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PROBIOTIC MICROBES IN FERMENTED FOODS AND PROBIOTIC SUPPLEMENTS: A COMPREHENSIVE COMPARATIVE REVIEW

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ABSTRACT

Fermented foods have long been recognized as important dietary sources of probiotic microorganisms that contribute to human health through their diverse microbial communities and bioactive metabolites. This review critically examines the diversity, identification, functional attributes, and health-promoting potential of probiotic microorganisms associated with fermented foods, with particular emphasis on yogurt, kimchi, sauerkraut, kefir, and other traditional fermented products. Recent advances in culture-dependent methods, 16S rRNA gene sequencing, metagenomics, and metabolomics have substantially improved the characterization of probiotic microorganisms and their functional properties. The review discusses the mechanisms by which probiotics modulate gut microbial homeostasis, strengthen intestinal barrier integrity, regulate immune responses, inhibit pathogenic microorganisms, and influence the gut–brain axis through the production of bioactive compounds, including short-chain fatty acids, bacteriocins, vitamins, and postbiotics. A comparative evaluation of fermented foods and commercial probiotic supplements highlights that fermented foods provide greater microbial diversity, complex food matrices, and naturally occurring metabolites, whereas probiotic supplements offer standardized microbial strains, controlled dosages, and improved shelf stability. Although both approaches contribute to health promotion, fermented foods exhibit unique synergistic interactions between microorganisms and fermentation-derived metabolites that may enhance probiotic functionality. Despite substantial progress, current evidence is constrained by methodological inconsistencies, strain-specific variability, and the limited availability of well-designed human clinical trials. Future research integrating multi-omics technologies with standardized clinical investigations is essential to elucidate host–microbe interactions, validate strain-specific health benefits, and optimize the development of evidence-based functional foods and next-generation probiotic formulations. Overall, this review provides a comprehensive synthesis of current knowledge on fermented food-derived probiotics and their emerging significance in nutrition, health promotion, and sustainable functional food development.

Key words: Fermented foods; Probiotics; Lactic acid bacteria; Gut microbiota; Bioactive metabolites; Functional foods; Probiotic supplements.

Introduction

Probiotics are defined as live microorganisms that, when administered in adequate amounts, confer a health benefit on the host, according to the Food and Agriculture Organization (FAO) and the World Health Organization (WHO). Over the past few decades, probiotics have attracted considerable scientific and commercial interest

because of their potential to promote gastrointestinal health, enhance immune function, regulate metabolic processes, and improve overall well-being. Among the various sources of probiotics, traditional fermented foods have gained increasing attention as natural reservoirs of beneficial microorganisms and bioactive metabolites that contribute to human health.

Fermentation is one of the oldest methods of food preservation, practiced for thousands of years across diverse cultures to improve the shelf life, safety, sensory characteristics, and nutritional value of foods. Traditional fermented foods such as yogurt, kimchi, sauerkraut, kefir, tempeh, fermented cereals, and indigenous fermented vegetables harbor complex microbial communities dominated by lactic acid bacteria (LAB), including species of *Lactobacillus*, *Lactiplantibacillus*, *Leuconostoc*, *Bifidobacterium*, *Pediococcus*, and *Lactococcus*, along with beneficial yeasts and other microorganisms. These microbial consortia not only facilitate fermentation but also produce a wide array of bioactive compounds, including organic acids, bacteriocins, exopolysaccharides, vitamins, bioactive peptides, and postbiotic metabolites that contribute to improved digestive health, immune regulation, antioxidant activity, and modulation of the gut–brain axis (Kwofie *et al.*, 2020; Palmnäs-Bédard *et al.*, 2023; Pyo *et al.*, 2024).

The concept of probiotics originated in the early twentieth century following observations that regular consumption of fermented milk products was associated with improved longevity and intestinal health. Since then, advances in microbiology, molecular biology, and next-generation sequencing technologies have considerably expanded our understanding of probiotic microorganisms and their interactions with the host microbiome. Contemporary research has demonstrated that fermented foods serve as dynamic microbial ecosystems, with their microbial composition influenced by raw materials, geographical origin, fermentation conditions, processing methods, and storage practices. Consequently, different fermented foods exhibit distinct microbial communities and functional characteristics that influence their probiotic efficacy (Paul *et al.*, 2023; Tingirikari *et al.*, 2024).

Growing awareness of the relationship between gut microbiota and human health has further intensified research on probiotic-rich foods. Alterations in gut microbial composition, commonly referred to as dysbiosis, have been associated with several chronic disorders, including inflammatory bowel disease, obesity, diabetes mellitus, cardiovascular diseases, allergies, and neurological disorders. Numerous studies have demonstrated that regular consumption of fermented foods can enhance microbial diversity, strengthen intestinal barrier function, regulate immune responses, suppress pathogenic microorganisms, and contribute to improved metabolic and psychological health (Meena and Rai, 2023; Nugroho *et al.*, 2024; Khan *et al.*, 2024). These health-promoting effects are largely attributed to the synergistic interactions among diverse microbial

populations and the complex matrix of bioactive metabolites generated during fermentation.

In parallel with the increasing popularity of fermented foods, commercial probiotic supplements have emerged as a convenient alternative for delivering beneficial microorganisms. Probiotic capsules, tablets, powders, and sachets typically contain carefully selected bacterial strains at standardized concentrations, enabling precise dosage and longer shelf life. However, unlike naturally fermented foods, commercial probiotic formulations generally contain a limited number of microbial strains and often lack the diverse microbial interactions and metabolite-rich food matrix that characterize traditional fermented products (Urbas *et al.*, 2024; Meena and Rai, 2023). This distinction has generated considerable scientific interest regarding whether probiotic supplements can provide health benefits comparable to those derived from naturally fermented foods.

Comparative studies indicate that fermented foods generally possess greater microbial diversity and functional complexity than probiotic supplements. For example, yogurt is predominantly enriched with *Lactobacillus* and *Bifidobacterium* species, whereas fermented vegetables such as kimchi and sauerkraut harbor a broader range of LAB, including *Lactiplantibacillus plantarum*, *Leuconostoc mesenteroides*, *Weissella* spp., and *Pediococcus* spp. The viability, colonization potential, and functional efficacy of these microorganisms are influenced by factors such as fermentation conditions, storage, processing, and the surrounding food matrix. Furthermore, heat treatment or cooking may alter microbial viability while preserving beneficial postbiotic compounds, thereby influencing the overall physiological effects of fermented foods (Gaudioso *et al.*, 2022; Nugroho *et al.*, 2024; Saha *et al.*, 2025; Yordanova *et al.*, 2024).

Despite remarkable advances in probiotic research, important knowledge gaps remain regarding the comparative effectiveness of probiotic microorganisms derived from fermented foods and those supplied through commercial supplements. Although probiotic supplements offer standardized microbial doses and targeted therapeutic applications, fermented foods provide naturally occurring multispecies microbial communities, diverse functional metabolites, and synergistic interactions that may enhance probiotic functionality. Existing evidence remains fragmented due to differences in microbial strains, food matrices, processing technologies, dosage, and study design, making direct comparisons challenging (Jeong *et al.*, 2021; Urbas *et al.*, 2024).

Therefore, the present review critically synthesizes recent literature on probiotic microorganisms present in major fermented foods and commercial probiotic supplements. Particular emphasis is placed on microbial diversity, mechanisms of probiotic action, bioactive metabolites, health-promoting properties, and recent advances in molecular characterization. Furthermore, the review highlights current research gaps, discusses practical implications for human health and the food industry, and outlines future research directions for developing evidence-based probiotic interventions.

Microbial Diversity and Identification in Fermented Foods

The microbial diversity of fermented foods has been extensively characterized using culture-dependent techniques together with molecular approaches such as 16S rRNA gene sequencing and metagenomic analysis. These techniques have revealed that fermented foods harbor diverse probiotic microorganisms, predominantly lactic acid bacteria (LAB), whose composition varies according to the substrate, fermentation process, geographical origin, and storage conditions (Palmnäs-Bédard *et al.*, 2023; Yordanova *et al.*, 2024).

Yogurt is primarily dominated by *Lactobacillus*, *Bifidobacterium*, and *Streptococcus thermophilus*, whereas fermented vegetables such as kimchi and sauerkraut contain abundant populations of *Lactiplantibacillus plantarum*, *Leuconostoc mesenteroides*, *Lactobacillus brevis*, *Weissella*, and *Pediococcus* species. These microbial consortia contribute not only to fermentation and food preservation but also to the production of bioactive metabolites that enhance probiotic functionality and product quality (Gaudioso *et al.*, 2022; Nugroho *et al.*, 2024).

Although next-generation sequencing has considerably improved microbial characterization, several methodological limitations remain. Differences in sampling procedures, sequencing depth, DNA extraction methods, and bioinformatic pipelines can influence microbial diversity estimates and reduce comparability among studies. In addition, low-abundance yet functionally important taxa may be underestimated or overlooked because of analytical limitations, emphasizing the need for standardized protocols in microbial identification and functional validation (Petroviæ *et al.*, 2011; Zhou *et al.*, 2018; Bati and Boyko, 2016).

Beyond taxonomic identification, several studies have demonstrated that probiotic microorganisms isolated from fermented foods possess desirable functional attributes, including acid and bile tolerance, antimicrobial activity,

adhesion to intestinal epithelial cells, antioxidant capacity, and immunomodulatory potential (Jeong *et al.*, 2021; Pandey *et al.*, 2024; Sagioglu *et al.*, 2023). However, most evidence is derived from laboratory investigations or animal experiments, whereas well-controlled human intervention studies directly comparing fermented foods with commercial probiotic supplements remain limited (Li *et al.*, 2019; Urbæ *et al.*, 2024). Consequently, integrating molecular identification with functional and clinical validation will be essential for accurately assessing the probiotic potential of microorganisms associated with fermented foods.

Health Benefits of Probiotic Microbes from Fermented Foods

Probiotic microorganisms present in fermented foods provide a wide range of health benefits by maintaining gut microbial homeostasis, strengthening intestinal barrier function, regulating immune responses, and inhibiting the growth of pathogenic microorganisms. These beneficial effects are largely mediated through the production of organic acids, bacteriocins, exopolysaccharides, and other bioactive metabolites generated during fermentation (Tingirikari *et al.*, 2024; Meena and Rai, 2023).

Regular consumption of fermented foods has been associated with improved digestive health, enhanced nutrient absorption, and restoration of gut microbial balance. Several probiotic strains isolated from yogurt, kimchi, sauerkraut, and other fermented foods exhibit antimicrobial, antioxidant, and anti-inflammatory activities that contribute to improved gastrointestinal and immune health (Park *et al.*, 2017; Pandey *et al.*, 2024; Sagioglu *et al.*, 2023). In addition, probiotic metabolites have been reported to modulate cytokine production and reduce oxidative stress, thereby contributing to protection against chronic inflammatory and metabolic disorders (Pyo *et al.*, 2024; Saha *et al.*, 2025).

Emerging evidence also highlights the role of fermented food-derived probiotics in regulating the gut–brain axis. Certain lactic acid bacteria produce neuroactive compounds, including γ -aminobutyric acid (GABA) and serotonin precursors, which influence neuronal signaling and may alleviate stress, anxiety, and depression-like symptoms (Sun *et al.*, 2024; Hao *et al.*, 2024). These findings further support the broader physiological significance of fermented foods beyond digestive health.

Despite encouraging evidence, most studies investigating probiotic functionality are based on *in vitro* experiments or animal models, whereas randomized controlled human trials directly comparing fermented foods with commercial probiotic supplements remain

limited. Moreover, differences in microbial strains, viable cell counts, food matrices, product formulation, and intervention duration contribute to inconsistencies in reported health outcomes (Yu *et al.*, 2013; Urbas *et al.*, 2024). Therefore, well-designed clinical studies employing standardized methodologies are required to validate the long-term health benefits of fermented food-derived probiotics and establish evidence-based dietary recommendations.

Comparison Between Fermented Foods and Probiotic Pills

Fermented foods and commercial probiotic supplements differ considerably in their microbial composition, functional properties, and mode of delivery. Fermented foods naturally contain multispecies microbial communities together with bioactive metabolites such as organic acids, bacteriocins, exopolysaccharides, and peptides, whereas probiotic supplements generally contain a limited number of well-characterized strains formulated to deliver standardized microbial doses (Kwofie *et al.*, 2020; Meena and Rai, 2023). The complex food matrix of fermented products may further enhance microbial survival and functionality through synergistic interactions among microorganisms and their metabolites.

Naturally fermented foods generally contain viable microbial populations ranging from 10^6 to 10^8 CFU mL⁻¹ or g⁻¹, although microbial abundance varies with the fermentation substrate, duration, and storage conditions (Orgeron *et al.*, 2016; Zhou *et al.*, 2018). Appropriate fermentation and refrigerated storage help maintain microbial viability, whereas pasteurization, prolonged storage, and thermal processing may significantly reduce the number of viable probiotic cells and alter microbial composition (Gaudio *et al.*, 2022; Nugroho *et al.*, 2024). In contrast, probiotic supplements employ encapsulation and other formulation technologies to improve microbial stability, extend shelf life, and ensure consistent dosage (Urbæ *et al.*, 2024).

Several comparative studies have reported that probiotic strains isolated from fermented foods exhibit superior acid and bile tolerance, antimicrobial activity, adhesion to intestinal epithelial cells, and colonization potential compared with some commercially available probiotic formulations (Jeong *et al.*, 2021; Choi *et al.*, 2014; Song *et al.*, 2010). These characteristics enhance their ability to survive gastrointestinal transit and contribute to improved probiotic functionality. However, strain-specific performance varies considerably, and probiotic efficacy cannot be generalized solely based on the source of isolation.

Despite increasing research, direct comparisons between fermented foods and probiotic supplements remain limited because of differences in microbial strains, food matrices, formulation technologies, dosage, and study design. Furthermore, consumer preference, convenience, shelf life, and product standardization continue to influence the widespread use of commercial probiotic supplements (Paul *et al.*, 2023). Future randomized clinical studies employing standardized protocols are required to establish the comparative efficacy of fermented foods and probiotic supplements for specific health outcomes (Petrovis *et al.*, 2011; Urbæ *et al.*, 2024).

Mechanisms of Probiotic Action

Probiotic microorganisms exert their beneficial effects through multiple interconnected mechanisms involving modulation of gut microbial ecology, competitive exclusion of pathogens, production of antimicrobial compounds, enhancement of intestinal barrier function, and regulation of host immune responses. These activities collectively contribute to improved gastrointestinal health and maintenance of microbial homeostasis (Feng *et al.*, 2015; Ge *et al.*, 2009).

Several probiotic strains isolated from fermented foods interact with intestinal epithelial and immune cells to regulate cytokine production, suppress pro-

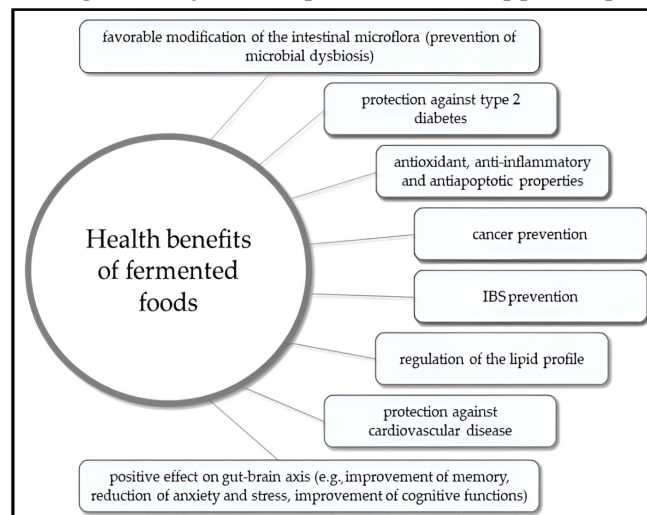


Fig. 1: Health benefits of fermented foods. [Major health benefits associated with fermented foods, including modulation of gut microbiota, antioxidant and anti-inflammatory activities, regulation of lipid metabolism, protection against type 2 diabetes and cardiovascular diseases, prevention of irritable bowel syndrome (IBS), cancer prevention, and modulation of the gut–brain axis leading to improved cognitive function, reduced stress, and enhanced mental well-being. Source: Adapted from Cha *et al.*, 2024. Licensed under the Creative Commons Attribution 4.0 International (CC BY 4.0) license].

inflammatory responses, and stimulate anti-inflammatory pathways. In addition, the production of bacteriocins, organic acids, and short-chain fatty acids inhibits the growth of pathogenic microorganisms while promoting the proliferation of beneficial gut microbiota (Pyo *et al.*, 2024; Meena and Rai, 2023).

Recent studies have also highlighted the importance of the gut–brain axis, where certain lactic acid bacteria produce neuroactive metabolites that influence neuronal signaling, stress responses, and cognitive function. These findings suggest that probiotic microorganisms may provide benefits beyond gastrointestinal health by contributing to mental well-being and neuroprotection (Sun *et al.*, 2024; Hao *et al.*, 2024).

Despite substantial progress, the molecular mechanisms underlying probiotic activity remain only partially understood. Most mechanistic studies have focused on individual probiotic strains under controlled laboratory conditions, whereas the complex interactions among multispecies microbial communities, host metabolism, and dietary components remain largely unexplored. Integrating multi-omics approaches with longitudinal clinical studies will improve understanding of host–microbe interactions and facilitate the identification of key molecular pathways responsible for probiotic functionality (Gaudioso *et al.*, 2022; Khan *et al.*, 2024).

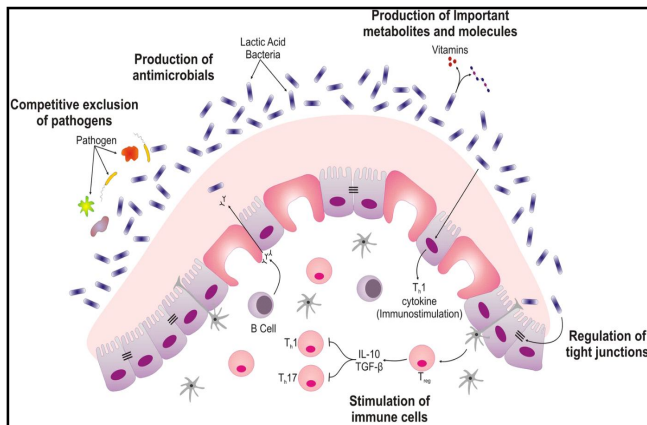


Fig. 2: Mechanisms of probiotic action in the intestinal environment. [Schematic representation of the mechanisms by which probiotic microorganisms, particularly lactic acid bacteria (LAB), exert beneficial effects in the intestinal environment. Probiotic microorganisms competitively exclude pathogenic bacteria, produce antimicrobial compounds and essential metabolites, regulate epithelial tight junctions, enhance intestinal barrier integrity, and modulate innate and adaptive immune responses, thereby maintaining gut microbial homeostasis and promoting host health. Source Adapted from Azad *et al.*, 2019. Licensed under the Creative Commons Attribution 4.0 International (CC BY 4.0) license].

Metabolites and Bioactive Compounds in Fermented Foods

Fermentation generates a wide variety of bioactive compounds, including lactic acid, acetic acid, amino acids, bioactive peptides, vitamins, exopolysaccharides, and short-chain fatty acids, which collectively enhance the nutritional and functional properties of fermented foods. These metabolites contribute to antioxidant, antimicrobial, anti-inflammatory, and immunomodulatory activities that support host health (Wijaya *et al.*, 2024; Meena and Rai, 2023).

In addition to live probiotic microorganisms, increasing attention has been directed toward postbiotics, which comprise non-viable microbial cells, cell components, and metabolites produced during fermentation. These bioactive compounds retain physiological activity even after microbial inactivation, thereby extending the health-promoting potential of fermented foods beyond the presence of viable probiotic cells (Nugroho *et al.*, 2024).

The composition and concentration of fermentation-derived metabolites are influenced by the microbial community, substrate composition, fermentation duration, and processing conditions, resulting in considerable variation among fermented food products (Gaudioso *et al.*, 2022; Wijaya *et al.*, 2024). Consequently, differences in metabolite profiles often contribute to inconsistencies in the reported functional properties of fermented foods.

Although metabolomic technologies have considerably improved the characterization of fermentation-derived bioactive compounds, the absence of standardized analytical workflows limits comparisons across studies and hampers mechanistic interpretation. Future investigations integrating metabolomics with microbiome analysis and clinical validation will provide a more comprehensive understanding of how these metabolites contribute to human health and probiotic efficacy (Khan *et al.*, 2024).

Theoretical and Practical Implications

The findings synthesized in this review reinforce the concept that fermented foods are complex microbial ecosystems capable of delivering health benefits beyond those provided by conventional probiotic supplements. The coexistence of diverse probiotic microorganisms, together with fermentation-derived bioactive metabolites, supports ecological theories emphasizing the importance of microbial interactions and food matrices in determining probiotic functionality (Palmnäs-Bédard *et al.*, 2023; Yordanova *et al.*, 2024). Furthermore, the emerging recognition of postbiotics broadens the conventional definition of probiotics by demonstrating that non-viable

microbial cells and their metabolites can also contribute to immunomodulatory and antioxidant activities (Nugroho *et al.*, 2024).

From a practical perspective, fermented foods represent sustainable and culturally acceptable dietary sources of probiotics with potential applications in nutrition, public health, and functional food development. The food industry can exploit naturally occurring microbial diversity to develop next-generation fermented products with improved stability and functionality, while public health programs may encourage the inclusion of traditional fermented foods in dietary recommendations as complementary alternatives to probiotic supplements (Kwofie *et al.*, 2020; Saha *et al.*, 2025). Future probiotic formulations may also benefit from incorporating multispecies microbial consortia and fermentation-derived metabolites to better replicate the functional complexity of fermented foods (Sagiroglu *et al.*, 2023).

Limitations and Future Research Directions

Despite considerable advances in probiotic research, several limitations continue to restrict the translation of experimental findings into clinical applications. Many published studies rely on *in vitro* assays or animal models, while relatively few long-term randomized clinical trials have evaluated the health benefits of fermented foods in human populations. In addition, variations in fermentation processes, microbial enumeration, strain identification, and analytical methodologies reduce reproducibility and limit comparisons among studies (Mahasneh *et al.*, 2015; Urbæ *et al.*, 2024).

Future research should prioritize standardized fermentation protocols, harmonized analytical approaches, and well-designed human intervention studies. Integrating multi-omics technologies, including metagenomics, metabolomics, transcriptomics, and microbiome profiling, will improve understanding of microbial interactions, metabolite production, and host responses. Such integrated approaches will facilitate the identification of functionally important probiotic strains and strengthen evidence supporting the therapeutic potential of fermented foods (Pandey *et al.*, 2024; Wu *et al.*, 2021).

Conclusion

Fermented foods are valuable natural sources of probiotic microorganisms that provide diverse microbial communities together with bioactive metabolites capable of promoting digestive, immune, metabolic, and neurological health. Compared with commercial probiotic supplements, fermented foods generally offer greater microbial diversity and a complex food matrix that may enhance probiotic functionality through synergistic

interactions among microorganisms and their metabolites. Nevertheless, probiotic supplements remain advantageous where standardized dosing, product stability, and targeted strain delivery are required.

Current evidence indicates that both fermented foods and probiotic supplements have complementary roles in promoting human health rather than functioning as competing alternatives. However, substantial gaps remain regarding strain-specific efficacy, optimal dosage, and long-term clinical outcomes. Future research integrating standardized clinical trials with advanced molecular and metabolomic approaches will provide stronger evidence for developing evidence-based dietary recommendations and next-generation probiotic products.

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