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Based Biofortification of Agricultural Foods: Enhancing Nutritional Quality, Functional Properties, and Food Safety

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Abstract
Background: Agricultural foods, including cereals, pulses, legumes, millets, fruits, vegetables, roots and tubers, form the foundation of global food and nutritional security. However, their nutritional value is frequently limited by antinutritional factors (phytate, tannins, oxalates, protease inhibitors) that reduce nutrient bioavailability.
Objective: This review examines fermentation as a biological biofortification strategy to improve nutritional quality, functional properties and food safety of agricultural commodities.
Methods: Peer-reviewed literature from major scientific databases was synthesised, focusing on microbial mechanisms, nutrient enhancement, antinutritional-factor reduction and safety outcomes across solid-state and submerged fermentation systems.
Results: Lactic acid bacteria, yeasts, *Bacillus* spp. and selected filamentous fungi produce enzymes (phytase, protease, amylase) and organic acids that degrade antinutrients, liberate minerals (Fe, Zn, Ca, Mg), synthesise or increase B-group vitamins (folate, riboflavin, niacin) and bioactive compounds, and improve protein digestibility. Concurrent acidification and antimicrobial metabolite production enhance microbial safety and shelf life.
Conclusion: Fermentation-based biofortification offers a sustainable, low-cost route to nutritionally superior functional foods. Standardisation of starter cultures, process parameters and sensory quality remains essential for industrial translation and contribution to food and nutritional security.

Keywords: Fermentation, Biofortification, Agricultural Foods, Nutrient Bioavailability, Antinutritional Factors, Functional Foods, Food Safety, Lactic Acid Bacteria

1. Introduction

Agricultural foods supply the majority of dietary energy, protein and micronutrients worldwide and remain central to food and nutritional security, particularly in low- and middle-income regions [1, 2]. Cereals, pulses, legumes, millets and other plant commodities contain substantial macronutrients, minerals and phytochemicals; yet their effective utilisation is constrained by limited nutrient bioavailability [3]. Antinutritional factors—phytic acid, tannins, oxalates, protease inhibitors, saponins and lectins—form complexes with proteins and minerals, reducing digestibility and absorption [4, 5].

Biofortification conventionally relies on agronomic practices or genetic selection to elevate nutrient density in edible portions. Fermentation-based biofortification provides a complementary, post-harvest biological approach that simultaneously enhances nutrient content or accessibility, degrades antinutrients and generates bioactive metabolites [6, 7]. Fermentation is a sustainable, low-energy technology compatible with traditional food systems and modern controlled bioprocessing [8]. Beneficial microorganisms transform substrates through enzymatic hydrolysis and secondary metabolism, improving nutritional profiles without external chemical fortificants [9].

Despite extensive traditional use, systematic understanding of strain-specific mechanisms, process optimisation and industrial scalability for targeted biofortification remains incomplete. This review synthesises current evidence on the scientific basis, nutritional and functional outcomes, safety implications and applications of fermentation-based biofortification of agricultural foods, identifying research gaps and future directions.

2. Fermentation and Biofortification: Scientific Basis

Food fermentation is the controlled microbial conversion of organic substrates under anaerobic or microaerophilic conditions, producing organic acids, alcohols, CO_2 and a range of metabolites [10]. Principal microorganisms include lactic acid bacteria (LAB: *Lactiplantibacillus plantarum*, *Levilactobacillus brevis*, *Lactobacillus* spp.), yeasts (*Saccharomyces cerevisiae*), *Bacillus* spp. and filamentous fungi (*Rhizopus*, *Aspergillus*, *Pleurotus*) [11,12]. Homofermentative LAB generate primarily lactic acid; heterofermentative strains also produce acetic acid, ethanol and CO_2. Solid-state fermentation (SSF) operates on moist solid substrates with limited free water and is particularly suited to cereals and legumes; submerged fermentation (SmF) occurs in liquid media [13].

Nutritional enhancement arises from microbial enzymes—phytase, protease, amylase, cellulase and tannase—that hydrolyse antinutrients and complex macromolecules, together with de novo synthesis of vitamins and bioactive peptides [14,15]. Fermentation parameters (pH, temperature, duration, moisture, oxygen availability and starter-culture composition) critically determine the extent of nutrient improvement [16].

3. Fermentation-Based Enhancement of Nutritional Quality

3.1. Proteins and Amino Acids

Microbial proteases increase protein digestibility and liberate free amino acids and peptides. Essential amino acids such as lysine and leucine, often limiting in cereal–legume diets, rise substantially after LAB or fungal fermentation [17,18]. Reduction of protein-complexing antinutrients further improves bioavailability.

3.2. Vitamins

Selected LAB and propionibacteria synthesise folate, riboflavin and, under specific conditions, vitamin B_{12}. *Bacillus subtilis* elevates menaquinone (vitamin K_2) in fermented soybeans. Increases of several-fold in B-group vitamins have been documented in cereals and legumes [19–21].

3.3. Minerals and Mineral Bioavailability

Phytase activity and organic-acid production lower phytate–mineral molar ratios, markedly improving solubility and estimated bioavailability of iron, zinc, calcium, magnesium and phosphorus [22–24]. Reductions in phytate of 50–90 % are commonly reported, translating into 1.5- to >2-fold higher mineral accessibility.

3.4. Bioactive and Antioxidant Compounds

Fermentation releases bound phenolics and flavonoids, generates bioactive peptides and organic acids, and elevates overall antioxidant capacity through microbial biotransformation of plant phytochemicals [25,26].

4. Reduction of Antinutritional Factors

Phytic acid is degraded by endogenous and microbial phytases activated under the acidic conditions of fermentation [27]. Tannins are hydrolysed by tannase; oxalates, protease inhibitors, saponins and lectins decline through enzymatic and acid-mediated mechanisms [28,29]. These reductions improve protein digestibility, mineral absorption and gastrointestinal tolerance [30].

5. Functional Properties and Health-Promoting Potential

Fermented agricultural foods exhibit improved digestibility, modulated glycaemic response, elevated antioxidant activity and the capacity to deliver viable probiotics or generate prebiotic oligosaccharides [31]. Bioactive peptides may exert anti-inflammatory or antihypertensive effects *in vitro* and in animal models; however, robust human evidence remains limited and strain- and matrix-dependent [32].

6. Fermentation and Food Safety

Organic acids, bacteriocins and competitive exclusion suppress foodborne pathogens and spoilage organisms, extending shelf life [33]. Certain fermentations reduce mycotoxins. Process control of pH, temperature, duration, moisture and starter cultures is essential to ensure safety and prevent unwanted microbial growth or toxin formation [34].

7. Agricultural Food Applications

Successful applications include LAB or mixed-culture fermentation of cereals and millets (sorghum, finger millet, maize), pulses and legumes (soybean, chickpea, faba bean, lentil), oilseeds, cassava and other roots/tubers, and selected fruits and vegetables [35]. Integration into value-added products supports sustainable processing and circular-bioeconomy goals.

8. Materials and Methods / Review Methodology

Literature was retrieved from PubMed, Scopus, Web of Science and Google Scholar using combinations of the terms “fermentation”, “biofortification”, “phytate”, “mineral bioavailability”, “lactic acid bacteria”, “cereals”, “legumes” and related keywords. Peer-reviewed English-language articles (primarily 2015–2025, with seminal earlier works) reporting quantitative nutritional, functional or safety outcomes were included. Data on nutrient changes, antinutrient reduction and process parameters were extracted and synthesised narratively, with emphasis on mechanistic consistency across studies.

9. Results / Evidence Synthesis

Across substrates, fermentation consistently elevates protein digestibility (typically 10–15 % or greater), free amino acids, selected B vitamins and phenolic content while reducing phytate, tannins and other antinutrients by 40–90 %. Mineral bioavailability indices improve correspondingly. Outcomes vary with microorganism, substrate matrix and process conditions; SSF often favours phenolic release and enzyme activity, whereas SmF may enhance soluble nutrients. Variability among studies underscores the need for standardised protocols.

10. Discussion

Fermentation is effective because it simultaneously activates endogenous enzymes, supplies microbial enzymes and creates an acidic microenvironment that favours nutrient liberation and pathogen control. Strain selection and parameter optimisation are decisive. Industrial scalability requires robust starter cultures, reproducible processes and acceptable sensory profiles. Consumer acceptance, regulatory frameworks for novel fermented foods, and economic feasibility in diverse settings remain practical considerations. Evidence is strongest for phytate reduction and mineral bioavailability; claims regarding specific health outcomes require further controlled trials.

11. Future Perspectives

Precision fermentation, genomic and metagenomic strain engineering, AI-assisted culture selection, multi-omics optimisation, and development of synbiotic products from underutilised and climate-resilient crops offer substantial opportunities. Controlled industrial systems and personalised nutrition applications represent logical next steps.

12. Conclusion

Fermentation-based biofortification improves nutritional quality of agricultural foods through microbial enzyme action and metabolite production, reduces antinutritional factors, enhances functional properties and contributes to food safety and sustainability. Realisation of its full potential for food and nutritional security depends on standardised processes, rigorous validation and integration into scalable food systems.

Table 1: Major microorganisms used in fermentation-based biofortification and their nutritional functions

Microorganism	Food substrate	Major metabolic activity	Nutritional improvement	Functional benefit
Lactiplantibacillus plantarum	Cereals, legumes, millets	Phytase, protease, organic acids	Phytate ↓, minerals ↑, lysine ↑	Digestibility, mineral bioavailability
Lactobacillus spp. / LAB consortia	Cereals, pulses	Folate & riboflavin synthesis, acidification	B vitamins ↑, protein digestibility ↑	Probiotic potential, antioxidant activity
Saccharomyces cerevisiae	Cereals, legumes	Proteolysis, vitamin synthesis	Free amino acids ↑, B vitamins	Flavour, digestibility
Bacillus subtilis	Soybeans, legumes	Alkaline fermentation, menaquinone	Vitamin K_2 ↑, protein enrichment	Bioactive peptides
Rhizopus / Aspergillus spp.	Soy, legumes, cereals	Protease, phytase, tannase	Protein digestibility ↑, antinutrients ↓	Antioxidant capacity
Propionibacterium freudenreichii	Plant by-products, cereals	Vitamin B_{12} synthesis	Vitamin B_{12} enrichment	Micronutrient fortification

Table 2: Effects of fermentation on nutrients and antinutritional factors in agricultural foods

Food category	Nutrient/component	Fermentation effect	Mechanism	Expected nutritional significance
Cereals & millets	Phytate	50–90 % reduction	Phytase + acidification	Fe, Zn, Ca bioavailability ↑
Legumes & pulses	Protein digestibility	10–15 % or greater increase	Proteolysis + inhibitor ↓	Amino-acid availability ↑
Cereals, legumes	Folate, riboflavin	Several-fold increase	Microbial synthesis	B-vitamin status improvement
Various plant foods	Tannins, oxalates	Substantial reduction	Tannase, acid hydrolysis	Mineral & protein absorption ↑
Cereals, legumes	Phenolics & antioxidants	Release & biotransformation	Enzymatic liberation	Antioxidant capacity ↑
Soy & legumes	Vitamin K_2, B_{12}	Enrichment	Microbial biosynthesis	Micronutrient density ↑

Table 3: Technological parameters, benefits, limitations and applications of fermentation-based biofortification

Fermentation method	Key parameters	Major advantages	Limitations	Food applications	Future opportunities
Solid-state (SSF)	Moisture 40–70 %, 25–40 °C, 24–96 h	High enzyme activity, low effluent, residue utilisation	Heat & mass transfer control	Cereal/legume flours, tempeh-type products	Precision SSF, underutilised crops
Submerged (SmF)	Liquid medium, controlled pH/temperature	Uniform mixing, scalable	Higher water use	Beverages, soymilk, porridges	Continuous systems, probiotic carriers
Spontaneous	Ambient conditions, natural microbiota	Low cost, traditional	Variable outcomes	Traditional fermented staples	Starter-culture standardisation
Controlled starter	Defined strains, optimised time/pH	Reproducibility, targeted biofortification	Culture cost & maintenance	Functional foods, industrial products	AI/omics-guided selection

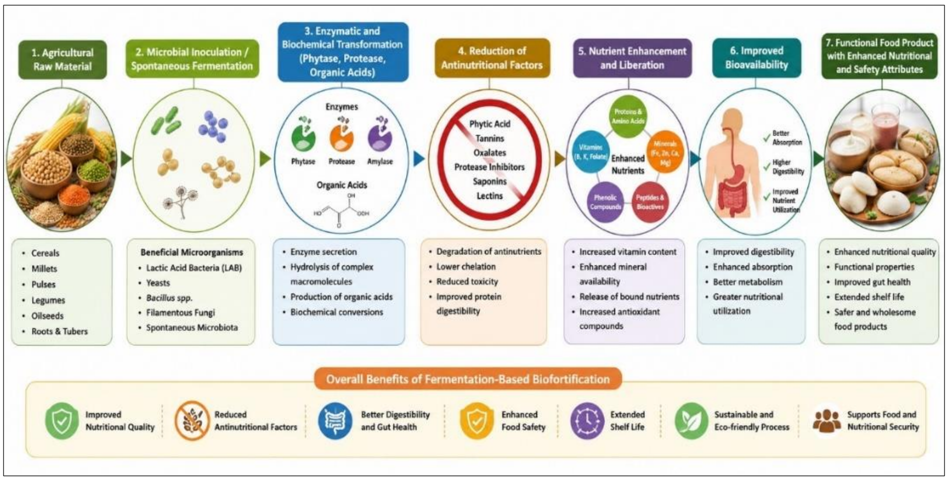

Fig 1: Schematic representation of the fermentation-based biofortification pathway

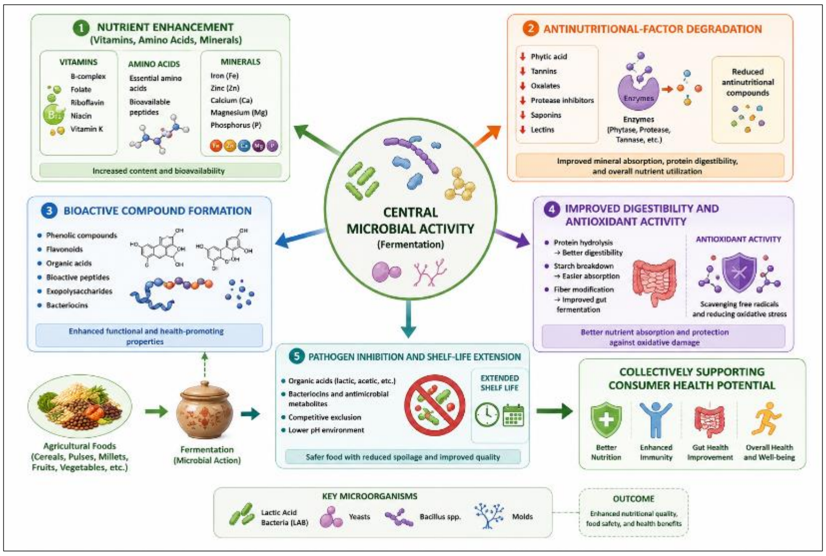

Fig 2: Integrated effects of fermentation on nutritional quality, functional properties and food safety

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