Microbial Fermentation of Plant-Based Foods: Advances in Nutrient Bioavailability, Functional Compounds, and Sustainable Food Processing

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Article Info

ISSN (online): 3107-6467
Volume: 02
Issue: 03
Received: 14-03-2026
Accepted: 12-04-2026
Published: 10-05-2026
Page No: 40-45

Abstract
Background: Global demand for plant-based foods is rising due to health, environmental and ethical considerations. Cereals, legumes, pulses, pseudocereals, fruits, vegetables, nuts, seeds and oilseeds form the core of sustainable diets, yet their nutritional value is limited by low protein digestibility, restricted mineral bioavailability and the presence of antinutritional factors.
Objective: This review synthesises current evidence on microbial fermentation as a biological strategy to enhance nutrient bioavailability, generate functional compounds and support sustainable processing of plant-based foods.
Methods: Peer-reviewed literature from major scientific databases was critically analysed with respect to microbial systems, process parameters, nutritional and functional outcomes, food safety and sustainability implications.
Results: Lactic acid bacteria, yeasts, *Bacillus* spp. and selected filamentous fungi degrade phytate, tannins and other antinutrients through enzymatic and acid-mediated mechanisms, improve protein digestibility and mineral accessibility, synthesise or liberate B-group vitamins, and transform plant phytochemicals into more bioavailable phenolics, flavonoids and bioactive peptides. Controlled fermentation also enhances microbial safety and shelf life while enabling valorisation of agricultural by-products.
Conclusion: Microbial fermentation offers a scientifically robust route to nutritionally superior, functional and sustainable plant-based foods. Industrial translation requires standardised starter cultures, optimised process control and stronger human clinical evidence.

Keywords: Microbial fermentation, Plant-based foods, Nutrient bioavailability, Functional compounds, Lactic acid bacteria, Antinutritional factors, Food safety, Sustainable processing

1. Introduction
1.1. Global Rise of Plant-Based Foods
Plant-based foods are central to contemporary dietary transitions driven by concerns over health, climate change and resource efficiency [1]. Cereals, legumes, pulses, millets, pseudocereals, fruits, vegetables, nuts, seeds and oilseeds supply the majority of global dietary energy and plant protein while supporting food security in diverse agro-ecological zones [2]. Their production generally requires fewer land, water and greenhouse-gas inputs than animal-source foods, aligning plant-based diets with sustainable food-system goals [3].

1.2. Nutritional Limitations of Plant-Based Foods
Despite favourable macronutrient and phytochemical profiles, plant matrices frequently exhibit incomplete protein quality, limited essential-amino-acid balance and low mineral bioavailability [4]. Antinutritional factors—phytic acid, tannins, oxalates, saponins, protease inhibitors and lectins—form insoluble complexes with proteins and minerals, impairing digestibility and absorption [5,6]. Structural barriers such as cell-wall polysaccharides further restrict nutrient release during gastrointestinal

digestion. Compositional variability among cultivars and growing conditions adds complexity to nutritional outcomes [7].

1.3. Fermentation as a Biological Processing Strategy
Microbial fermentation is the controlled metabolic conversion of organic substrates by microorganisms under anaerobic or microaerophilic conditions [8]. Historically applied for preservation and flavour development, modern controlled fermentation employs selected starter cultures to achieve reproducible nutritional and functional improvements [9]. Compared with thermal or chemical treatments, fermentation simultaneously enhances nutrient accessibility, reduces antinutrients, generates bioactive metabolites and improves sensory and safety attributes with relatively low energy input [10].

1.4. Research Rationale and Objectives
Although traditional fermented plant foods are widely consumed, systematic optimisation of microbial systems for targeted biofortification, functional-compound enrichment and industrial scalability remains incomplete. This review examines microbial systems, technological approaches, nutrient-bioavailability enhancement, antinutrient reduction, functional-compound formation, health-related effects, food safety, applications across plant-food categories and contributions to sustainable processing. The objective is to provide an evidence-based synthesis that integrates nutrition, microbiology, food technology and sustainability.

2. Microbial Systems Involved in Plant-Based Food Fermentation
Lactic acid bacteria (LAB), particularly *Lactiplantibacillus plantarum*, *Levilactobacillus brevis* and related species, dominate many plant fermentations through homo- or heterofermentative pathways that generate lactic and acetic acids, lower pH and produce enzymes including phytase and proteases [11]. Bifidobacteria contribute to carbohydrate metabolism and short-chain-fatty-acid precursors in specialised applications. Yeasts such as *Saccharomyces cerevisiae* perform alcoholic fermentation, proteolysis and vitamin synthesis while interacting synergistically with LAB [12]. *Bacillus* spp. mediate alkaline fermentations of legumes, elevating protein digestibility and vitamin K_2 [13]. Filamentous fungi (*Rhizopus*, *Aspergillus*, *Pleurotus*) excel in solid-state systems through extensive protease, phytase and tannase activities [14]. Mixed-culture fermentations exploit complementary metabolic pathways. Starter cultures offer reproducibility and safety advantages over spontaneous fermentations, with selection criteria emphasising enzyme profiles, acidification kinetics, sensory neutrality and absence of virulence factors [15].

3. Fermentation Processes and Technological Approaches
3.1. Solid-State Fermentation
Solid-state fermentation (SSF) occurs on moist solid substrates with limited free water. It is well suited to cereals, legumes and agro-residues, supports high enzyme titres and generates minimal effluent [16]. Limitations include heat and mass-transfer constraints and process monitoring challenges.

3.2. Submerged Fermentation
Submerged fermentation (SmF) employs liquid media, facilitating precise control of pH, temperature and aeration. It is widely applied to plant-based beverages and hydrolysates but requires greater water and energy inputs [17].

3.3. Spontaneous Versus Controlled Fermentation
Spontaneous fermentation relies on indigenous microbiota, yielding high microbial diversity but variable nutritional and sensory outcomes. Controlled starter-culture fermentation improves reproducibility, safety and targeted metabolite profiles, facilitating industrial scale-up [18].

3.4. Key Fermentation Parameters
Temperature, pH, duration, moisture, oxygen availability, inoculum size and substrate composition critically determine enzyme activity, acidification rate and final product quality. Optimisation of these parameters maximises nutrient liberation and functional-compound formation while minimising undesirable metabolites [19].

4. Enhancement of Nutrient Bioavailability
4.1. Protein Digestibility and Amino Acid Availability
Microbial proteases hydrolyse storage proteins, generate peptides and free amino acids, and reduce protein–antinutrient interactions, elevating in-vitro and in-vivo digestibility [20]. Essential amino acids such as lysine and leucine increase notably in fermented cereals and legumes.

4.2. Mineral Bioavailability
Phytase activity and organic-acid production degrade phytate and chelate minerals, improving solubility and estimated bioavailability of iron, zinc, calcium, magnesium and phosphorus [21,22]. Phytate reductions of 50–90 % are commonly reported, with corresponding improvements in mineral accessibility.

4.3. Vitamin Enhancement
Selected LAB and propionibacteria synthesise folate and riboflavin; *Bacillus* and certain fungi elevate vitamin K_2 or contribute to B_{12} under specific conditions. Fermentation may also liberate bound vitamin forms, increasing overall bioavailability [23].

4.4. Carbohydrate Transformation
Amylolytic activity reduces starch crystallinity, modifies dietary fibre, and generates oligosaccharides that may act as prebiotic substrates. These changes can lower glycaemic response and supply precursors for short-chain fatty acids [24].

5. Reduction of Antinutritional Factors
Phytic acid is degraded by endogenous and microbial phytases activated under acidic conditions [25]. Tannins are hydrolysed by tannase; oxalates, protease inhibitors, saponins and lectins decline through enzymatic and acid-mediated mechanisms [26]. Reductions improve protein digestibility and mineral absorption, although extent varies with strain, substrate and process conditions [27].

6. Formation and Enhancement of Functional Compounds

Fermentation liberates bound phenolics and flavonoids, generates bioactive peptides via proteolysis, and produces organic acids, exopolysaccharides and bacteriocins [28]. These transformations elevate antioxidant capacity and radical-scavenging activity *in vitro*. Demonstrated biological effects remain primarily laboratory- and animal-based; human clinical evidence is still emerging [29].

7. Impact on Digestibility, Gut Microbiota, and Health

Improved macronutrient digestibility and delivery of live or residual microorganisms and metabolites can modulate intestinal microbiota composition and activity. Prebiotic oligosaccharides and short-chain-fatty-acid precursors support gut-barrier function in experimental models. Associations with metabolic health markers have been observed, yet robust long-term human trials remain limited [30].

8. Food Safety and Shelf-Life Extension

Rapid acidification, competitive exclusion and bacteriocin production suppress foodborne pathogens and spoilage organisms, extending shelf life [9]. Certain fermentations reduce selected mycotoxins. Risks include biogenic-amine formation, residual mycotoxins or contamination under uncontrolled conditions, underscoring the necessity of hygienic starter cultures and process control [18].

9. Applications Across Plant-Based Food Categories

Cereals and millets benefit from phytate reduction and B-vitamin enrichment; pulses and legumes show improved protein quality and reduced flatulence factors; soy-based products gain digestibility and vitamin K_2; fruits, vegetables and roots/tubers exhibit enhanced phenolic profiles and safety; plant-based beverages and meat analogues utilise fermentation for flavour, texture and nutritional upgrading [1 1,14,2 0].

10. Sustainable Food Processing and Circular Bioeconomy

Fermentation valorises cereal bran, legume residues, fruit and vegetable by-products and other agro-industrial streams into functional ingredients, reduces waste, extends shelf life and lowers reliance on chemical processing [16]. Locally adapted systems support climate-resilient and resource-efficient food production.

11. Materials and Methods / Review Methodology

11.1. Literature Search

Literature was retrieved from PubMed, Scopus, Web of Science, Google Scholar and ScienceDirect.

11.2. Search Terms

Combinations of "plant-based food fermentation", "microbial fermentation", "nutrient bioavailability", "functional compounds", "lactic acid bacteria", "antinutritional factors", "fermented plant foods" and "sustainable food processing" were used.

11.3. Selection Criteria

Peer-reviewed original research and relevant reviews reporting nutritional, functional, microbiological, safety or sustainability outcomes of plant-based fermentations were included. Non-scientific sources, duplicates and studies lacking methodological detail were excluded.

11.4. Evidence Synthesis

Findings were compared by substrate, microorganism, fermentation method, process conditions and reported outcomes.

12. Results and Evidence Synthesis

Across plant substrates, controlled fermentation consistently improves protein digestibility, mineral bioavailability indices and selected vitamin levels while reducing phytate, tannins and other antinutrients. Phenolic accessibility and antioxidant activity increase through enzymatic transformation. Safety and shelf-life benefits are well documented under controlled conditions. Outcomes differ by microbial strain, matrix and process parameters; SSF often favours enzyme production and phenolic release, whereas SmF facilitates soluble-nutrient enhancement. Variability among studies highlights the need for standardised protocols.

13. Discussion

Microbial fermentation improves plant-food nutritional quality by combining enzymatic hydrolysis, acidification and secondary metabolism. Strain-specific enzyme profiles and substrate composition determine the magnitude of benefit. Parameter optimisation is essential for reproducibility. Food-safety gains are substantial yet contingent on process hygiene. Sensory acceptance, industrial scalability, starter-culture standardisation, regulatory frameworks and economic feasibility remain practical challenges. Current evidence is strongest for compositional and in-vitro bioavailability improvements; long-term human trials and standardised process metrics are still limited.

14. Future Perspectives

Precision fermentation, multi-omics strain characterisation, AI-assisted process optimisation, synthetic consortia, high-throughput screening and digital monitoring offer routes to next-generation starter cultures and personalised functional foods. Fermentation of underutilised and climate-resilient crops, coupled with by-product valorisation, can further strengthen sustainable plant-based food systems.

15. Conclusion

Microbial fermentation substantially enhances nutrient bioavailability, reduces antinutritional factors, generates functional compounds and improves safety and shelf life of plant-based foods. These effects support the development of nutritionally superior and sustainable products. Realisation of full potential requires standardised processes, robust starter cultures and stronger clinical validation.

Table 1: Microorganisms and fermentation mechanisms influencing the nutritional and functional properties of plant-based foods

Microorganism	Representative food substrate	Major metabolic activity	Nutritional effect	Functional effect
Lactiplantibacillus plantarum & LAB	Cereals, legumes, millets	Phytase, protease, organic-acid production	Phytate ↓, minerals ↑, protein digestibility ↑	Antioxidant activity, probiotic potential
Saccharomyces cerevisiae	Cereals, plant beverages	Alcoholic fermentation, proteolysis	Free amino acids ↑, B vitamins	Flavour development, digestibility
Bacillus subtilis	Soy, legumes	Alkaline fermentation, menaquinone synthesis	Protein enrichment, vitamin K_2 ↑	Bioactive peptides
Rhizopus / *Aspergillus* spp.	Soy, legumes, cereals	Extensive protease, phytase, tannase	Antinutrients ↓, digestibility ↑	Phenolic release, antioxidant capacity
Mixed LAB–yeast cultures	Cereals, pulses	Complementary acidification & proteolysis	Balanced nutrient enhancement	Sensory quality, safety

Table 2: Effects of microbial fermentation on nutrients, antinutritional factors, bioactive compounds, and food quality

Food category	Component	Fermentation-induced change	Proposed mechanism	Nutritional/functional significance
Cereals & millets	Phytate	50–90 % reduction	Microbial & endogenous phytase + acidification	Fe, Zn, Ca bioavailability ↑
Legumes & pulses	Protein digestibility	Significant increase	Proteolysis + inhibitor reduction	Amino-acid availability ↑
Various plant foods	Phenolics & flavonoids	Liberation & biotransformation	Enzymatic hydrolysis of bound forms	Antioxidant capacity ↑
Cereals, legumes	Folate, riboflavin	Increase	Microbial synthesis & liberation	B-vitamin status improvement
Soy & legumes	Tannins, protease inhibitors	Substantial reduction	Tannase, proteolytic activity	Digestibility & mineral absorption ↑
Plant matrices	Organic acids, bacteriocins	Accumulation	Primary & secondary metabolism	Pathogen inhibition, shelf-life extension

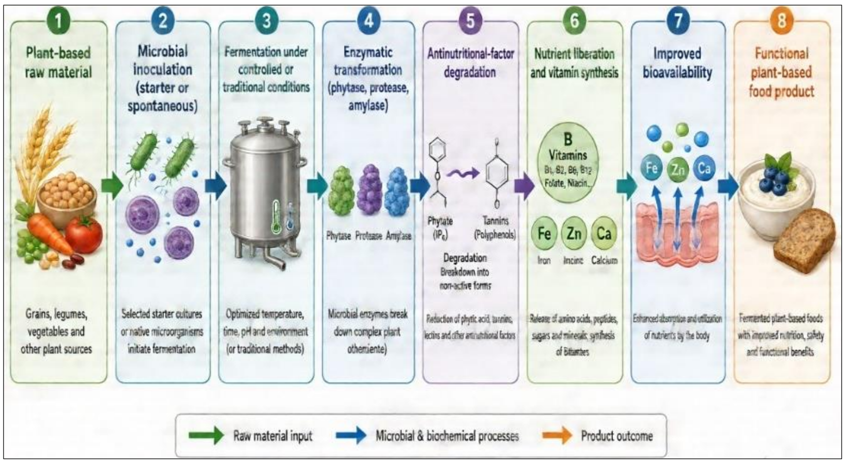

Fig 1: Microbial fermentation pathway for improving nutritional quality and bioavailability of plant-based foods

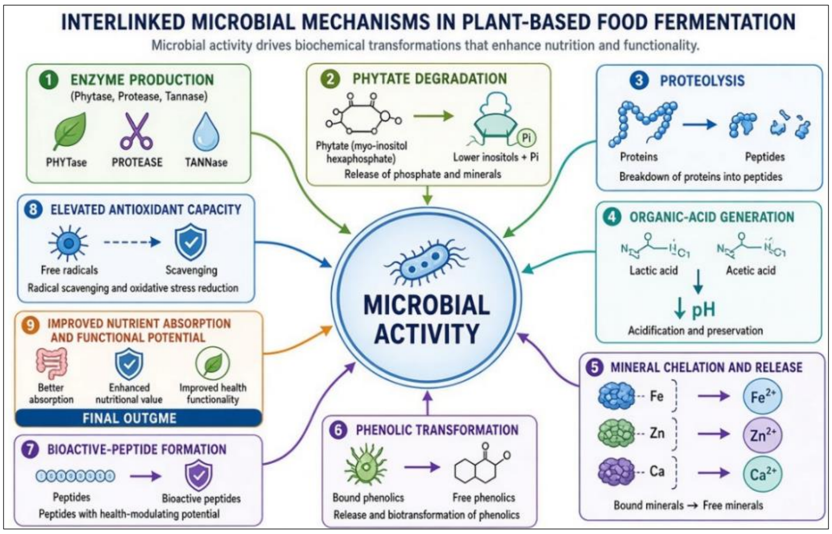

Fig 2: Microbial mechanisms responsible for functional-compound formation and nutritional enhancement

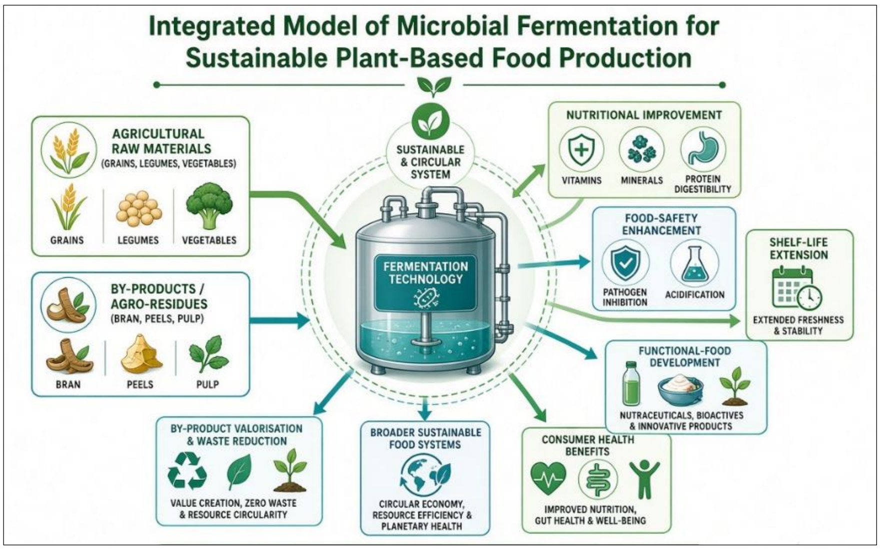

Fig 3: Integrated model of microbial fermentation for sustainable plant-based food production

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How to Cite This Article
Kapoor P. Microbial fermentation of plant-based foods: advances in nutrient bioavailability, functional compounds, and sustainable food processing. Int J Agric Food Ferment. 2026;2(3):40-45.

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