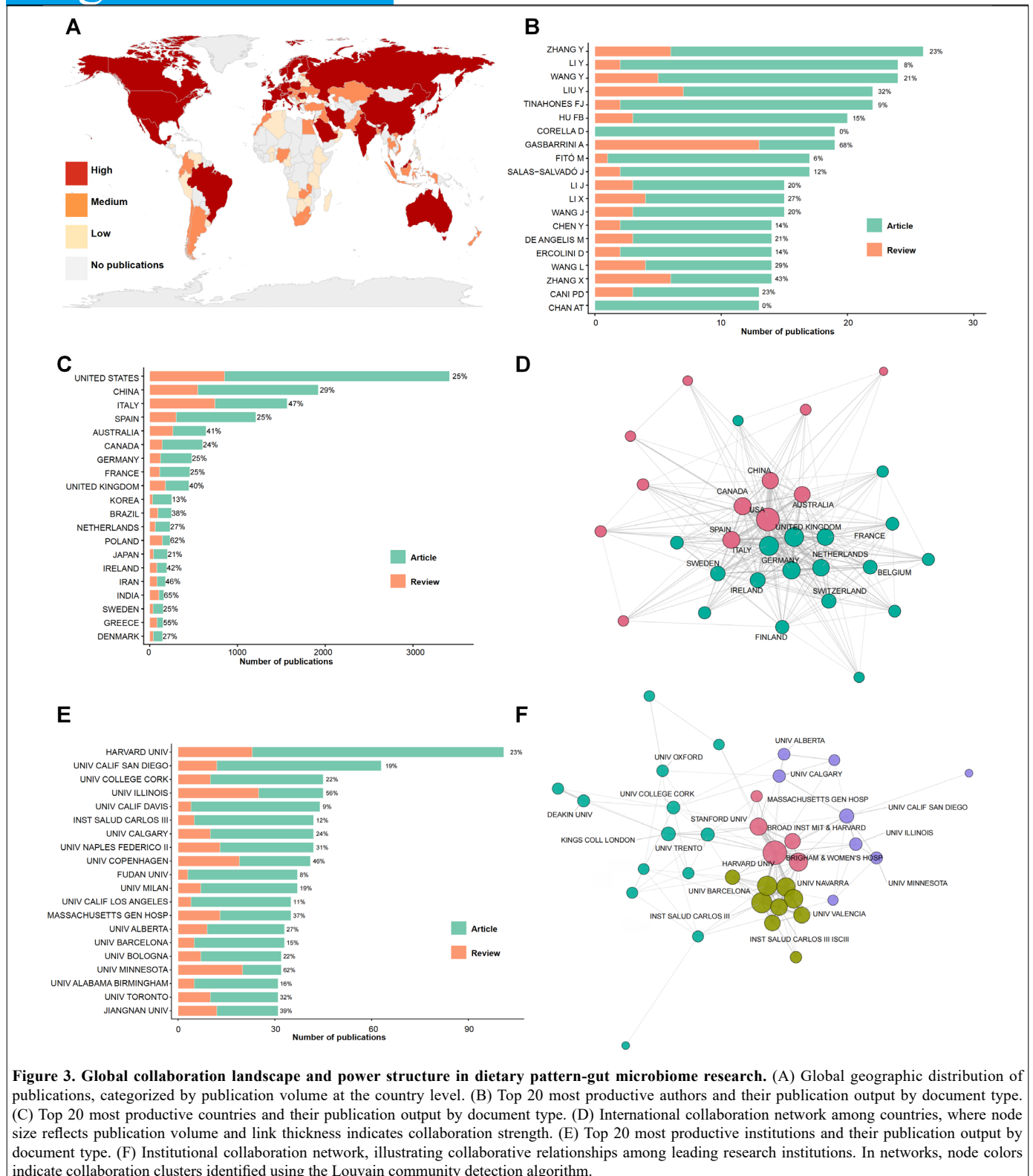
As shown in Figure 2, research on dietary pattern-gut microbiome relationships demonstrated a pronounced and sustained increase in annual publication output from 2010 to 2025, accompanied by distinct phase-specific dynamics. During the initial period from 2010 to 2014, annual publication output remained low and relatively stable, reflecting an exploratory stage characterized by dispersed research efforts and limited cumulative momentum. From 2015 onward, publication output began to increase steadily, indicating growing and more consistent scholarly engagement with this research area. After 2018, the growth rate accelerated markedly, with annual publication counts rising rapidly and reaching their highest level by 2025. This acceleration suggests a transition from gradual development to a phase of rapid expansion and consolidation of research activity. Throughout the study period, original research articles constituted the majority of publications and were the principal driver of overall growth. At the same time, the number of review articles increased progressively, leading to a higher relative contribution of reviews in recent years. This shift reflects the maturation of the field, with accumulating empirical evidence prompting greater demand for synthesis, integration, and conceptual framing. In contrast to the increasing volume of publications, the temporal pattern of average citations per publication followed an inverse trajectory. In the early years, when publication numbers were limited, average citation counts per article were relatively high, likely reflecting concentrated scholarly attention on a small number of foundational studies. As publication output expanded rapidly over time, the average number of citations per publication declined and stabilized at a lower level in more recent years. This divergence between output growth and average citation impact indicates that scholarly attention has become increasingly distributed across a larger and more heterogeneous body of literature.

### 3.2. Collaboration patterns and power structure

Analysis of collaboration patterns revealed a highly uneven and centralized research ecosystem in dietary pattern-gut microbiome studies, with pronounced concentration observed at the geographic, national, institutional, and author levels (Figure 3). At the global level, research output was predominantly concentrated in North America, Europe, and selected Asia-Pacific countries (Figure 3A). These regions occupied central positions in the global publication landscape, whereas large areas of Africa, South America, and parts of Asia contributed relatively few publications, highlighting substantial geographic disparities in research participation and output. At the author level, a small group of highly productive researchers accounted for a disproportionate share of publications (Figure 3B). Marked heterogeneity was observed in both publication volume and document type composition among leading authors, with some authors primarily contributing original research articles and others showing a comparatively higher proportion of review publications. This pattern suggests differentiated roles in knowledge generation and synthesis within the field. At the country level, the top 20 most productive countries contributed the majority of publications in this research area (Figure 3C). A limited number of countries dominated both original research and review output, indicating sustained investment, established research infrastructure, and long-term academic influence. International collaboration network analysis further demonstrated that these high-output



**Figure 2. Annual publication output, document type distribution, and average citations in dietary pattern-gut microbiome research (2010-2025).** Stacked bars indicate the annual number of publications by document type (articles, reviews). The line represents the average number of citations per publication for each year. Data were retrieved from the Web of Science Core Collection.



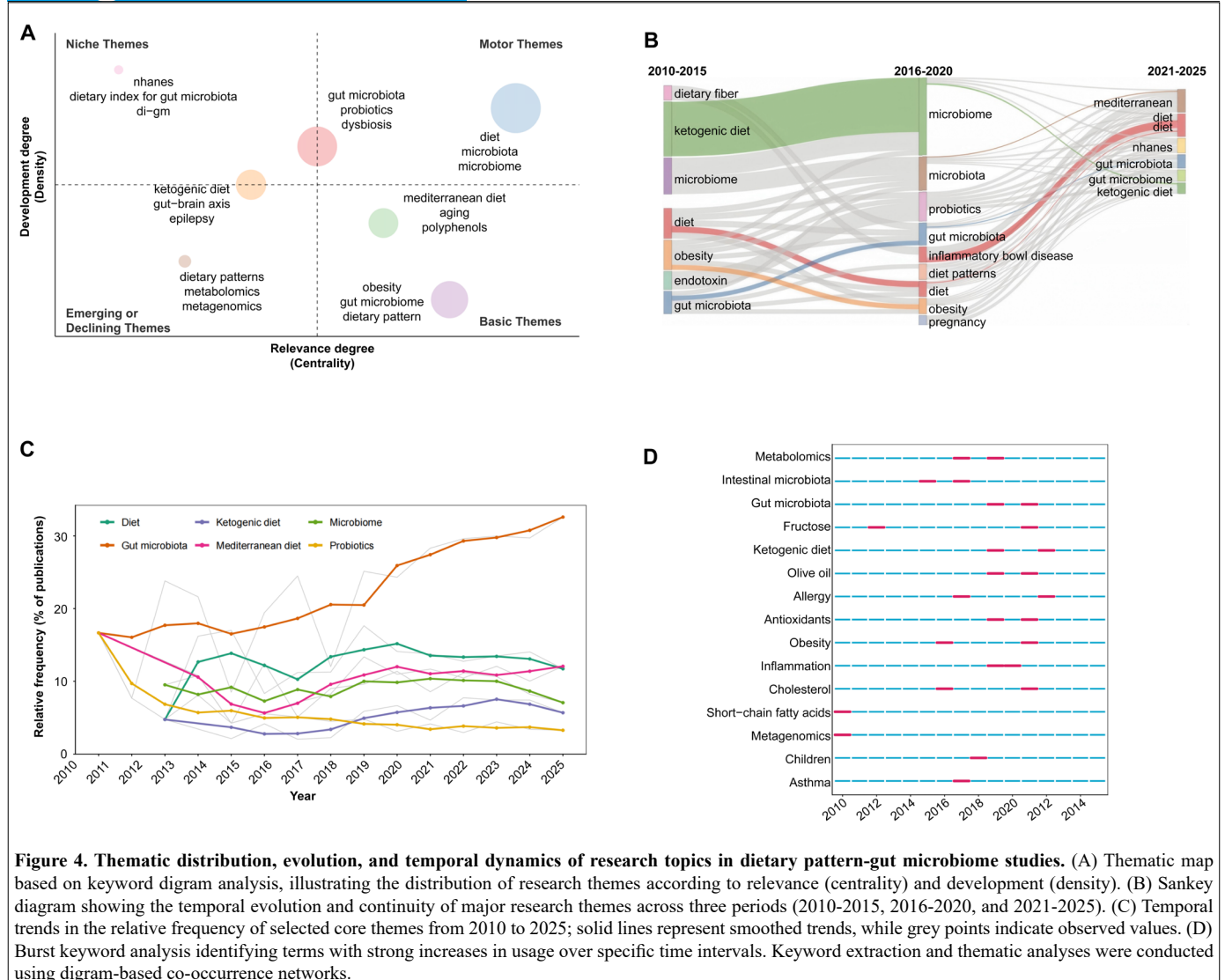
**Figure 3. Global collaboration landscape and power structure in dietary pattern-gut microbiome research.** (A) Global geographic distribution of publications, categorized by publication volume at the country level. (B) Top 20 most productive authors and their publication output by document type. (C) Top 20 most productive countries and their publication output by document type. (D) International collaboration network among countries, where node size reflects publication volume and link thickness indicates collaboration strength. (E) Top 20 most productive institutions and their publication output by document type. (F) Institutional collaboration network, illustrating collaborative relationships among leading research institutions. In networks, node colors indicate collaboration clusters identified using the Louvain community detection algorithm.

countries formed a densely connected core, characterized by strong bilateral and multilateral collaborations, while many lower-output countries occupied peripheral positions with weaker or fewer collaborative links (Figure 3D). A similar concentration pattern was observed at the institutional level. The most productive institutions were primarily located in high-output countries (Figure 3E), and institutional collaboration networks exhibited a hierarchical structure in which a small number of institutions functioned as central hubs connecting multiple collaboration clusters (Figure 3F). In contrast, many institutions participated in the network through limited or indirect collaborative ties. Taken together, analyses across authors, countries, and

institutions consistently indicate that both research output and collaborative activity in dietary pattern-gut microbiome research are characterized by strong centralization and unequal participation, resulting in a stratified research ecosystem with clearly differentiated core and peripheral actors.

### 3.3. Distribution and evolution of research themes

Digram-based keyword analysis (a co-occurrence network constructed from keyword pairs, as implemented in the bibliometrix package) revealed a clearly structured thematic landscape in dietary pattern-gut microbiome research,



**Figure 4. Thematic distribution, evolution, and temporal dynamics of research topics in dietary pattern-gut microbiome studies.** (A) Thematic map based on keyword digram analysis, illustrating the distribution of research themes according to relevance (centrality) and development (density). (B) Sankey diagram showing the temporal evolution and continuity of major research themes across three periods (2010-2015, 2016-2020, and 2021-2025). (C) Temporal trends in the relative frequency of selected core themes from 2010 to 2025; solid lines represent smoothed trends, while grey points indicate observed values. (D) Burst keyword analysis identifying terms with strong increases in usage over specific time intervals. Keyword extraction and thematic analyses were conducted using digram-based co-occurrence networks.

characterized by systematic differentiation along dimensions of thematic relevance (centrality) and internal development (density) (Figure 4A). Themes centered on diet-microbiota-microbiome occupied the high-centrality and high-density quadrant, indicating their role as core driving themes that anchor the overall research field. In contrast, themes such as obesity-gut microbiome-dietary pattern exhibited high relevance but comparatively lower internal development, positioning them as basic themes that are strongly connected to the broader research landscape but remain less conceptually consolidated. Meanwhile, specialized themes including dietary index for gut microbiota displayed relatively high internal development but limited connectivity with other topics, suggesting focused yet comparatively isolated research directions. Themes related to dietary patterns-metabolomics-metagenomics were located in regions of both low relevance and low development, indicating a peripheral position within the thematic structure during the study period.

Analysis of thematic evolution across successive time periods revealed both continuity and adaptive reconfiguration of research focus (Figure 4B). During the early phase (2010-2015), research attention was largely concentrated on specific dietary components and their associations with the gut microbiome. In the intermediate phase (2016-2020), themes related to microbiota, gut microbiota, and probiotics emerged as central organizing concepts, demonstrating strong continuity with earlier dietary-focused themes. In the most recent phase (2021-2025), these core themes persisted while branching into multiple diet-related and microbiome-related subthemes, reflecting thematic diversification built upon a stable conceptual foundation. Temporal trend analysis further highlighted marked heterogeneity in the trajectories of thematic attention over time (Figure 4C). Themes related to gut microbiota showed a sustained and progressive increase in relative frequency throughout the study period and remained dominant in recent years. By contrast, themes

such as diet and Mediterranean diet exhibited more gradual strengthening during the middle and later stages, whereas probiotics and certain intervention-oriented themes showed comparatively modest temporal variation. Smoothed trend patterns indicated that thematic prominence evolved asynchronously across topics rather than following a uniform temporal trajectory.

Burst keyword analysis provided additional insight into short-term dynamics within the broader thematic evolution (Figure 4D). Several keywords exhibited pronounced bursts during specific time intervals, many of which were associated with mechanistic pathways (e.g., short-chain fatty acids, metabolomics) or targeted dietary interventions (e.g., ketogenic diet). The timing of these bursts largely aligned with phases of thematic reorganization identified in the evolution analysis, indicating periods of intensified focus on specific mechanisms or intervention strategies. Collectively, these results indicate that while a set of core themes has maintained sustained centrality over time, the field has undergone continuous differentiation and realignment, producing a dynamically evolving thematic landscape characterized by stable foundations alongside episodic innovation.

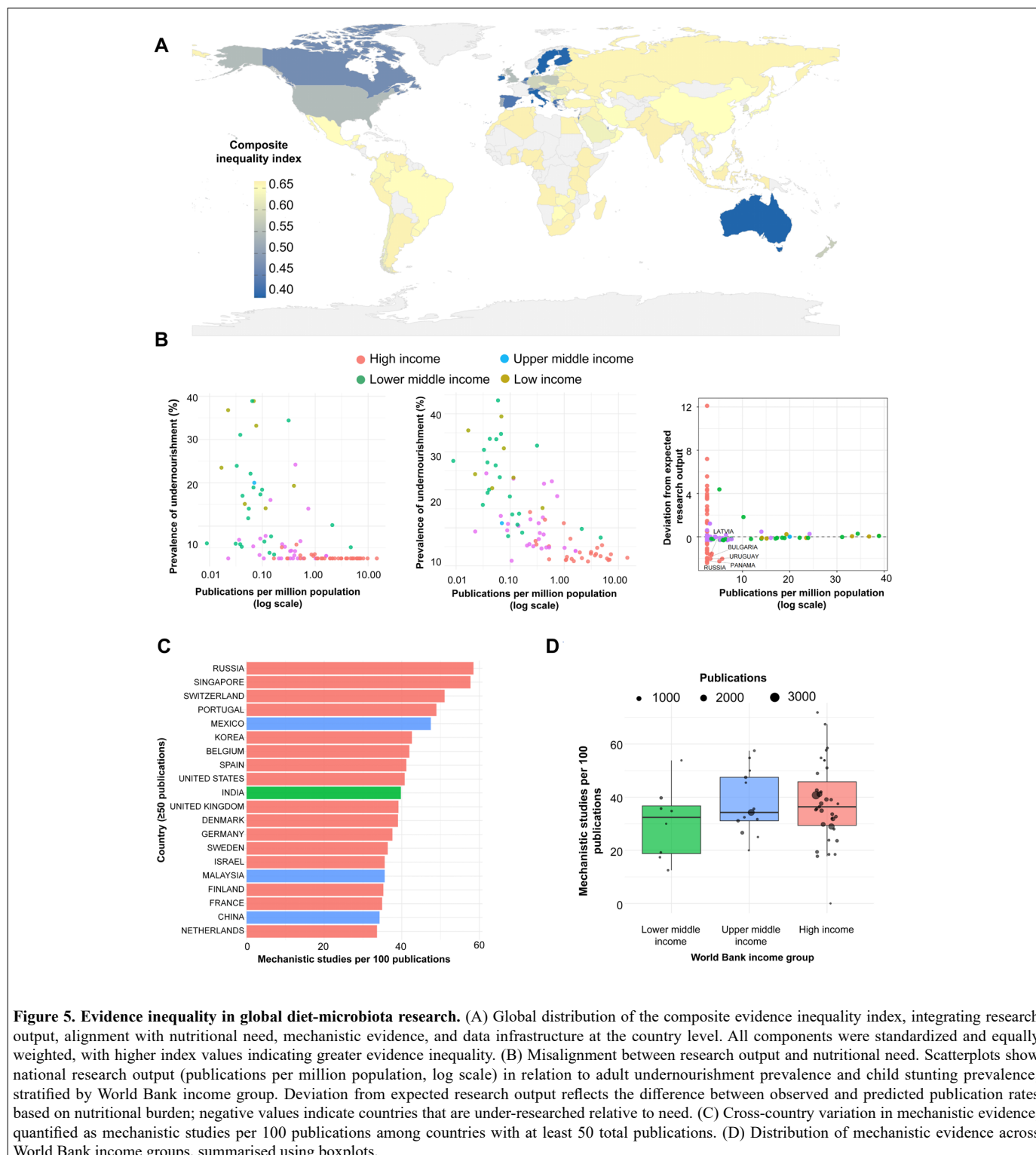
### 3.4. Evidence inequality in global diet-microbiota research

Analyses based on the composite Evidence Inequality Index revealed pronounced and geographically structured disparities in the generation of diet-microbiota research evidence across countries (Figure 5A). Evidence inequality was not uniformly distributed but instead showed clear clustering by region and income level. In general, high-income countries tended to exhibit lower composite inequality scores, whereas many low- and middle-income countries displayed substantially higher levels of evidence inequality, reflecting persistent gaps in evidence generation. Importantly, these disparities

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were not driven by research output volume alone. Examination of the relationship between research output and nutritional burden demonstrated a systematic misalignment between scientific activity and population-level need (Figure 5B). Countries with a high prevalence of adult undernourishment or child stunting frequently exhibited low publication output per million population, while several countries with relatively low nutritional burden showed disproportionately high research output. This pattern was observed across World Bank income groups, indicating that misalignment between research activity and nutritional need is a widespread structural feature rather than a phenomenon confined to a specific economic stratum. Deviation analysis further highlighted countries whose observed research output fell substantially below levels expected based on their nutritional

burden (Figure 5B, right). Negative deviations were particularly evident among countries with high undernutrition prevalence, identifying settings that are systematically under-represented in the literature when contextualized by need. Together, these results indicate that global research activity does not scale proportionally with nutritional vulnerability. Beyond misalignment in research volume, marked heterogeneity was observed in the depth of evidence generated across countries. Among countries with comparable overall publication volumes, the proportion of studies explicitly addressing biological mechanisms varied widely, ranging from fewer than 20 to more than 60 mechanistic studies per 100 publications (Figure 5C). This variability indicates substantial cross-country differences in the extent to which research advances beyond descriptive associations toward mechanistic understanding.



**Figure 5. Evidence inequality in global diet-microbiota research.** (A) Global distribution of the composite evidence inequality index, integrating research output, alignment with nutritional need, mechanistic evidence, and data infrastructure at the country level. All components were standardized and equally weighted, with higher index values indicating greater evidence inequality. (B) Misalignment between research output and nutritional need. Scatterplots show national research output (publications per million population, log scale) in relation to adult undernourishment prevalence and child stunting prevalence, stratified by World Bank income group. Deviation from expected research output reflects the difference between observed and predicted publication rates based on nutritional burden; negative values indicate countries that are under-researched relative to need. (C) Cross-country variation in mechanistic evidence, quantified as mechanistic studies per 100 publications among countries with at least 50 total publications. (D) Distribution of mechanistic evidence across World Bank income groups, summarised using boxplots.

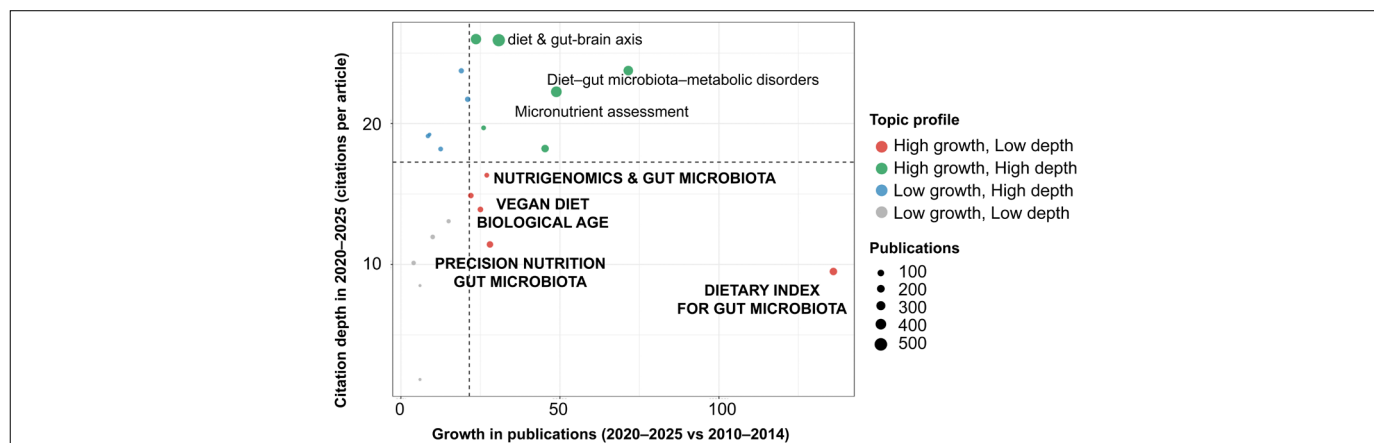
Stratification by World Bank income group revealed that inequality in mechanistic evidence persisted across economic contexts (Figure 5D). While high-income countries generally exhibited higher median levels of mechanistic evidence, considerable dispersion was observed within all income groups, particularly among middle-income countries. This finding suggests that economic classification alone does not fully account for disparities in evidentiary depth. Collectively, these results demonstrate that global inequities in diet-microbiota research are multidimensional. Evidence inequality extends beyond disparities in publication volume to encompass systematic misalignment with nutritional need and uneven generation of mechanistic evidence, resulting in a fragmented global evidence base that is least developed in settings with the greatest nutritional burden.

### 3.5. Joint analysis of topic growth and citation depth reveals structural research gaps

A joint analysis of publication growth and citation depth was conducted to identify structural imbalances and emerging gaps within diet-gut microbiota research. By positioning individual research topics according to recent growth in publication volume and mean citation depth, topics could be systematically classified into distinct developmental profiles (Figure 6). Overall, substantial heterogeneity was observed across topics, indicating that rapid expansion in research output does not necessarily translate into proportional accumulation of influential or widely cited evidence. Topics located in the high-growth but low-citation depth quadrant exhibited marked increases in publication activity accompanied by comparatively limited citation impact. These topics constitute

a prominent subset of the current research landscape and represent emerging research gaps, where scientific attention has expanded faster than evidence consolidation. Notably, many of these topics were related to dietary indices for gut microbiota, precision nutrition, vegan or alternative dietary patterns, and biologically oriented aging metrics. This pattern suggests that a considerable proportion of recent research activity has focused on methodological innovation or descriptive characterization, while robust mechanistic validation and longitudinal evidence remain relatively underdeveloped (Figure 6).

In contrast, a smaller group of topics occupied the high-growth and high-citation depth quadrant, reflecting concurrent increases in publication volume and scholarly impact. These topics were predominantly associated with nutrigenomics, diet-microbiota functional interactions, and the gut-brain axis, indicating the emergence of more integrated and conceptually mature research directions that have achieved sustained recognition within the scientific community (Figure 6). Additional topics were positioned in low-growth quadrants, either with relatively high citation depth or limited impact, suggesting research directions that are either conceptually established but no longer rapidly expanding, or peripheral themes that have attracted limited attention over time. Taken together, the growth-depth framework reveals pronounced disparities in the developmental trajectories of diet-gut microbiota research topics. While some areas have achieved balanced growth and impact, a substantial fraction of rapidly expanding topics remain characterized by shallow citation depth, underscoring the need for deeper mechanistic investigation, longitudinal study designs, and integrative approaches to consolidate emerging lines of research.



**Figure 6. Emerging research gaps in diet-microbiota research.** Each bubble represents a research topic positioned by publication growth (2020-2025 vs 2010-2014) and citation depth (mean citations per article, 2020-2025). Dashed lines denote median values dividing topics into four quadrants. Topics with high growth but low citation depth were classified as emerging research gaps. Selected emerging-gap topics are labelled using biologically relevant keywords. Representative high-growth/high-depth topics are shown for reference. Bubble size indicates recent publication volume.

## 4. Discussion

This study provides a structured assessment of the global evidence landscape in dietary pattern-gut microbiota research and demonstrates that inequality in this field is fundamentally multidimensional and structural in nature. By integrating bibliometric indicators with measures of nutritional need, evidentiary depth, and thematic development, our analyses reveal that disparities in this research domain extend beyond the uneven distribution of publication output to encompass systematic differences in how evidence is generated, consolidated, and advanced across countries, institutions, and research themes. Research activity is highly concentrated within a limited set of high-income countries, yet this concentration shows weak alignment with the global distribution of nutritional burden. Even among entities with comparable publication volume, marked variation exists in the proportion of mechanistic and data-intensive studies, indicating that evidence inequality in dietary pattern-gut microbiota research is driven not only by how much research is produced, but also by the stage and structure of knowledge development. At the thematic level, joint analysis of publication growth and citation depth further reveals the coexistence of mature research cores alongside rapidly expanding but weakly consolidated topic areas. Together, these patterns indicate that evidence inequality in this field reflects a structural configuration of the global research ecosystem that cannot be adequately captured by single-dimensional metrics.

Our analysis reveals a persistent mismatch between research output and nutritional burden, which reflects the structural organisation of the global research system rather than a lack of scientific concern for undernutrition-related issues. Previous studies have consistently shown that research funding, advanced infrastructure, and capacity for high-impact publication remain highly concentrated in a limited number of high-income countries, a distribution that does not align with the global geography of disease or nutritional burden<sup>[17,18]</sup>. As a result, the spatial pattern of research activity is strongly shaped by institutional capacity, funding availability, and international collaboration networks, all of which are predominantly anchored in high-income settings<sup>[19]</sup>. Consequently, countries facing substantial nutritional burden may generate relatively low research output despite clear public health need, owing to structural and institutional constraints. In many high-burden contexts, undernutrition-related research is oriented toward programme implementation, monitoring, or policy reporting, with outputs that do not conform to the publication formats prioritised by leading international journals. Such work including evaluations conducted by governments or international organisations, national surveillance reports, and technical documents produced by non-governmental organisations plays a critical role in practice but is systematically under-represented in bibliometric analyses based on major literature databases<sup>[20,21]</sup>. Similar decoupling between disease burden and research output has been documented across multiple areas of global health,

reflecting a broader and persistent misalignment between research investment priorities and epidemiological need<sup>[22]</sup>. Within the context of dietary pattern-gut microbiota research, this structural bias implies that existing evidence disproportionately reflects populations living in well-nourished environments, while contexts characterised by undernutrition remain under-represented, thereby constraining the global applicability and external validity of current findings for nutrition research and practice.

Beyond differences in publication volume, our analysis reveals pronounced cross-country and cross-institutional variation in the depth and structure of evidence generation. This pattern cannot be explained by publication quantity alone, but instead reflects structural imbalance in how dietary pattern-gut microbiota evidence progresses across stages of knowledge development. Even among countries or institutions with comparable research output, the proportion of mechanistic studies and studies supported by complex data infrastructures varies substantially, indicating that inequality in this field is more closely linked to evidentiary maturity than to the sheer number of publications<sup>[23,24]</sup>. Within dietary pattern-gut microbiota research, mechanistic insight typically depends on longitudinal or interventional study designs combined with multi-omics approaches, such as metagenomics and metabolomics, to elucidate causal relationships between dietary patterns, microbial functions, and host metabolic or immune responses<sup>[25]</sup>. Studies exemplifying this evidentiary stage such as controlled dietary interventions demonstrating microbiota-mediated immune or metabolic modulation require extended follow-up, multidisciplinary expertise, and stable experimental and computational platforms, and are therefore disproportionately conducted in resource-rich research environments<sup>[26,27]</sup>. By contrast, in settings with more limited infrastructure or constrained research capacity, studies more frequently focus on cross-sectional associations between dietary factors or dietary patterns and microbial composition. Although this body of work plays an important role in characterising population-level patterns and expanding the descriptive evidence base, its capacity for causal inference, mechanistic interpretation, and integration across biological levels remains limited<sup>[28-30]</sup>. At the field level, this imbalance implies that mechanistic understanding of diet-microbiota interactions is derived predominantly from a narrow set of research environments and population contexts. From a structural perspective, these findings suggest that advancing dietary pattern-gut microbiota research depends less on increasing publication volume than on promoting more equitable development of mechanistic research capacity and high-quality data infrastructure, particularly in underrepresented nutritional and geographic settings.

At the thematic level, integrating publication growth with citation depth reveals pronounced differences in the developmental maturity of research topics within the dietary pattern-gut microbiota field. Rapid expansion in publication volume does not necessarily translate into the formation of established research cores. Several topics exhibit substantial growth in output while maintaining relatively low levels of citation accumulation, indicating that evidence consolidation has lagged behind research activity. Such patterns are characteristic of transitional stages of development rather than conceptually mature research domains. Many rapidly expanding yet weakly consolidated topics relate to specific dietary patterns, the construction of dietary or microbiome-related indices, nutrition-based predictive models, and integrative applications of multi-omics data. Although studies examining associations between food types or dietary patterns and gut microbiota composition have proliferated, much of this literature relies on cross-sectional designs or preliminary association analyses, resulting in limited consensus regarding causal mechanisms. Similarly, increasing interest in dietary indices as proxies for microbiome health has not yet been matched by extensive validation or detailed mechanistic interpretation<sup>[31]</sup>. Experimental dietary intervention studies combining metagenomic profiling with immune or metabolic phenotyping have provided important mechanistic insights into diet-microbiota interactions<sup>[32-35]</sup>. Nevertheless, such evidence remains relatively sparse, and conceptual frameworks linking dietary patterns, microbial functions, and host responses are still under development. In contrast, topics characterised by concurrent growth in publication volume and citation accumulation tend to focus on explicit links between dietary interventions and defined biological pathways, as well as on longitudinal associations between diet quality and microbial functional traits. These themes exhibit more balanced expansion and impact, suggesting a higher degree of conceptual consolidation and evidentiary maturity. From a structural perspective, joint analysis of publication growth and citation depth provides a useful lens for distinguishing emerging but weakly consolidated research directions from more mature thematic cores, and for identifying areas where further mechanistic clarification, longitudinal validation, and integrative synthesis are most urgently needed.

Several limitations should be acknowledged. As a bibliometric, data-driven analysis, this study relies on information retrievable from major literature databases and may underrepresent research activities disseminated through non-peer-reviewed channels, such as project reports, policy documents, or practice-oriented outputs from high-burden settings. In addition, while topic identification and clustering approaches enable systematic characterisation of research structure and temporal dynamics, they cannot replace study-level assessment of methodological quality or causal inference. Within these constraints, this study offers a macro-level framework for examining structural imbalances in dietary pattern-gut microbiota research by integrating research output, nutritional burden, evidentiary depth, and thematic development. The findings indicate that addressing evidence inequality in this field requires more than increasing publication volume alone. Progress will depend on the more equitable development of mechanistic research capacity and high-quality data infrastructure across diverse nutritional contexts. In particular, longitudinal, interventional, and multi-omics studies in underrepresented populations will be essential for strengthening the generalisability and practical relevance of diet-microbiota evidence for global nutrition research and policy.

## 5. Conclusions

Global dietary pattern-gut microbiota research exhibits substantial structural inequality, with uneven distribution of research output and mechanistic evidence and weak alignment with nutritional burden. More balanced development of mechanistic and data-supported research across diverse nutritional contexts is essential to strengthen the global evidence base.

## Author Contributions

Conceptualization, G.Y. and Y.L.; methodology, G.Y.; software, G.Y.; validation, G.Y. formal analysis, G.Y.; investigation, G.Y.; resources; data curation, G.Y.; writing—original draft preparation, Q.H.; writing—review and editing, Y.L., G.Y. and Q.H.; visualization, G.Y.; supervision, G.Y.; project administration, Y.L.. All authors have read and agreed to the published version of the manuscript.

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## Informed Consent Statement

Not applicable.

## Data Availability Statement

All data analyzed in this study are derived from publicly available sources. Bibliometric records were retrieved from the Web of Science Core Collection databases using predefined search strategies. National-level nutritional indicators and demographic data were obtained from international public databases, including the World Health Organization, World Bank, and FAO databases. Processed datasets and analysis scripts supporting the findings of this study are available from the corresponding author upon reasonable request.

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## Conflicts of Interest

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

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