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Indian Probiotic Traditional Foods: Bibliometric Review of Health Impacts and Mechanistic Insights

SHIVALINGSARJ VIJAYKUMAR. DESAI[1]*, VEERANNA SHIVAPUTRAYYA HOMBALIMATH[1], LAXMIKANT RAMACHANDRA PATIL[1], FARHAN ZAMEER[2] and SHRIDHAR NARASIMHAMURTHY MATHAD[3]

[1]Department of Biotechnology, KLE Technological University, Hubballi, India.
[2]Department of Dravyaguna, Alva's Ayurveda Medical College, Moodubidire, India.
[3]Department of Physics, KLE Institute of Technology, Hubballi, India.

Abstract

Traditional fermented foods in India represent one of the oldest biotechnological practices, deeply rooted in diverse cultural and regional culinary traditions. These foods, enriched with probiotic microorganisms, notably lactic acid bacteria (LAB), have gained increasing scientific interest for their multidimensional health advantages including anti-hypertensive, anti-diabetic, anti-obesity, antioxidant, and antimicrobial effects. This bibliometric review reflects the scientific landscape of Indian probiotic traditional foods over the past decade (2015–2024) using data from the Web of Science database. The study analyses 370 publications to identify research trends, prominent authors, core journals, and thematic clusters. Co-occurrence network analyses reveal strong research focus on LAB strains, gut microbiota modulation, bioactive compounds, and microencapsulation technologies. Mechanistic insights highlight the metabolic pathways through which fermented foods exert health-promoting effects, such as modulation of lipid and glucose metabolism, antioxidative enzyme activities, and inhibition of pathogenic microbes. Despite significant advancements, gaps remain in clinical validation, strain characterization, and translational applications of the products. This review emphasizes the strategic importance of integrating traditional knowledge with modern omics and biotechnological approaches to harness the full functional potential of Indian fermented foods while contributing to sustainable food systems and public health objectives.

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CONTACT Shivalingsarj Vijaykumar. Desai kmastanj@ptfos.hr Department of Biotechnology, KLE Technological University, Hubballi, India.

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Introduction

The word fermentation is derived from Latin-*fermentum*, meaning "boiling," and is broadly described as a process in which products are processed through the intervention of microbial activity.[1] Traditional fermented foods represent one of the earliest forms of biotechnology, developed by local communities who leveraged on inherited knowledge and artisanal methods to convert regionally available plant- or animal-based substrates into culturally significant edible products. These foods are produced either naturally or with the addition of starter cultures containing microorganisms, which biochemically and organoleptically modify the substrates.[2]

In India, fermented foods reflect age-old wisdom from ancient civilizations, with a rich heritage of diverse products varying in taste and texture that showcase cultural diversity. Such foods are predominantly prepared by rural folk following traditional practice either at the household or cottage-industry level.[3] Microorganisms involved in fermentation improve the sensory qualities, nutritional value, health-promoting attributes, and preservation, making fermented foods, an integral part of the human diet since ancient days.[1] Moreover, many traditional fermented foods are recognized as important sources of probiotics and are increasingly linked to functional food concepts such as prebiotics, synbiotics, and post-biotics, which together contribute to gut microbiota and overall well-being of human health.[4] These fermentation processes have not only sustained communities for centuries but continue to hold significance in modern food systems as well. Understanding their origins, methods, and cultural contexts provides valuable insights into their current and future relevance as health promoting foods.[2]

Bibliometrics is a branch of information science that applies quantitative and statistical methods to analyze scientific publications and research trends.[5] It involves measuring publication patterns, citation networks, keyword co-occurrence and collaborations to map how knowledge in a particular field evolves over time.[6] Bibliometric analysis offers valuable insights into research productivity, prominent authors, institutions, key journals, and emerging thematic areas.[7]

Globally, bibliometric studies on fermented foods have helped in identifying trends in areas such as microbial diversity, probiotics, functional food development, and food safety.[8] However, despite India's rich heritage of traditional fermented foods, there is a significant lack of focused bibliometric reviews that systematically map the research landscape specific to this domain. This gap limits a holistic understanding of how research on Indian fermented foods has evolved, what topics have dominated, and which areas remain underexplored. Conducting a bibliometric review in this context is vital for collating fragmented literature, identifying knowledge clusters, thematic aspects and providing strategic directions for future research. Such an analysis can serve as a decision-making tool for researchers, industry stakeholders, policymakers, and funding agencies to prioritize emerging areas, strengthen collaborations, and advance the scientific and socio-economic potential of traditional fermented foods in India.[7]

This review aims to systematically map and analyze the scientific literature on Indian traditional fermented foods using bibliometric methods, with the goal of identifying key research trends, thematic clusters, and knowledge gaps to guide future studies.

The article covers the historical and cultural context of Indian fermented foods, explores the diversity of microbial communities, particularly lactic acid bacteria (LAB) and examines the mechanistic insights related to major health-promoting properties. It further highlights the role played by gut microflora and modern biotechnological perspectives in advancing these traditional foods as functional dietary components.

History of Fermented Foods

Fermentation is recognized as one of the oldest and most significant biotechnological processes developed by early human civilizations to ensure food security and nutritional sustenance.[9] Across the globe, ancient communities adopted diverse fermentation methods to extend the shelf life of surplus plant and animal produce, especially perishable and seasonal commodities. Archaeological and anthropological evidence suggests that organized fermentation practices likely emerged around 7,000–

8,000 BC, with early traces identified in regions such as the Middle East and the Indus Valley.[10]

Long before the emergence of the Harappan and Mesopotamian civilizations, ancient cultures such as the Egyptians, Greeks, and Romans had been adopted the practice of fermentation involving dairy products, alcoholic beverages, fruits, and cereals.[10] Such traditional methods, including fermentation, drying, smoking, and salting, were key technological milestones that not only preserved food but also enhanced its nutritional value, flavour, and safety - representing a critical step in the global history of food culture.[11]

Fermented foods and beverages have been playing a pivotal role in daily diets and cultural practices of Indian population since ages. The origin of Indian fermented foods are deeply rooted in the Indus Valley civilization, where archaeological findings and ancient inscriptions indicate the use of clay pots for the preparation of fermented products. Historical records substantiate that various fermented foods were produced and consumed in India as early as 3,000 BC, with extensive documentation in literary and archaeological sources.[12,13]

The Rigveda (circa 1,500 BC), one of the oldest Indian scriptures, provides concrete references to early fermentation practices, notably the preparation of Soma rasa - an inebriating ritual beverage and Sura, a fermented drink produced from boiled rice or barley.[10] Fermented beverages such as Medaka (rice beer), Prasanna (wheat beer), and Asava (sugarcane beer) became popular across different regions of India during post-Vedic period.[11]

The remarkable diversity of fermented foods in India stems from the use of locally available crops and resources, leading to region-specific products that reflect the unique culinary traditions of various ethnic communities.[14] These fermentation practices have endured through centuries not only as cost-effective methods for food preservation but also for their benefits in enhancing digestibility, flavour, nutritional value, and potential functional or pharmacological properties.9 Today, fermented foods continue to hold significant social, cultural, and nutritional relevance, underlining their significant role in India's rich heritage of foods.

Materials and Methods

This review employed a bibliometric approach to systematically map research trends on fermented foods, probiotics, and related microbial aspects in India. Bibliometric analysis is widely recognised for its ability to quantify research output, visualise collaboration networks, and highlight emerging themes in the area of research chosen.[7]

Data Source and Search Strategy

The Web of Science Core Collection was employed as the primary data source, for conducting the bibliometric investigation in view of its credibility and widespread acceptance.[15] The search was conducted in April, 2025, using the Boolean search string- "fermented food*" OR "traditional fermentation" OR "microbial fermentation" OR "lactic acid bacteria" OR "bioactive compound*" OR "probiotic microorganism*" AND "biochemical*" OR "microbial diversity" OR "metagenomics" OR "nutritional*" AND "India" OR "Indian".

The search covered the title, abstract, and keywords fields to ensure comprehensive coverage of the review scope.

Inclusion and Exclusion Criteria

The study focused on peer-reviewed journal articles and review papers published in English between 2015 and 2024. Books, conference proceedings, and non-English publications were excluded to maintain scientific rigour. An initial total of 469 records were identified based on search criteria. Following the exclusion of 99 records that did not meet the inclusion criteria, a total of 370 publications were retained for bibliometric analysis.

Data Processing and Analysis

Bibliographic information comprising publication year, author details, article titles, source journals, and citation metrics was exported in plain text format, including complete records and cited references. Duplicate records were removed and author names and keywords were standardised prior to analysis. Basic descriptive analyses, such as annual publication trends, leading authors, core journals, and citation distributions, were performed using Web of Science tools and Microsoft Excel.

Network visualisations were generated using VOS viewer version 1.6.19.[16] Co-authorship, co-occurrence of keywords, and co-citation analyses were carried out to map collaboration patterns and research themes. The similarity between items was calculated using the association strength normalisation method, which positions the related items close together on a two-dimensional map.[17] This structured approach provides insights into the research landscape and publications trends related to Indian probiotic traditional foods, highlighting research gaps and directions for future work.

Results

Progress of Research Publications

Progress of research publications in bibliometric analysis indicates the growth trend and scholarly output in a specific field. It helps in assessing the emerging interest, and developmental trajectory of the research domain over time. In the study conducted with the keywords, the analysis revealed a steady upward trend over the past decade. The number of published documents remained relatively modest during 2015 to 2020, averaging around 15–30 publications per year. A noticeable increase was observed from 2021 onwards, with the number of documents rising sharply to nearly 50 publications in 2021, peaking at over 70 in 2022. Despite a modest decrease in 2023 and 2024, publication output remained substantially elevated compared to earlier years, reflecting continued and expanding scholarly interest in the domain.

Subject-Wise Area Distribution

Subject-wise area distribution in bibliometric analysis highlights the disciplinary spread of research contributions within a given topic. It helps in identifying prominant fields and interdisciplinary overlaps, offering insights into the scope and impact of the research area.

The analysis of subject-wise area distribution showed that Food Science and Technology contributed the largest share (51%) of publications on Indian traditional fermented foods. Microbiology (18%) and Biotechnology & Applied Microbiology (16%) also constituted significant portions, indicating a strong research focus on microbial and biotechnological aspects. Nutrition and Dietetics (10%) and Biochemistry & Molecular Biology (5%) reflected emerging interests in nutritional and molecular studies.

Co-Occurrence of Authors' Keywords

Co-occurrence of authors' keywords in bibliometric analysis reveals the thematic structure and conceptual linkages within a research domain by identifying frequently paired terms across publications. This helps in mapping emerging trends, research hotspots, and interdisciplinary connections, guiding future investigations and policy decisions.

A frame-view of network visualization in regard to co-occurrence of authors keywords analysis is showed that themes such as lactic acid bacteria, bioactive compounds and microbial diversity, emphasising the research community's focus on probiotic potential and health benefits.[18] This aligns with studies showing that traditional Indian fermented foods, like curd, *Kanji, Khadi, Ambli* and fermented pickles, harbour unique strains of probiotics with promising functional attributes.

Keyword Clusters and Research Themes

Keyword clusters and research themes in bibliometric analysis group the related terms to highlight the core topics and subfields within a research area. This aids in visualizing how themes evolve and interconnect over a period of time. Keyword co-occurrence analysis identified four prominent thematic clusters as shown in Table 1. The red cluster focuses on Lactic Acid Bacteria, *Lactobacillus plantarum* and gut microbiota, indicating the way active research on the traditional fermented foods modulates the gut health. The green cluster highlights micro-encapsulation, probiotics and prebiotics, reflecting a growing interest in combining encapsulation technologies with prebiotic fibres to improve probiotic viability. The blue cluster centres on comparative studies of *Lactobacillus* strains for functional food applications, while the yellow cluster shows on-going work on mapping microbial diversity in various fermented foods.[18]

Countries Participating and Co-Authorship Patterns

The bibliometric analysis of countries participating and co-authorship patterns highlight the global research contributions and collaborative networks across different nations. This shows the extent of international cooperation, knowledge exchange, and the leading countries driving research in the field. The analysis of the present study showed that from 2015 to 2024, India recorded the highest output in probiotics and fermented foods with 359 documents and 8,257 citations. USA ranks as India's top international collaborator (22 documents, 784 citations, link strength 50), followed by China, Spain and Italy. China contributed sixteen, while Spain and Italy contributed nine documents each.

Table 1: Primary keywords and related thematic research clusters

Cluster	Color	Primary Keywords	Thematic clusters
1	Red	Lactic Acid Bacteria, Fermented Foods, *Lactobacillus plantarum*, Gut Microbiota.	Modulation of Gut Microbiota by Lactic Acid Bacteria in Fermented Foods
2	Green	Microencapsulation, Probiotic, Functional Foods, Prebiotics, Viability	Synergistic Effects of Prebiotics and Microencapsulated Probiotics on Gut Health
3	Blue	*Lactobacillus*, Probiotic, Strains, Microbiota	Comparative Evaluation of *Lactobacillus* Strains for Probiotic Potential
4	Yellow	Microorganism, Foods, Identification, Diversity	Microbial Diversity in Fermented Foods: Identification and Characterization

Prominent Authors in Indian Probiotic Research

In bibliometric analysis, identifying prominent authors helps in highlighting the key contributors who have significantly shaped the field through high publication output and citation impact. This insight reveals research leadership, collaboration potential, and the active researchers within the domain.

The co-authorship analysis identified five leading authors with the highest total link strength Among them, Amit Kumar Rai has the highest citation count (2293) across eight publications, indicating substantial influence in the field of Indian fermented foods and probiotics. Authors such as Kuntal Ghosh, Suman Kumar Halder and Keshab Chandra Mondal also contributed significantly, highlighting a small but productive network of researchers driving this domain forward. The relatively moderate link strengths suggest active intra-institutional or regional partnerships. It also highlights the opportunities for expanding collaborations to national and international levels.[8]

Table 2: Top five most cited articles in Indian probiotic and fermented food research

Title	Citations
Probiotic functional foods: Survival of probiotics during processing and storage[19]	813
Microbial Fermentation and Its Role in Quality Improvement of Fermented Foods[20]	370
Fermented foods in a global age: East meets West.[8]	352
Trends in non-dairy probiotic beverages.[21]	352
Functional Properties of Microorganisms in Fermented Foods.[2]	333

Highest Number of Citations by Ranking

In bibliometric analysis, ranking publications by the highest number of citations helps identify the most prominent and relevant studies in the research field. Analysis of the top five cited articles (Table 2) shows that the paper by Tripathi and Giri19 on probiotic functional foods has the highest citations (813), highlighting foundational work on probiotic survival during processing and storage. Other highly cited works include, studies on microbial fermentation quality improvement, global perspectives of fermented foods, trends in probiotic beverages and functional properties of fermented foods.

Co-Citation Patterns by Cited Sources

The co-citation patterns by cited sources in bibliometric analysis are examined to understand the frequency of two documents being cited together in other works. This reveals conceptual linkages, foundational literature, and the structure of knowledge within the research field.

A network visualization of co-citation relationships among key sources showed that studies related to *L. plantarum*[22] and probiotics in metabolic diseases[23] are frequently cited alongside works on functional properties and non-dairy probiotic trends.[21] This suggests strong thematic integration across health applications, strain characterisation and new product development[24] in the sphere of fermented foods.

Source Clusters and Research Focus

An analysis of source co-citation and related research focus is shown in Table 3. It revealed three major clusters of journals that shape the research landscape on Indian probiotic and fermented foods. The red cluster includes key journals- Indian Journal of Dairy Science, Journal of Agriculture and Food Research, Journal of Food Processing and Preservation, and Journal of Food Science and Technology. These journals primarily publish research related to dairy science, food processing, nutrition and agriculture, with a strong focus on food quality, safety, and health benefits.

Table 3: Source clusters and key journals contributing to probiotic and fermented food research

Cluster	Code	Key Sources	Characteristics
1	Red	Indian Journal of Dairy Science, Journal of Agriculture and Food Research, Journal of Food Processing and Preservation, Food Bioscience, Current Research in Nutrition, Nutrition and Food Science, Journal of Food Science and Technology	Focus on research in dairy, food processing, nutrition, and agricultural sciences, emphasizing food quality, safety, technology, and health impacts.
2	Green	Frontiers in Nutrition, Food Research International, Frontiers in Microbiology, Fermentation Basel, Journal of Microbiology and Biotechnology, Indian Journal of Traditional Knowledge.	Cover research in food science, fermentation, biotechnology, and traditional knowledge, highlighting innovations in health and microbial applications.
3	Blue	Probiotics and Anti-Microbial Proteins, Current Nutrition and Food Science, LWT Food Science and Technology	Emphasize research on probiotics, antimicrobial compounds, nutritional science, and advances in food processing and technology.

The green cluster features, journals like Frontiers in Nutrition, Food Research International, Frontiers in Microbiology, Fermentation Basel, Journal of Microbiology and Biotechnology, and the Indian Journal of Traditional Knowledge. The blue cluster includes sources such as Probiotics and Anti-Microbial Proteins, Current Nutrition and Food Science, and LWT Food Science and Technology, which focus on probiotics, antimicrobial compounds, and advanced food processing technologies.

Sustainable Development Goals Addressed

The Sustainable Development Goals (SDGs) provide a global framework to align research priorities with societal impact, making bibliometric analysis a valuable tool to map, quantify, and track scholarly contributions toward these goals. Incorporating SDGs in bibliometrics helps identify knowledge gaps and guide future research toward sustainable solutions. The analysis shows that research on Indian probiotics and traditional fermented foods contributes strongly to multiple Sustainable Development Goals (SDGs). The largest share (90%) of the reviewed literature aligns with SDG 3: Good Health and Well-Being, indicating the dominant focus on probiotics, gut health, and functional food applications.

A smaller proportion (6%) addresses SDG 2: Zero Hunger, showing that some studies explore how fermented foods can enhance food security and nutritional status. Minor linkages were also noted for SDG 12: Responsible Consumption and Production and SDG 13: Climate Action, highlighting growing interest in sustainable food systems and reducing food waste through fermentation by increasing shelf-life.[8,18]

Discussion

The temporal rise in progress of publications year-on-year reflects a growing academic and industrial interest in the health potential and scientific validation of traditional fermented foods. The noticeable increase in publications post-2018 appears to stem from converging factors such as enhanced consumer demand for functional foods and increased policy-level recognition of nutraceuticals. These developments have accelerated research not only in India but also in other developing nations where fermented foods are integral to cultural and dietary practices.[8]

The subject-wise area distribution indicated that Food Science and Technology played a central role among traditional fermented foods within applied food research, particularly in processing, safety, and sensory evaluation domains. Significant representation from Microbiology and Biotechnology reflects sustained scholarly attention to microbial diversity, fermentation mechanisms, and functional strains such as lactic acid bacteria. The contributions from Nutrition and Dietetics, along with Biochemistry and Molecular Biology, suggest a growing interdisciplinary interest in elucidating the nutritional benefits and molecular mechanisms underlying health-promoting properties.

The keyword co-occurrence network reveals a clear convergence of themes around lactic acid bacteria, gut microbiota, and functional foods, indicating the central role of probiotics in fermented food research. The strong associations between traditional fermented products and bioactive microbial metabolites suggest an evolving interest in exploring indigenous knowledge of Indian traditional fermented foods through scientific validation. The integration of metagenomic tools and encapsulation technologies further reflects a shift toward precision microbiology and targeted delivery of functional benefits.

The four clusters in regard to the identified keywords reflect the multidimensional nature of current research on Indian fermented foods. The prominence of lactic acid bacteria and gut microbiota underscores the emphasis on microbiome modulation and its health implications. The cluster on microencapsulation and prebiotics indicates an applied technological focus aimed at enhancing probiotic stability and functionality, revealing industry-driven innovations. The emphasis on microbial diversity highlights a continued interest in cataloguing and preserving indigenous microbial resources, reinforcing the interplay between traditional knowledge and modern microbial ecology.

The participation of various countries in probiotic research, along with observed authorship patterns, underscores India's leading role in the field. Its strong scientific output, coupled with active international collaborations, reflects the country's growing influence and leadership in probiotic and fermented food research. The prominent partnerships with the USA, China, Spain, and Italy suggest a growing recognition of India’s traditional knowledge and scientific contributions in this domain. These collaborations not only enhance technological exchange and research capacity but also broaden the global applicability and validation of findings related to Indian fermented foods. The emerging global network indicates a trend toward interdisciplinary and cross-border research aimed at functional food development and public health advancement.

The identification of prominent authors underscores the pivotal role individual researchers are playing the Indian probiotic and fermented food research landscape. The substantial citation impact of contributors like Amit Kumar Rai reflects both the quality and relevance of their work within the scientific community. The presence of closely collaborating researchers such as Kuntal Ghosh, Suman Kumar Halder, and Keshab Chandra

Mondal suggests the development of a focused and interconnected research cluster. Such author networks are instrumental in setting research agendas, fostering innovation, and mentoring the next generation of scientists in this emerging field.

The ranking of highly cited publications reveals the studies that have significantly influenced the research landscape on probiotics and fermented foods. The most cited article by Tripathi and Giri on probiotic survival underscores the importance of functional stability during processing and storage. Similarly, frequently cited works focusing on microbial fermentation, non-dairy probiotic beverages, and functional attributes of fermented foods point to the research emphasis on health benefits and technological innovations. The trend reflects the growing scholarly interest in optimizing both the efficacy and application of fermented products across various food systems.

The visualization of Co-Citation patterns reveals that India's probiotic research community draws heavily from a core body of global work while contributing to regionally relevant studies on traditional fermented foods.[2,25] The citation impact and co-citation clusters show that Indian probiotic research is anchored in well-cited global frameworks. It can further benefit from more diverse international citations and cross-disciplinary collaborations resulting in further addition to the existing body of knowledge.[8,19,24] The journals indicated serve as key publication platforms for studies emphasizing dairy science, food technology, and nutrition and underscores the multidisciplinary nature of the probiotic research.This co-citation pattern demonstrates that Indian research in probiotics and fermented foods is deeply rooted in region-specific agricultural and dairy contexts while aligning with global advances in functional foods, gut microbiome research, and health applications.
In context of SDG's, the bibliometric analysis reveals that Indian probiotic and fermented food research is closely aligned with global sustainability objectives. A substantial portion of the literature is directed toward SDG 3 (Good Health and Well-Being), reflecting the emphasis on gut health, probiotics, and functional food innovations. Contributions to SDG 2 (Zero Hunger) indicate growing interest in leveraging fermented foods to address food security and nutritional deficiencies. Additionally, emerging links to SDGs 12 and 13 suggest an evolving focus on sustainable food practices, shelf-life extension, and climate-resilient food systems through fermentation technologies.

Indian Fermented Foods: Lactic Acid Bacteria, Gut Microbiota and Mechanistic Insights

Gut Microbiota and the Role of Lactic Acid Bacteria (LAB)

Fermented foods are known for their ability to impart health benefits by modulating the composition of gut microbiota.[9] Studies have demonstrated that naturally existing gut microflora play a crucial role in enriching food substrates with micronutrients, macronutrients, phytochemicals, and functional components during fermentation.[26] These transformations help in maintaining a good gut microbiota, which in turn protects against various infections, physiological homeostasis, and gut-brain axis modulation in human host.[27]

LAB are the major group of microorganisms associated with the fermentation of numerous foods and beverages worldwide. They are Gram-positive, non-spore-forming, generally non-motile bacteria that rely on fermentable carbohydrates for active growth.[26] They rapidly lower the pH of the substrate to levels that inhibit spoilage and pathogenic microorganisms, thereby ensuring both preservation and safety of the food involved. For example, *Leuconostoc* and *Lactococcus* species can lower the pH to 4.0–4.5, while some *Lactobacillus* and Pediococcus species can reduce it to around 3.5.[26]

The traditional use of LAB as starter cultures is widely regarded as safe, contributing not only to the microbiological stability of fermented foods but also to impart desirable sensory properties such as flavour, aroma, and texture.[11] The main genera of LAB include *Lactobacillus*, *Lactococcus*, *Enterococcus*, *Streptococcus, Pediococcus, Leuconostoc,* and *Weissella.* These bacteria show extensive genetic diversity and habitat adaptation, resulting in species-specific variations in growth conditions and environmental tolerances.9 Although LAB generally benefit food safety and quality, they can occasionally contribute to spoilage or undesirable off-flavours if the process is not properly controlled.[26]

Metabolic Pathways in Fermented Foods

During the fermentation process of foods, the ingredients get converted to simpler products as a result of enzymatic degradation.[28] The lactic acid fermentation pathway is fundamental to the role of LAB in food fermentation process. LAB can be classified as homo-fermentative, hetero-fermentative or facultative fermenters, depending on the metabolic end-products formed. Homo-fermentative LAB, such as *L. lactis, Streptococcus thermophilus*, and many species of *Lactobacillus* (e.g., *L. delbrueckii subsp. bulgaricus, L. acidophilus*), primarily produce lactic acid from glucose. This occurs through Embden–Meyerhof–Parnas (EMP) pathway, which converts glucose to lactic acid and creates an acidic environment in foods thus imparting a tangy flavour.[29]

In hetero-lactic acid fermentation, the pentose sugars are broken down to yield small amounts of lactic acid, alcohol, acetic acid and carbon-dioxide. Hetero-fermentative LAB, including *Leuconostoc* spp. and *LimosiLactobacillus* reuteri produce lactic acid along with ethanol, carbon dioxide, and acetic acid. Facultative LAB such as *L. plantarum* can shift between these pathways depending on substrate availability and environmental conditions.[30]

The Potential Health benefits Associated with LAB-Fermented Foods are Supported by

substantial evidence linking their regular consumption to improved gut health, metabolic balance, and immunomodulatory effects.[14] Metchnikoff first hypothesized that the increased life expectancy of certain Balkan populations could be attributed to their significant consumption of lactic acid–fermented milk.[27] This concept laid the foundation for modern probiotic research. Many LAB strains have since been granted probiotic status because they can survive gastrointestinal transit, adhere to intestinal mucosa, and provide health benefits to the host.[31] LAB are widely used as probiotics in foods and are assigned GRAS (Generally Recognized as Safe) status by the United States Food and Drug Administration (USFDA). While conventional probiotics mainly include LAB and Bifidobacteriaceae, recent attention has turned to native gut microbiota as sources of next-generation probiotics (NGP) with targeted health applications.[32] Nevertheless, LAB-fermented foods continue to represent a safe, cost-effective, and accessible approach to supporting human health and nutritional well-being.

Major Indian Fermented Foods

India is a host to several traditional fermented foods which span across the all the regions of the nation. The communities in different regions have been practising the consumption of several fermented cuisines based on staple crops in the area. The foods are integral to the cultural ethos and have a strong bearing with the consumption pattern and life-style of the population. Table 4 reflects the different prominent traditional fermented foods prevalent across the Indian sub-continent.

Table 4: Major Indian Fermented Foods

Food	Region	Ingredients	Dominant Microorganisms	Benefits
Idli	South India	Rice, black gram dal	*Leuconostoc mesenteroides, Lactobacillus. fermentum*	Anti-Obese[11]
Dosa	South India	Rice, black gram dal	*Leuconostoc spp., Lactobacillus spp.*	Bio-availability[11]
Dhokla	Gujarat	Bengal gram flour	*L. delbrueckii, Leuconostoc spp.*	Digestive[10]
Jolada Ambli	Karnataka	Sorghum flour	*L. plantarum*	Low-calorific[10]
Ragi Koozh	Tamil Nadu	Finger millet flour	*L. fermentum*	Cooling[10]
Appam	Kerala	Rice, coconut milk	*L. mesenteroides*	Nutritive[11]
Rabadi	Rajasthan	Pearl millet flour, buttermilk	*Lactobacillus spp.*	Reduces antinutritional factors[11]

Jalebi	North India	Refined flour, yogurt	*Lactobacillus spp., yeasts*	Energy booster[10]
Shrikhand	Maharashtra	Strained curd	*L.lactis, Lactobacillus spp.*	Nutritive9
Lassi	North India	Yogurt, spices	*L. delbrueckii, Streptococcus thermophilus*	Digestiv[11]
Kanji	Punjab	Black carrots, mustard	*L. plantarum*	Antimicrobial[10]
Gundruk	Sikkim	Leafy greens (mustard)	*L. plantarum, Leuconostoc spp.*	Appetizer[11]
Churpi	Sikkim/ Himalayan	Yak/cow milk	*Lactococcus spp., Streptococcus spp.*	Anti-hypertensive[11]
Hentak	Manipur	Fish, herbs	*Lactobacillus spp., Bacillus spp.*	Convalescent[10]
Sinki	Sikkim	Radish roots	*L. plantarum*	Anti-diarrhoeal[9]
Sol Kadhi	Goa/Konkan	Kokum, coconut milk	*Lactobacillus spp.*	Blood purifier[10]
Apong	Assam/ Nagaland	Rice	Yeasts, LAB	Antioxidant[10]
Sel Roti	Sikkim/ Darjeeling	Rice flour, sugar	*Lactobacillus spp.*	Glutenandtrans-fat free[9]
Panta Bhath	Bengal/Odisha	Cooked rice, water	*L. fermentum*	Digestive[11]
Kinema	Sikkim	Soybeans	*Bacillus subtilis*	Vitamin rich[11]

Mechanisms of Health Benefits of Probiotic Fermented Foods

Fermented Foods as Anti-Hypertensive Agents

Fermented foods have gained recognition for their potential role in managing hypertension through the generation of bioactive peptides and functional metabolites during microbial fermentation. These compounds are proven to modulate key pathways involved in blood pressure regulation, offering a dietary approach to complement conventional antihypertensive therapies. The anti-hypertensive potential of LAB-fermented products is primarily attributed to the release of specific bioactive peptides generated through extensive proteolysis during fermentation.

The proteins and peptides in the foods being fermented acts as substrates for proteases and peptidases and result in the release of metabolites with Angiotensin I-Converting Enzyme (ACE) inhibitory activity.[33] These peptides, such as Ile-Pro-Pro (IPP) and Val-Pro-Pro (VPP), act as competitive inhibitors by binding to the active C-terminal site of ACE, thereby attenuating its catalytic function.[34]

ACE is known to convert inactive decapeptide, angiotensin I to octapeptide angiotensin II which serves as vasoconstrictor by promoting smooth muscle contraction in arteriolar walls and stimulating aldosterone secretion for sodium and water retention. By inhibiting ACE, these bioactive peptides effectively downregulate the synthesis of angiotensin II, resulting in reduced vasoconstrictive signalling. Simultaneously, ACE inhibition preserves circulating levels of bradykinin, a potent endogenous vasodilator peptide, which further promotes endothelium-dependent nitric oxide release and vascular smooth muscle relaxation.[35]

This dual mode of action - suppression of vasoconstriction through reduced angiotensin II formation and enhancement of vasodilation by bradykinin preservation contributes to decreased peripheral vascular resistance and sustained blood pressure reduction. Such mechanisms substantiate the rationale for recommending regular dietary intake (RDA) of LAB-fermented food matrices as an adjunct non-pharmacological intervention in hypertension management.[36]

Mechanism of Anti-Obesity property

Obesity has been considered as metabolic disorder influenced by multiple physiological pathways, including lipid synthesis, appetite regulation, and gut microbiota balance. Fermented foods and their bioactive components exert anti-obesity effects through diverse mechanisms and act synergistically

Inhibition of Lipid Synthesis in the Liver

A consortium of *Lactobacillus* species modulate the gene expression of metabolic regulators- fatty acid synthetase (FAS), peroxisome proliferator-activated receptor-γ (PPAR-γ), adenosine monophosphate-activated protein kinase-α (AMPK-α) and. acetyl CoA carboxylase (ACC), This results in reduced synthesis of fat and its storage which helps in alleviating the obese related disorders.

Different strains of LAB's are reported to contribute to address obesity disorder by inhibiting the lipid storage, adipocyte differentiation, gain in body weight, lipid accumulation and insulin resistance through down regulation of adipokine proteins such as C-reactive protein (CRP), lipocalin-2,ANGPT-L3 (angiopoietin-like),monocyte chemoattractant protein-1 (MCP-1) leptin and insulin-like growth factor binding proteins (IGFBPs) in white adipose tissue. Also, some fermented foods like Kochujang are known to help in reduction of body weight by Upregulating the carnitine palmitoyl transferase-1 (CPT-1), acyl-CoA synthetase (ACS) and uncoupling protein-1 (UCP-1), while downregulating ACC gene expression.[37]

Short-chain fatty acids (SCFAs), the key metabolites of fermented foods, are also recognized for their appetite-suppressing effects thereby reduce the glucose intake leading to lipid profile management.[38] SCFAs modulate appetite through peripheral activation of ACC, satiety neuropeptides and involving hypothalamus and GABAergic neurons.[39]

Reduction of Appetite Hormones

Fermented food products slow gastric emptying, thereby influencing postprandial responses of blood glucose, insulin, and lipids. SCFAs generated during fermentation contribute significantly to appetite suppression through the same peripheral and central mechanisms as described earlier.[39] Johansson *et al*.[40] demonstrated the appetite-reducing effects of fermented whole grain bread as compared to refined and unfermented grains.[38]

Inhibition of Pro-Inflammatory Cytokines

Excessive deposition of white adipose tissue disrupts the normal secretion of adipokines, resulting in an altered inflammatory cytokine profile and the development of chronic, low-grade inflammation characteristic of obesity.[41] Such disruption in the balance of pro- and anti-inflammatory cytokines disturbs energy homeostasis and promotes increased recruitment of inflammatory immune cells, notably neutrophils, mast cells, M1 macrophages, $CD8^+$ T lymphocytes, and Th1 cells. Such chronic inflammation promotes lipolysis in peripheral tissues such as muscle, liver, and pancreas, which can result in lipotoxicity and insulin resistance.[42]

Mechanism of Anti-Diabetic Properties

The anti-diabetic potential of LAB fermented foods is attributed to multiple, interrelated mechanisms targeting key metabolic pathways implicated in type 2 diabetes mellitus. During microbial fermentation, the activities of α-amylase, α-glucosidase, and angiotensin-converting enzyme (ACE) inhibitors increase resulting in an elevated concentration of bioactive compounds such as tyrosol, while simultaneously reducing salidroside levels and strengthening the overall α-glucosidase inhibitory effect.[43] Controlled inhibition of α-amylase is particularly relevant as excessive inhibition can lead to undesirable gastrointestinal effects such as flatulence and bloating, whereas selective α-glucosidase inhibition provides a more gradual glucose release, supporting glycemic control with improved patient tolerance.[44]

LAB fermented foods are also known to contribute to improved glycemic homeostasis by modulating gut microbiota composition and function. Fermentation-derived strains, including various *Lactobacillus* and *Bifidobacterium* spp., enhance the concentration of short-chain fatty acid (SCFA)-producing microbes, leading to increased levels of butyrate, propionate, and acetate. These SCFAs have been shown to regulate hepatic gluconeogenesis, improve insulin receptor sensitivity, and modulate entero-endocrine hormone release, such as glucagon-like peptide-1 (GLP-1) and peptide YY (PYY), which collectively improve glucose tolerance.[45]

Furthermore, the fermentation process can biotransform complex polyphenolic compounds and increase the bioavailability of bioactive phenolics like tyrosol, which exert antioxidant and anti-inflammatory effects that mitigate oxidative stress–induced insulin resistance.[36] Fermentation also reduces anti-nutritional factors, such as phytates and tannins, which otherwise impair mineral absorption and insulin signalling pathways.

Another emerging mechanistic insight is the modulation of intestinal barrier integrity by LAB-derived exopolysaccharides (EPS) and bacteriocins, which can suppress low-grade systemic inflammation, reduce endotoxemia, and preserve pancreatic β-cell function.[44,45] Together, these multi-targeted actions highlight how LAB fermented foods can serve as functional dietary adjunct to conventional anti-diabetic strategies by synergistically regulating glucose metabolism, gut microbial ecology and host immune responses.

Mechanism of Anti-Oxidant Activity

Fermented foods enriched with lactic acid bacteria (LAB) exhibit antioxidant activity via diverse biochemical and cellular pathways, collectively reducing oxidative stress- a central factor in the development of metabolic disorders such as diabetes and cardiovascular diseases.[44,45]

Lactic acid bacteria (LAB) strains harbor inherent antioxidant enzyme systems- catalase, glutathione peroxidase-like activities and superoxide dismutase (SOD)- that enable effective scavenging of reactive oxygen species (ROS) within both the food matrix and the gastrointestinal environment of the host.[46] During fermentation, the metabolic activity of lactic acid bacteria leads to the release and biotransformation of bioactive compounds such as phenolic acids, flavonoids, and bioactive peptides with demonstrated radical-scavenging capacity.[36,46]

Furthermore, fermentation processes can increase the bioavailability of antioxidant micronutrients by degrading anti-nutritional factors like phytates and tannins that otherwise chelate essential minerals required for endogenous antioxidant enzyme systems.[44] LAB-derived exopolysaccharides (EPS) and short-chain fatty acids (SCFAs) have also been reported to modulate oxidative stress indirectly by maintaining gut barrier integrity and suppressing pro-inflammatory pathways that generate ROS.[35]

In vivo and *in vitro* studies indicate that regular consumption of LAB-fermented foods supports systemic redox homeostasis by enhancing plasma antioxidant capacity, reducing lipid peroxidation, and preserving cellular membrane stability.[36] These multifaceted effects reinforce the role of fermented foods as an integral part of functional dietary strategies aimed at counteracting oxidative stress–mediated metabolic dysfunction.

Mechanism of Anti-Microbial Activity

The antimicrobial efficacy of LAB-fermented foods is primarily attributed to the metabolic activities of LAB, which produce a diverse spectrum of antimicrobial compounds that collectively inhibit pathogenic and spoilage microorganisms.[36,46] Organic acids, predominantly lactic and acetic acids, are synthesized during carbohydrate fermentation, leading to a reduction in pH and the creation of a hostile environment for acid-sensitive pathogens.[2] The undissociated forms of these acids permeate microbial cell membranes, dissociate intracellularly, and disrupt proton motive force, resulting in cytoplasmic acidification and growth inhibition.

Additionally, certain LAB strains produce bacteriocins, (low molecular weight antimicrobial peptides) nisin and pediocin, which act by forming pores in the target cell membrane or by interfering with cell wall biosynthesis, thereby exerting bactericidal effects.[46] Hydrogen peroxide, reuterin, and diacetyl further contribute to the antimicrobial spectrum by generating oxidative stress or interfering with pathogen metabolism.[36] Additionally, LAB inhibit pathogen establishment in the gastrointestinal tract by competing for adhesion sites and essential nutrients, thereby strengthening colonization resistance and supporting the stability of gut microbial communities. The synergistic action of these mechanisms underscores the integral role of LAB-fermented foods in enhancing food safety, extending shelf-life, and supporting host defence against enteric pathogens.

Conclusion

This bibliometric review provides an overview of the evolving research landscape on Indian probiotic traditional foods and their mechanistic health impacts. The findings demonstrate that research in this domain has grown steadily, driven by heightened interest in leveraging indigenous fermentation knowledge for functional food development. The co-occurrence and co-authorship analyses reveal an emerging trend with focus on LAB-mediated gut microbiota modulation, bioactive metabolite production, and sustainable food preservation strategies. Mechanistic insights present the evidence for the role of these foods in managing hypertension, diabetes, obesity, oxidative stress, and microbial infections. However, challenges persist in translating this knowledge into validated products and scalable applications. Strengthening interdisciplinary collaborations, expanding subject studies and integrating modern biotechnological tools will be crucial to bridge existing gaps. Advancing this field can play a significant role in addressing national nutrition security, achieving multiple Sustainable Development Goals, and revitalizing India's rich heritage of probiotic traditional foods for contemporary health and wellness. innovative product development.

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Author Contributions
- **Shivalingsarj Vijaykumar Desai:** Conceptualization, bibliometric analysis and original draft.
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- **Laxmikant Ramachandra Patil:** Methodology design and visualizations.
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- **Shridhar Narasimhamurthy Mathad:** Critical revisions and conceptual guidance.

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